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The aim of the conference is to bring together researchers and administrators from different countries, and to discuss theoretical and practical issues in all fields of Engineering, Technology and Basic Sciences.

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A Data-Driven, Survey-Based Bottom-Up Load Modeling and Optimization Framework for Hybrid Renewable Energy Systems in Standalone Microgrids

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Abstract: The precise configuration of standalone hybrid renewable microgrid systems in remote regions is frequently obstructed by a critical lack of historical consumption data. This paper introduces a mathematically rigorous, data-driven framework that bridges this "information gap" by merging bottom-up, appliance-level load modeling with stochastic Monte Carlo simulations. In contrast to conventional top-down modeling, which frequently results in inefficient over-capitalization or compromised energy reliability, this research adopts an approach that captures the inherent stochasticity of both human behavior and environmental fluctuations. By leveraging scenario-driven stochastic optimization grounded in a 95th-percentile (P95) design benchmark, the study identifies an optimal configuration of 1,000 kWp in solar PV capacity coupled with an 800 kWh battery storage system. This specific architecture is engineered to sustain grid stability even during protracted multi-day solar deficits within the project zone. From a techno-economic perspective, the system achieves a leveled cost of energy between \$0.17 to \$0.52 per kWh and a substantial 87% reduction in carbon footprint. Ultimately, this framework offers a transferable and scalable model for implementing sustainable power solutions in data-limited regions globally.

Keywords: Microgrid, Optimal sizing, Renewable energy, Load modeling

Introduction

The global shift toward decentralized energy systems has positioned standalone microgrids as a primary mechanism for achieving universal energy access in isolated and islanded communities (Lassalle & Martínez, 2021; Vera et al., 2022). However, the successful implementation of these systems is often compromised by a fundamental lack of prior demand data (Sayani et al., 2022). When engineers rely on aggregated regional benchmarks (top-down estimation), they frequently miss the nuanced, stochastic usage patterns of rural households (Alahmed & Al-Muhaini, 2021; Dosa et al., 2025). This misalignment typically results in "sizing mismatches," where the system is either prohibitively expensive due to over-engineering or unreliable due to under-capacity (Qiu & Entchev, 2024; Sayani et al., 2022).

Recent advancements in the field emphasize that high renewable penetration (exceeding 90%) is only attainable through granular, bottom-up modeling that captures specific appliance-level behaviors (Alahmed & Al-Muhaini, 2021; Qiu & Entchev, 2024; Rajbhandari et al., 2023). Furthermore, the dual uncertainty of weather-dependent generation and unpredictable user demand requires a transition from rigid deterministic models to scenario-

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based stochastic optimization (Antoniadou-Plytaria et al., 2022; Cabrera-Tobar et al., 2022; Takam & Fruiba, 2025). This study fills a critical gap in contemporary research by presenting a six-stage methodology that integrates on-site ethnographic data with advanced probabilistic analytics to optimize both technical reliability and economic feasibility (Farhadi & Iqbal, 2024).

Method

The proposed framework utilizes a structured, sequential workflow designed to eliminate the guesswork from remote microgrid design. Fig. 1 presents the proposed six-stage methodology for data-driven microgrid sizing.



Figure 1. Proposed six-stage methodology for data-driven microgrid sizing

The survey data collection successfully captured appliance-level usage patterns from 119 responses across 383 fields, including 84 appliance-related fields. Survey data includes appliance ownership, rated wattage, quantity, and hourly usage patterns for residential, commercial, and institutional loads.

Bottom-Up Data Acquisition: Primary demand data were gathered through on-site household surveys, capturing detailed inventories of appliances, rated power, and daily usage cycles (Sayani et al., 2022). Utilization factors were applied per hour to each appliance category to reflect realistic daily peaks, particularly the evening residential surges common in off-grid settings (Lassalle & Martínez, 2021).

Diversity Factor Application: To avoid the trap of coincidence peak overestimation, a diversity factor was applied to the total connected load, ensuring the system is sized for realistic simultaneous usage (Yamegueu et al., 2024).

Probabilistic Scenario Simulation: Thousands of potential demand and solar irradiance scenarios were generated using Monte Carlo simulations (Cabrera-Tobar et al., 2022; Ghasemi et al., 2022). K-means clustering was then utilized for scenario reduction to maintain computational efficiency while preserving real-world variability (Pothireddy & Vuddanti, 2024).

Techno-Economic Multi-Objective Optimization: System sizing for the PV arrays, battery energy storage systems, and diesel backup was conducted to minimize both the Net Present Cost and carbon emissions (Farhadi and Iqbal, 2024; Maoulida et al., 2025; Zhu et al., 2022).

Uncertainty Assessment: Sensitivity analysis was performed to test the system's resilience against exogenous variables like fuel price shocks and varying annual demand growth rates (Barnes et al., 2022; Maoulida et al., 2025).

The study was conducted in the Municipality of Agutaya, located in the Province of Palawan, Philippines, selected due to its critical need for a sustainable microgrid system. The specific site of interest is the island village of Concepcion, which faces ongoing challenges in achieving reliable and efficient energy access. Table 1 shows the techno-economic input parameters used for hybrid PV–diesel–battery system modeling and optimization.

To establish a robust framework for system sizing and performance optimization, an annual electrical consumption of 1,615,123 kWh was defined as the primary load baseline. The financial architecture of the solar photovoltaic array includes an initial capital investment of PHP 65,000 per kW and an annual operational and maintenance allocation of PHP 1,400 per kW. Given the site's average solar irradiance of 4.39 kWh/kWp/day, the high resource potential reinforces the economic and technical feasibility of large-scale PV integration in this context.

Conversely, the diesel generation component exhibits a distinct cost profile, requiring a lower upfront expenditure of PHP 28,000 per kW but incurring higher variable operating costs of PHP 2.5 per kWh plus fixed O&M fees. This disparity underscores a fundamental trade-off: while diesel units offer lower entry costs, their long-term operational burdens often outweigh the higher initial investment required for renewable alternatives. Table 2 shows the mathematical equations utilized for the calculations.

Table 1. Techno-economic input parameters

Parameter	Unit	Value
Project Lifetime	Years	20
Discount Rate	%	9.0
Annual Load Growth	%/year	4.0
Initial Load Demand	kWh/year	1,615,123
PV Capital Cost	PHP/kW	65,000
PV O&M Cost	PHP/kW/year	1,400
Solar Irradiance	kWh/kWp/day	4.39
Diesel CAPEX	PHP/kW	28,000
Diesel OPEX (Variable)	PHP/kWh	2.5
Diesel OPEX (Fixed)	PHP/kW/year	300
Fuel Consumption Rate	L/kWh	0.30
Diesel Fuel Price	PHP/L	65
Fuel Price Escalation	%/year	3.0
Battery CAPEX	PHP/kWh	27,000
Battery O&M Cost	PHP/kWh/year	405
Battery Efficiency	%	90
Depth of Discharge	%	80
Battery Lifetime	Years	10
System Losses	%	5.0
Stability Factor	% of Load	40

Table 2. Mathematical equations for load modeling and optimization.

Eq.	Equation	Variables / Description
(1)	$P_{i,t} = N_i \cdot P_i^{\text{rated}} \cdot U_{i,t}$	$P_{i,t}$: power of appliance i at time t (kW); N_i : number of units; P_i^{rated} : rated power (kW); $U_{i,t}$: utilization factor
(2)	$P_t^{\text{total}} = \sum P_{i,t}$	P_t^{total} : total load (kW); n : number of appliance types
(3)	$E_{\text{annual}} = \sum (P_t^{\text{total}} \cdot \Delta t)$	E_{annual} : annual energy (kWh); Δt : time step (h)
(4)	$P_{\text{max,div}} = P_{\text{connected}} / DF$	$P_{\text{connected}}$: connected load (kW); DF : diversity factor
(5)	$X^{(k)} \sim f_x(x)$	$X^{(k)}$: random sample; $f_x(x)$: probability distribution
(6)	$E[P_i] = (1/N) \sum P_i^{(k)}$	$E[P_i]$: expected load; N : number of simulations
(7)	$P_i^{\text{p95}} = \text{Percentile}_{95}(P_i^{(k)})$	P_i^{p95} : 95th percentile load
(8)	$E^{\text{PV}} = P^{\text{PV}} \cdot H \cdot PR$	P^{PV} : PV capacity (kW); H : irradiance (kWh/kWp/day); PR : performance ratio
(9)	$F = \alpha E^{\text{DG}} + \beta P^{\text{DG,Grated}}$	F : fuel consumption (L); α, β : coefficients
(10)	$E^{\text{DG}} = \sum (P^{\text{DG}}_{i,t} \cdot \Delta t)$	$P^{\text{DG}}_{i,t}$: diesel power (kW)
(11)	$\text{SOC}_t = \text{SOC}_{t-1} + (\eta_{\text{ch}} \cdot P_{\text{ch},t} - P_{\text{dis},t} / \eta_{\text{dis}}) / E_{\text{bat}}$	SOC_t : state of charge; $\eta_{\text{ch}}/\eta_{\text{dis}}$: efficiencies; E_{bat} : battery capacity
(12)	$\text{SOC}_{\text{min}} \leq \text{SOC}_t \leq \text{SOC}_{\text{max}}$	SOC limits
(13)	$\text{DOD} = 1 - \text{SOC}_{\text{min}}$	Depth of discharge
(14)	$P^{\text{PV}}_{i,t} + P^{\text{DG}}_{i,t} + P_{\text{dis},t} = P_{\text{load},t} + P_{\text{ch},t} + P_{\text{loss},t}$	Power balance
(15)	$\text{NPC} = \sum [C_i / (1+r)^i]$	NPC: net present cost; C_i : cost; r : discount rate
(16)	$\text{LCOE} = \sum [C_i / (1+r)^i] / \sum [E_i / (1+r)^i]$	LCOE: cost per kWh
(17)	$\text{CO}_2 = E_{\text{diesel}} \cdot F$	E_{diesel} : emission factor
(18)	$\min (w_1 \cdot \text{NPC} + w_2 \cdot \text{CO}_2)$	w_1, w_2 : weighting factors
(19)	$\text{REF} = E^{\text{PV}} / E_{\text{total}}$	Renewable fraction
(20)	$S = (\Delta \text{Output} / \text{Output}) / (\Delta \text{Input} / \text{Input})$	Sensitivity index
(21)	$P_{\text{supply},t} \geq P_{\text{load},t}^{\text{p95}}$	Reliability constraint

Results and Discussion

The synthesized load curves highlight a substantial evening peak, a characteristic stress point for battery storage in isolated microgrids (Lassalle and Martínez, 2021). Fig. 2 shows the result of the stochastic bottom-up load profile for the study area in year 5.

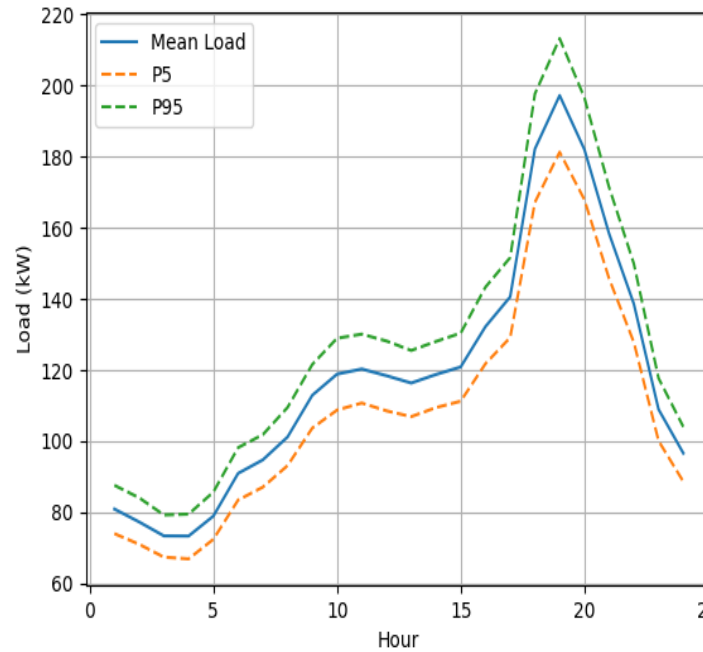


Figure 2. Daily load profile comparison: deterministic vs. stochastic (year 5)

The Monte Carlo simulation results for the Year 5 load profile illustrate the expected daily demand pattern along with its associated uncertainty. The mean curve represents the most probable load behavior, showing a gradual increase from early morning values of around 80 kW to a pronounced evening peak approaching 200 kW. This peak typically occurs between hours 18 and 19, reflecting higher consumption during nighttime activities.

The difference between the 5th (P5) and 95th (P95) percentiles provides a clear metric for quantifying load volatility, which is fundamentally tied to the daily demand cycle. While this interval remains relatively tight during low-utilization periods, it undergoes a marked expansion as the system approaches its peak, signifying a drop in predictive certainty during high-load scenarios. This correlation suggests that the grid is most susceptible to forecasting errors precisely when operational pressure is at its maximum. Consequently, the observed divergence in these probabilistic bounds underscores the necessity for maintaining robust reserve margins to buffer against unforeseen consumption surges.

The results confirm that initial demand forecasting errors are not linear; even small inaccuracies can lead to disproportionately high operational costs if the system relies too heavily on diesel backup (Sayani et al., 2022; Yamegueu et al., 2024). By adopting the P95 load profile, a standard ensuring the system meets demand in 95% of all simulated scenarios, the framework provides a robust "safety buffer" against unexpected surges and solar intermittency (Antoniadou-Plytaria et al., 2022; Melamu & Orumwense, 2025).

In the primary case study, an optimized 1,000 kWp solar PV and 800 kWh battery energy storage system configuration significantly outperformed traditional deterministic models. Specifically, the stochastic approach accounted for extended periods of low solar radiation that deterministic models typically ignore, thereby reducing the required operational run-time of carbon-intensive diesel generators (Rangel et al., 2023; Yamegueu et al., 2024). Economic viability was scrutinized over a 20-year project lifecycle using LCOE modeling (Elmouatamid et al., 2024; Farhadi and Iqbal, 2024). The year 5 load profile was employed during the optimization phase to ensure that the proposed system is capable of meeting the projected future energy demand of the study area.

Environmentally, the transition to this optimized hybrid configuration achieved a significant reduction in carbon intensity. While initial capital investment remains higher than diesel-only setups due to storage costs, the near 90% reduction in lifetime fuel consumption provides a strategic hedge against the extreme price volatility of global oil markets (Clairand et al., 2021; Rangel et al., 2023).

Technical assessments of the battery energy storage system components showed that while the levelized cost of energy (LCOE) is relatively stable across minor technical fluctuations, the environmental performance (CO₂ emissions) is highly sensitive to round-trip charging efficiency (Zhu et al., 2022, 2024). This underscores the necessity for future research studies to prioritize high-efficiency storage technologies, as battery losses directly correlate with increased diesel backup run-time (Moosavi et al., 2025; Zhu et al., 2024). Table 3 shows the summary of optimization results for the Hybrid PV–Diesel–Battery microgrid system.

Table 3. Summary of optimization results for the hybrid PV–diesel–battery system

Parameter	Unit	Value
Gross Annual Consumption	kWh/year	1,615,123
PV Capacity	kW	1,000
Battery Capacity	kWh	800
Diesel Capacity	kW	500
PV Generation	kWh/year	1,603,080
Diesel Generation	kWh/year	796,400
Battery Throughput	kWh/year	451,231.6
Fuel Consumption	L/year	268,378.4
LCOE	PHP/kWh	28.37
Renewable Energy Share	%	50

The optimization results demonstrate that the proposed hybrid energy system effectively meets the projected Year 5 demand profile. Analysis of the data indicates that the system supports an annual consumption of approximately 1.62 GWh, with a balanced contribution from both renewable and conventional sources. Notably, the installed 1,000 kW solar PV system generates approximately 1.60 GWh annually, accounting for a substantial portion of the total energy requirement and closely aligning with the overall demand.

To ensure reliability during peak and low solar periods, the system is complemented by an 800 kWh battery storage and a 500 kW diesel generator. Despite the presence of diesel backup, fuel usage remains relatively controlled at around 268,000 liters per year, indicating a strong reliance on renewable energy. The battery also plays a critical role, with a throughput exceeding 451 MWh annually, helping smooth fluctuations and enhance system stability.

Conclusion

This study demonstrates that the synthesis of bottom-up behavioral granularity and stochastic optimization offers a significantly more reliable foundation for microgrid design than traditional top-down estimation. By utilizing Monte Carlo simulations and a P95 design standard, we can ensure system resilience in the face of both demand and resource uncertainty. The findings validate that these integrated frameworks are not only cost-competitive, with LCOE values as low as \$0.17/kWh, but also essential for achieving the carbon reduction targets required for sustainable rural electrification.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Artificial Intelligence Reduced Order Observer Design for Output Feedback Control

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Abstract: In modern control engineering, the rising demand for streamlined state estimation in dynamic systems has made the development of reduced-order observers a critical area of study. This paper explores the integration of neural networks into observer design, utilizing their specialized ability to learn unknown dynamics and approximate complex nonlinear functions. In this paper, we propose the use of neural-network-based reduced-order observer designed which maps the relationship between system inputs, measurable outputs, and hidden state variables. The method uses the physics-in-formed neural networks formulation, which provides a powerful paradigm for solving partial differential equations for large dimensions of dynamical systems. The method facilitates precise estimation even when a comprehensive analytical plant model is unavailable. By utilizing a reduced-order architecture, the framework minimizes computational overhead, making it ideal for real-time practical applications. Furthermore, the approach exhibits high resilience against parameter uncertainties and system nonlinearities. Simulation data confirms that this intelligent observer configuration delivers significant accuracy and strong convergence performance.

Keywords: Reduced order observer, Output feedback control, State-space representation, Artificial intelligence, Neural networks.

Introduction

In modern control systems, output feedback control is widely employed when full state measurement of a dynamic system is not available or practical. Many real-world systems contain internal state variables that cannot be directly measured due to physical limitations, sensor cost, noise sensitivity, or technological constraints (Farkane et al., 2025). In such cases, an observer is designed to estimate the unmeasured states of the system using the available output measurements and knowledge of the system model. The observer functions as a dynamic estimator that reconstructs the internal state vector by comparing the measured system output with the estimated output and correcting the estimation error continuously (Miao & Gatsis, 2022). This estimated state information is then used within the feedback controller to achieve the desired control performance. Observer-based output feedback control is particularly valuable because it allows the implementation of state feedback strategies without requiring direct measurement of every state variable (Padovani et al., 2024). The design objective of the observer is to ensure that the estimation error converges to zero rapidly so that the estimated states closely track the true system states over time. Consequently, the observer becomes an essential component in many practical control applications where complete state measurement is unavailable.

A neural-network-based observer is an advanced estimation technique used to reconstruct the internal states of a dynamic system when an output feedback control is desired and the state variables cannot be directly measured. In conventional control systems, observers such as the Luenberger observer or Kalman filter rely heavily on accurate mathematical models of the plant (Yuan et al., 2020). Neural networks, as an artificial intelligence technique, on the other hand offer an alternative approach when the system is highly nonlinear, uncertain, or difficult to model precisely (Zhang et al., 2014). Neural-network-based observer design has therefore been considered as an important research direction for modeling of dynamic systems. Early work in this area proposed adaptive recurrent neural-network observers in which neural weights are updated online for estimation while maintaining observer stability. Subsequent research improved these methods by relaxing restrictive assumptions and broadening applicability to wider classes (Huang et al., 2005). More recent studies have developed robust adaptive observers using multi-time-scale neural networks, demonstrating that Lyapunov-based learning laws can ensure bounded state, output, and weight-estimation errors while improving convergence and robustness (Fu et al., 2016). Additional neural observer frameworks have been proposed for networked control systems, delayed systems, and uncertain plants, where adaptive estimators learn system nonlinearities online without exact prior knowledge of the plant model (Hua & Guan, 2014).

As a matter of fact, many researchers presented different methodologies in developing improved observer design for output feedback control (Asadi & Moallem, 2025; Ailiang et al., 2020). However, in spite of the many algorithms developed, no method can provide acceptable results for all kinds of networks, as presented by many different methods presented early (Alsmadi et al., 2024; Alsmadi et al., 2020). In this paper, we will present a different artificial neural network technique for a reduced order observer that will permit the design of output feedback control with some advantages as illustrated in this paper. The reduced-order observer focuses only on estimating the dominant dynamics of the system, leading to reducing computational complexity and implementation cost. This makes it especially useful in real-time and embedded control applications, where efficiency is critical (Shin et al., 2025). The order of the new observer is based on how perturbed the system is; that is, the reduction process depends on the system time scale (Alsmadi et al., 2019). This time scale typically separates the system into *slow* and *fast* subsystems, allowing analysts to study each behavior independently through different techniques such as time-scale decomposition and boundary layer analysis. The system in this case reduces to a lower-order “slow” subsystem, while the fast dynamics are assumed to have reached their quasi-steady state.

Reduced Order Observer ANN Design

Artificial Neural Networks technology is a modern technique that excels in dealing with linear and mainly nonlinear problems and effectively handles massive amounts of information. In control systems, ANNs can be extensively and efficiently used in reduced order observer designs due to its robustness and accuracy in system performance. ANNs are characterized by their speed, high responsiveness, and high reliability based on their training (Jamil et al., 2015). The ANN observer is designed by first collecting input-output data from the plant under different operating conditions and then training a neural network to learn the hidden relationship between measurable inputs, outputs, and internal states. The proposed design process is presented as laid in Figure 1 for a full seventh order system with a third order reduced observer. In this section, we will present the main methodology sections as to where and how the ANN has been employed.

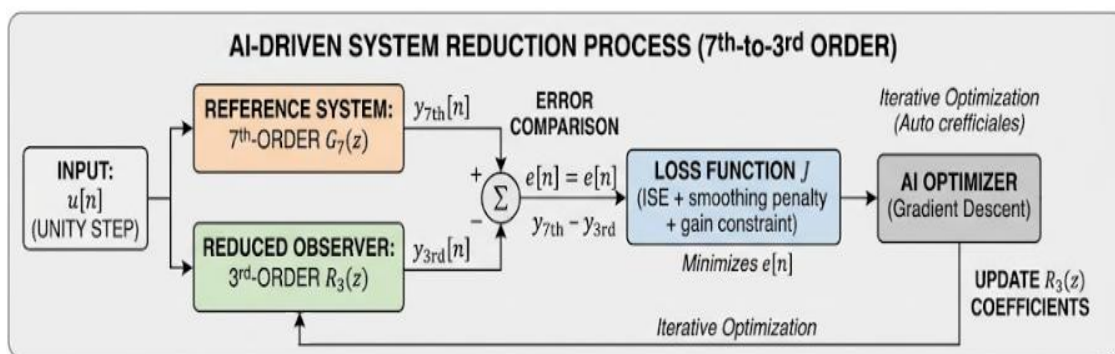


Figure 1. Reduced order observer design.

Here, we utilize a specialized type of Physics-Informed Neural Network (PINN) configured as an iterative optimization loop for system identification (Bai et al., 2026). This architecture does not only predict

coefficients; it also simultaneously predicts the coefficients and simulates the system to calculate the dynamic loss. The customized network for a third order reduced observer, seen in Figure 2, takes the system reference data as input and outputs the optimized coefficients of the minimized reduced-order observer. It consists of two main sections: A fully connected deep network to compress the dynamic features, and a physics-informed loss layer which uses the predicted coefficients (a_i, b_i) to simulate the discrete-time dynamics of the reduced observer.

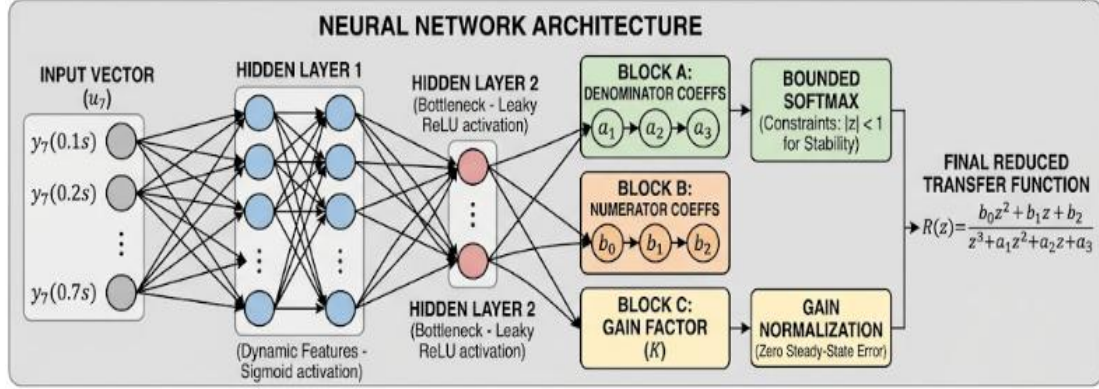


Figure 2. Neural network architecture of a reduced order observer design.

The initial section uses standard deep learning to map the full-order system response into a simplified vector representation. The network receives the vector containing the given samples of the full-order discrete-time response given as:

$$u_{input} = [y_{i_full_order}, i = 1, \dots, \# \text{ of sampled data}] \quad (1)$$

The input vector is then mapped through the first layer as following:

$$L_1 = \alpha_1[v_1 u_{input} + v_1] \quad (2)$$

where v_1 and v_1 are adjustable weights and biases of the first layer, and α_1 is the non-linear activation function.

The second hidden layer is an important layer as it forces the network to find the dominant poles (modes) while learning to reduce the observer to a minimized vector by applying the following representation:

$$L_{compressed} = \alpha_2[v_2 L_1 + v_2] \quad (3)$$

The output layer directly generates the coefficients of the reduced order observer,

$$\hat{C}_{coefficients} = [\hat{a}_i, \hat{b}_i]^T \quad (4)$$

while linear scaling and activation being used to ensure that the generated coefficients are maintained within a practical stable range as following:

$$\hat{C}_{coefficients} = \text{softmax}[v_3 L_{compressed} + v_3] \quad (5)$$

The primary equation driving the entire reduction process is the cost function (J), where the AI optimizer focuses on its minimization. The goal of training is to find a set of coefficients $(\hat{a}_i, \hat{b}_i)$ that minimizes the following total cost given by:

$$J(\hat{a}_i, \hat{b}_i) = w_1 \text{MSE} + w_2 \text{Spikiness_Penalty} \quad (6)$$

where w_i are customizable weights that define the optimization priorities, such as smoothness over absolute peak matching. Each term in the cost function represents a specific performance metric of the discrete-time system

response. The term MSE (Mean Squared Error) is used to force the reduced model observer to follow the original full order model through a given number, of samples. That is,

$$MSE = \frac{1}{N} \sum_{k=0}^{N-1} (y_{full_order}[k \Delta t] - y_{reduced_observer}[k \Delta t, \hat{a}, \hat{b}])^2 \quad (7)$$

where N is the total number of samples, and Δ is the sampling interval (0.1s).

The network updates are obtained by computing the partial derivative of the total cost with respect to all of the adjustable weights (v_i, v_i),

$$v_{new} = v_{old} - \eta \frac{\partial j}{\partial v_{old}} \quad (8)$$

In order to capture the important dynamics, especially at the transient period, we introduce the derivative penalty, where this term penalizes rapid changes. This term is given by:

$$Spikiness_Penalti = \frac{1}{N-1} \sum_{k=1}^{N-1} (y_{reduced_observer}[k] - y_{reduced_observer}[k-1])^2 \quad (9)$$

In addition to that, we enforce a constraint that ensures matching at the steady state. This constraint is given by

$$e_{gain} = (G_{full_order}(steady_state) - G_{reduced_observer}(steady_state))^2 \approx 0 \quad (10)$$

where G is the system DC gain.

Results and Discussion

To investigate the proposed reduced order observer model design, the following discrete 7th order system investigated in the literature is considered,

$$G(z)_{full} = \frac{2.0434z^6 - 4.9825z^5 + 6.57z^4 - 5.8189z^3 + 3.636z^2 - 1.4105z + 0.2997}{z^7 - 2.46z^6 + 3.433z^5 - 3.333z^4 + 2.546z^3 - 1.584z^2 + 0.7478z - 0.252}$$

As the system provides a response with different dynamics, especially for the transient response as seen in Figure 1, finding the reduced order observer was started with a very low order (i.e. 2nd order), then increasing finding the order as necessary to capture the dominant dynamics. Using the proposed methodology, the following 3rd order reduced observer was obtained

$$G(z)_{reduced_observer} = \frac{1.3268z^2 - 2.2378z + 1.0955}{z^3 - 2.1814z^2 + 1.8637z - 0.6288}$$

with two zeros and three poles.

To investigate the performance of this observer, the full order system and reduced order observer were simulated to a unity step input with results obtained as seen in Figure 3. As observed, the two responses converge within about 3 seconds, with a relatively acceptable range of error for the transient response. The new approach has also been investigated and compared with the performance of the work of (Telescu et al. 2013) Their reduced order model was obtained with a 5th order given as following:

$$G_r(z) = \frac{2.043z^5 - 3.057z^4 + 2.195z^3 - 1.545z^2 + 0.8617z}{z^5 - 1.518z^4 + 1.270z^3 - 1.032z^2 + 0.7539z - 0.3156}$$

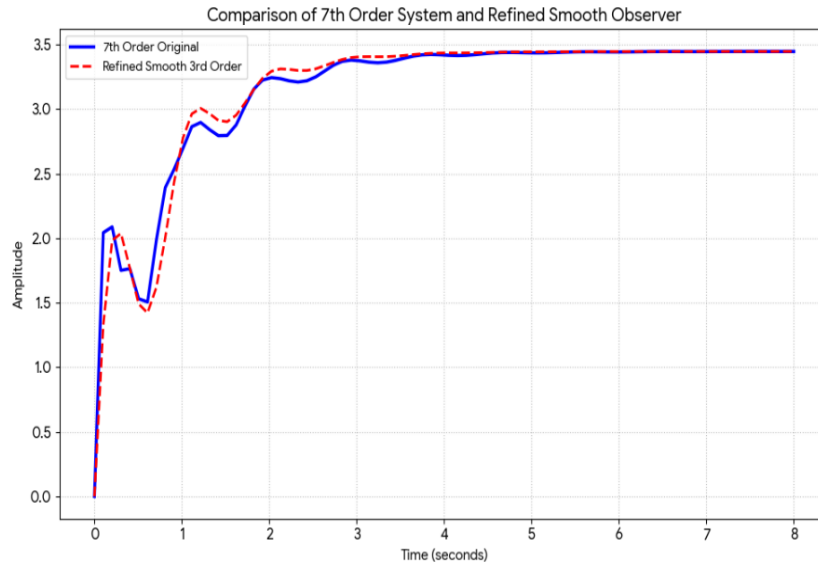


Figure 3. Full 7th order model and reduced 3rd order observer unity step responses.

Here, the model is given with five zeros and five poles (5th order reduced model), while ours is having only two zeros and three poles (3rd order reduced model). In addition to that, simulation results to a unity step inputs are obtained as shown in Figure 4. As observed, in addition to the previous notes, the Telescu's model diverges in less than two seconds.

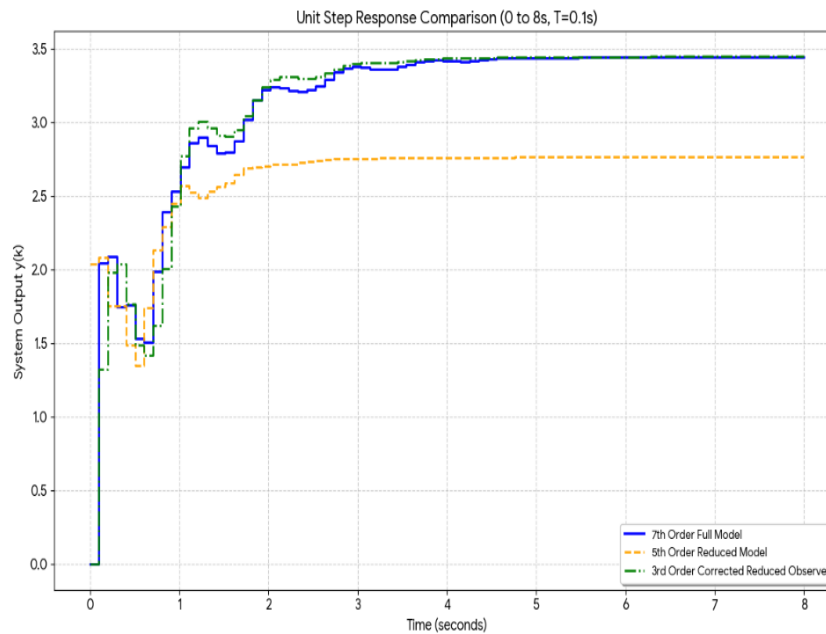


Figure 4. Full 7th order model, 5th and 3rd reduced order observers' unity step responses.

Conclusion

In this research, we have demonstrated that integrating artificial intelligence (AI) performed as (ANNs) into the design of reduced-order observers offers a highly effective and intelligent alternative to conventional estimation techniques derived from full-order systems. Using the learning capabilities of ANNs, the proposed approach successfully captures the essential system dynamics while significantly reducing model complexity for output feedback control. Results indicate that the neural-network-based reduced-order observer achieves superior estimation accuracy, faster convergence, and improved robustness when compared to traditional observer designs. This enhancement can be attributed to the adaptive nature of AI networks, which allows the observer to generalize nonlinear relationships and compensate for modeling inaccuracies that are typically difficult to handle using classical methods. Furthermore, the reduction in system order leads to lower computational

burden, making the approach more suitable for real-time implementation in practical control applications. Overall, the proposed methodology opens new directions for future research, particularly in extending the framework to strongly nonlinear systems where traditional methods may fail to deliver comparable performance.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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An Analysis on Recycled Aggregate Concrete Mixture Properties Through the Incorporation of Fava Bean Husk Fiber

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Abstract: Concrete recycling has been an important research topic considering minimizing energy consumption and its negative effects on the environment. After the February 6, 2023, earthquakes in Türkiye, construction and demolition waste (CDW), which is a huge amount, has been a major concern in order to eliminate environmental problems but also benefit from its possibilities as recycle concrete aggregate (RCA). Fly ash (FA) and blast furnace slugs (BFS) are one of the most used additives in RCA. This paper aims to examine both material properties and environmental performance of RC with a new bio-based fiber additive, fava bean husk fibers (FBHF). The study has two phases: (1) concrete mixture with FA and BFS are analyzed to have optimum performed sample and (2) C50S50 cod-ed sample is selected to create concrete mixture; FBHF are applied as secondary additives to the selected concrete mixture with different ratios, 3%, 6%, 9%, and their properties and environmental performance are evaluated. The findings point out that C50S50 coded sample is selected to create concrete mixture with FBHF. According to the analysis, S50FB3 is a good alternative to design non-loadbearing building materials. The use of concrete mixtures that contribute to the recycling of waste such as BFS and natural fiber, FBHF, used as admixtures contributes to reducing the environmental damage of these wastes.

Keywords: Recycled aggregate concrete mixture, Fava bean husk fiber, Mechanical analysis, Environmental analysis

Introduction

Cement production in concrete industry makes a huge contribution to CO₂ emissions and environmental damage. Cement factories responsible for more than 5% carbon dioxide emissions all around the world (Oh, 2014). Through concrete production, minimizing cement and natural aggregates decreases the negative effects of the concrete industry on the environment. Supplementary cementing materials (SCMs), like fly ash (FA) and blast furnace slugs (BFS) as additives roles for cement replacement may have been critical issue to contribute to reducing the CO₂ footprint of concrete production. Fly ash, waste marble, rubber, foundry sand slag are used as additives of concrete mixture (Bakharev et al., 2006; Imbabi et al., 2012; Rondi et al., 2016; De Domenico et al., 2018; Mwititi et al., 2018; Smirnova & Potyomkin, 2018; Smirnova et al., 2021). Recently, FA and BFS as additives have been commonly applied to concrete mix both for environmental concerns and improving material properties (Dinakar et al., 2013; Junak, 2015; Abbass et al., 2021; Ahmad et al., 2022; Tran et al., 2023).

It is pointed out that using ground-granulated blast slag (GGBS) in concrete mixture may reduce CO₂ emissions per ton of cementitious based materials (Thomas et al., 2012). Test results of a study present that compressive

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strength and strength of RAC mixtures, even though the cement replacement amount with BFS, reduced strength compared to NAC mixtures, however the strength gains for the BFS-based concrete are higher than the reference mixtures without BFS in long term (Lin & Wu, 2021). A study on RCA indicates that incorporation of 15% GGBS and 15% FA, 90 days compressive strength, frost resistance and chloride penetration resistance of RAC incorporating 50% RCA were performed better than an original concrete mixture (Chen et al., 2023). It is clear that using recycled aggregate is the most environmentally positive role in lower strength concrete compared to mechanical properties with natural aggregate concrete (NAC) (Bennett et al., 2022).

Besides additives, aggregates are the fundamental input that can directly affect engineering and economical properties of concrete mix. It is indicated that more than 165 million tons of natural aggregates are used in various constructions every year (Limbachiya et al., 2012). Considering the amount of aggregates used in concrete mix, it has been significant issue to preserve natural sources and find a beneficial way to have aggregate in concrete mix. Therefore, recycled concrete aggregates are a good alternative to minimizing natural source consumption and reuse of construction demolition waste.

In developing countries as Türkiye, based on fast growth and urbanization, a growing need for infra-structure and housing have been occurred. As a most demanded construction material, concrete has is required to develop sustainable solutions regarding global concerns. Concrete consists of approximately 50-70% natural coarse aggregate (NCA). Therefore, NCA plays a significant role in carbon footprint of concrete mix. Using recycled concrete aggregate instead of NCA in concrete mix is being prioritized to conserve natural resources. Construction and demolition waste (CDW) is the major source of RCA. After the February 6, 2023, earthquakes in Türkiye, CDW has been a critical issue. Doğdu and Alkan (2023) indicated that after Kahramanmaraş earthquakes approximately 38 million tons of concrete waste was generated. It is observed that using recycling concrete (RC) can be a good alternative of natural sources considering environmental sustainability (Alkan et al., 2025).

This study presents a novel approach to design a concrete mixture of recycled aggregate concrete, RAC through the effect of fly ash (FA), blast furnace slugs (BFS) and sustainable natural fibers, particularly fava bean husk fibers (FBHF). In the context of rapidly developing countries as Türkiye, where there is a critical concern considering sustainable construction materials due to the increasing infrastructure demands, this paper addresses a gap by examining alternative concrete mixture design with sustainable additives to optimize concrete performance of RAC for non-structural elements such as brick. While prior research has examined FA and BFS as additives, this study focuses on the comparative effectiveness of mechanical performance of FA and BFS in high-RCA mixes. This research is distinctive in its incorporation of FBHF in terms of economical and environmentally sustainable reinforcement while supporting ecological objectives using agricultural waste. Additionally, this study also evaluates the combined effects of activated BFS and natural fiber reinforcement, FBHF, aiming to design a concrete mixture for non-structural elements that balance strength, sustainability, and economic feasibility.

Method

The paper is structured into three phases in order to optimize and test samples for concrete mixtures' performance enhancement. The first phase presents laboratory test on concrete mixtures with RCA and different additives. EN 196-2 standard is applied for laboratory tests. In the second phase, environmental analysis of the samples is evaluated. Laboratory tests were done in two steps.

In the first step, mechanical tests results of FA and BFS as additives are analyzed. This phase identifies the most effective concrete mixture using FA and BFS additives. Various proportions of FA and BFS are tested to evaluate mechanical properties of the samples. The coded system is based on the ingredients and the proportion of the concrete mixtures. Letters and their codes are presented in the following: C: concrete, F: BFS, S: BFS, FB: FBHF. The second phase presents concrete mixture design with FBHF and mechanical tests of the samples. Based on the results of the first phase laboratory tests, C50S50 coded sample is selected to create concrete mixture with FBHF. %50 BFS with different percentages of FBHF reinforcements are tested in the second phase to determine an optimal concrete mixture design. The study concentrates on the relationships between BFS and FBHF in mechanical properties of concrete and the results obtained at two periods: 7 and 28 days. The concrete mixtures are grouped into three sets, each associated with the variation in FBHF content (3%, 6%, 9%). In this phase, the samples were examined to find out the best possible combination of BFS and FBHF. The third phase covers the environmental analysis of the samples applying a simplified life cycle assessment (LCA) approach. This analysis concerned: (i) carbon footprint (kg CO₂-equivalent per batch), (ii) natural resource

conservation, and (iii) waste utilization efficiency. For the first step of the laboratory tests, RCA with FA and BFS additives are designed. In Table 1, presented the samples and proportions.

Table 1. The concrete mixture with FA and BFS additives

Sample name	Cement (gr)	Fine aggregate (gr)	Recycled aggregate (gr)	Water (gr)	Fly ash (gr)	Blast furnace slugs (gr)
NA	250	1400	-	200	-	-
RA	250	-	1400	250	-	-
C50F50	125	-	1400	250	125	-
C25F75	62.5	-	1400	250	187.5	-
C50S50	125	-	1400	250	-	125
C25S75	62.5	-	1400	250	-	187.5

Laboratory Tests, Results and Discussions

Firstly, wet and dry weight of the samples are determined. The wet weight of the mixture, volume and unit volume weight of the samples is presented in Table 2. It is observed that when the additives ratio is increased, the unit volume weight of the concrete mixtures is reduced. However, there is not a specific difference between FA and BFS additives affecting unit volume weight of the concrete mixtures.

Table 2. The wet weight, volume, unit volume weight of the mixtures

Sample name	Wet weight of mixture (gr)	Volume of mixture (cm ³)	Unit volume weight of mixture (gr/cm ³)
NA	794.30	390	2.04
RA	736.4	390	1.89
C50F50	756.4	390	1.94
C25F75	736	390	1.89
C50S50	760.5	390	1.95
C25S75	744.9	390	1.91

The slump flow tests were studied (Figure 1). Based on the results, C50F50 and C50S50 have close value to NA concrete mixture. However, RA, C25F75 and C25S75 concrete mixtures' slump flow values are as close to 16 cm.

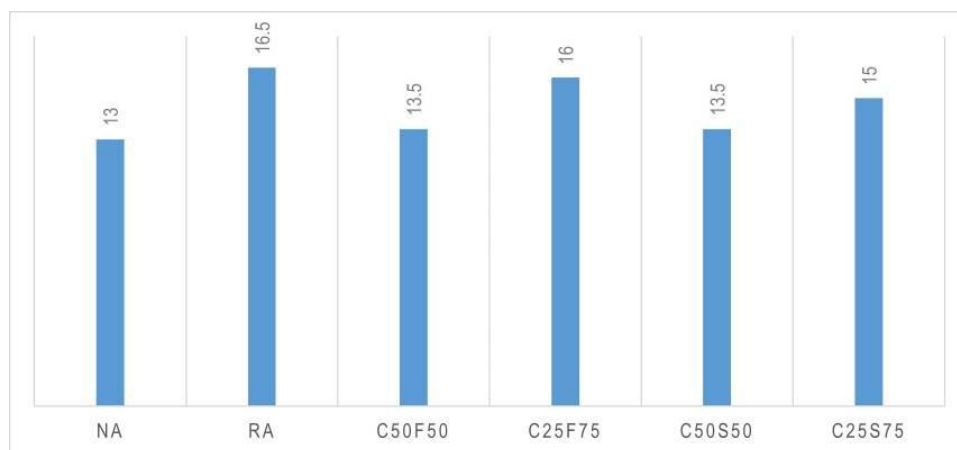


Figure 1. Slump flow test results

Figure 2 presents water absorption values of the samples after 7 and 28 days. It is clear that FA and BFS additives are directly related to water absorption values of the samples. C50F50 and C25F75 water absorption values both 7 and 28 days are indicated as approximately 100% higher than NA concrete mixture. Similarly, C50S50 and C25S75 water absorption values of 7 days are close to 100% higher than NA concrete mixture. Conversely, there is not a big difference between NA concrete mixture and C50S50, C25S75 water absorption values of 28 days.

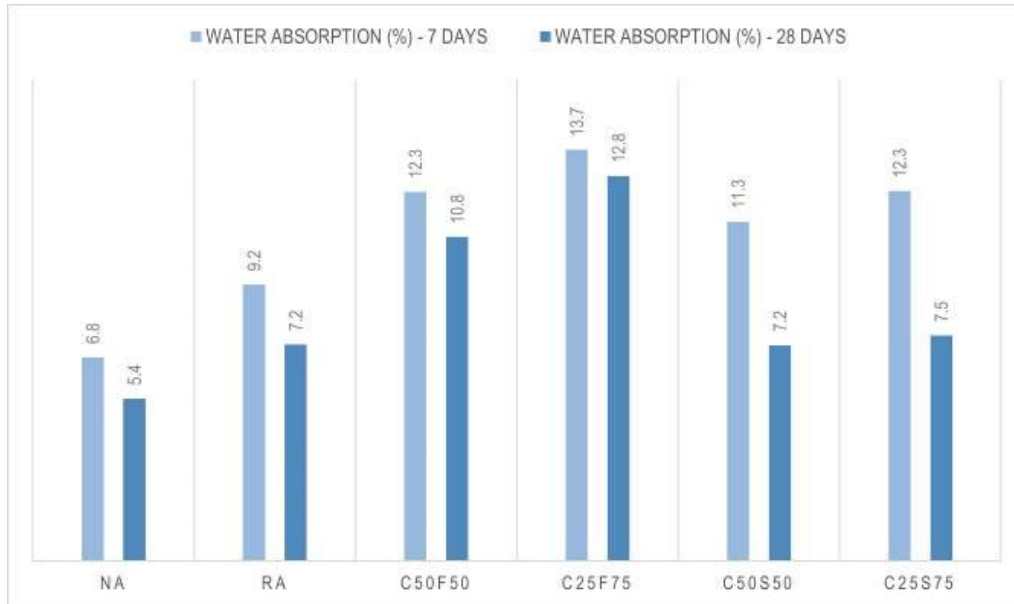


Figure 2. The water absorption values of the samples after 7 and 28 days

The compressive strength findings are illustrated in Figure 3. The results point out that there is not a specific difference in compressive strength values of both 7 and 28 days between NA concrete mixture and RA concrete mixture. The compressive strength value of NA concrete mixture is 15.61 N/mm² in 7 days and 23.15 N/mm² in 28 days. The compressive strength value of RA concrete mixture is 15.54 N/mm² in 7 days and 22.35 N/mm² in 28 days. Considering FA and BFS as additives, it is clear that samples with BFS performed better than FA especially after 28 days. To compare different ratios for BFS, compressive strength findings of C50S50 is better than C25S75 particularly in 28 days as 18.25 N/mm². On the other hand, compressive strength values of C25F75 are very low (2.01 N/mm² in 7 days, 5.20 N/mm² in 28 days).

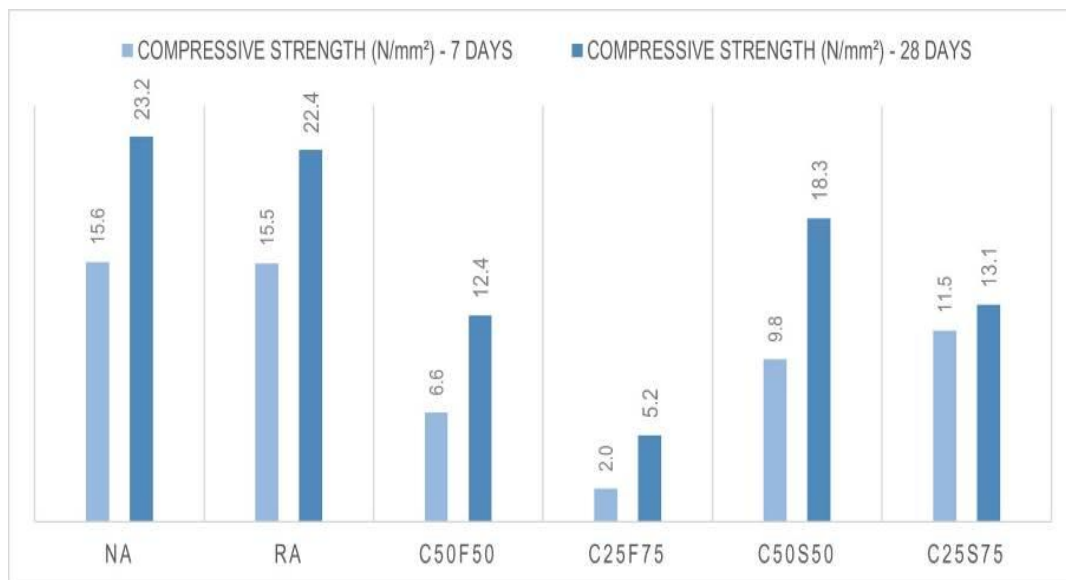


Figure 3. The compressive strength findings of the samples after 7 and 28 days

Figure 4 shows flexural strength findings. The results demonstrate that there is not a specific difference in flexural strength values of 28 days between NA concrete mixture and RA concrete mixture except 7 days values: 4.65 N/mm² for NA concrete mixture and 3.69 N/mm² for RA concrete mixture. The flexural strength value of NA concrete mixture is 4.11 N/mm² and the flexural strength value of RA concrete mixture is 4.48 N/mm² in 28 days. Regarding FA and BFS as additives, it is observed that samples with BFS performed better than FA especially after 28 days. To compare different ratios for BFS, flexural strength findings of C50S50 is better than C25S75 particularly in 28 days as 2.14 N/mm². Conversely, flexural strength values of C25F75 are very low (0.64 N/mm² in 7 days, 1.31 N/mm² in 28 days).

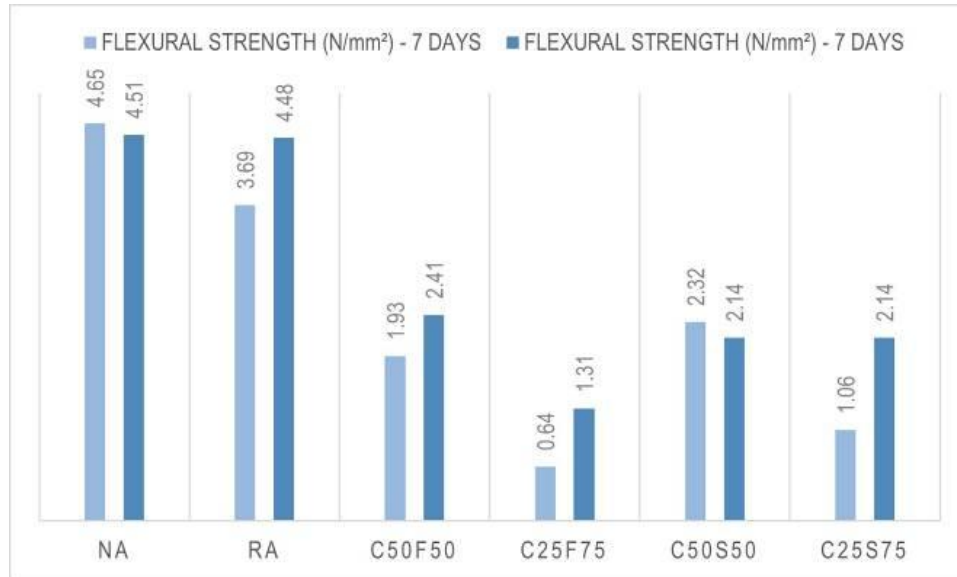


Figure 4. The flexural strength findings of the samples after 7 and 28 days

Depending on the results of mechanical analysis, C50S50 is selected as a concrete mixture for fiber concrete mixture design. In the first stage of the fiber mixture design process, fava bean husks were dried at room temperature. The dried fava bean husks were cut into 4-10 cm long fibers and 1-2 mm thick (Figure 5).



Figure 5. FBHF samples

Three different ratios have been determined for fiber mixtures. Table 3 shows the fiber mixtures and ratios.

Table 3. The fiber mixtures

Sample name	Cement (gr)	Recycled aggregate (gr)	Water (gr)	Blast furnace slug (gr)	Fava bean husk fibers (gr)
S50FB3	125	1400	250	125	3.45
S50FB6	125	1400	250	125	6.90
S50FB9	125	1400	250	125	10.35

Table 4 shows unit weight values of the samples. In order to make comparative analysis under the same situation the selected concrete mixture design, C50S50, is also re-evaluated throughout the test phases and named as C50S50-1.

Table 4. Wet weight, volume, unit volume weight and spread of the mixtures

Sample name	Wet weight of mixture (gr)	Unit weight (gr/cm³)
C50S50-1	701.7	1.80
S50FB3	699.7	1.79
S50FB6	722.4	1.85
S50FB9	713.7	1.83

The slump flow test results are represented in Figure 6. Based on the results, C50S50-1 and S50FB3 have same value as 16 cm. However, S50FB6 and S50FB9 concrete mixtures' slump flow values are same as 13.5 cm. It is observed that fiber addition may direct relation with slump flow of concrete mixtures.

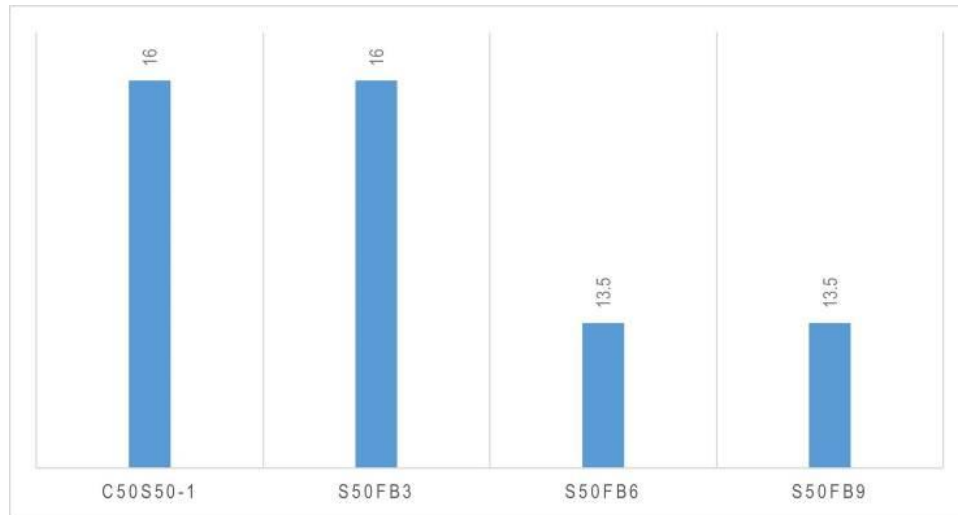


Figure 6. Slump flow test results

The water absorption values of the samples after 7 and 28 days are reported in Figure 7. It is seen that FBHF additive is directly affected by water absorption values of the samples. Especially in 28 days, water absorption values of the samples increased depending on the amount of FBHF in concrete mixtures. The water absorption value of C50S50-1 is 12.47% after 7 days and 9.01% after 28 days. The water absorption value of S50FB3 is 16.65%, S50FB6 is 16.03%, S50FB9 is 14.60% after 7 days. After 28 days, the water absorption value of S50FB3 is 11.30%, S50FB6 is 14.22%, S50FB9 is 17.53%. The differences in water absorption between S50FB3 and S50FB9 are approximately 6% after 28 days.

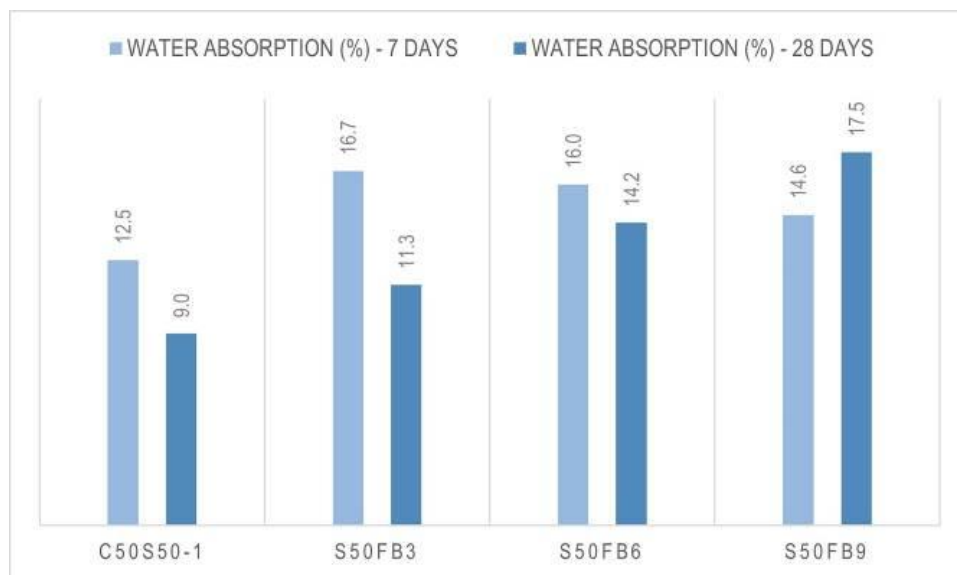


Figure 7. The water absorption values of the samples after 7 and 28 days

Figure 8 shows compressive strength findings (left) and flexural strength findings (right). The results indicate that there is a remarkable difference in compressive strength values between the samples and also 7 and 28 days. The compressive strength value of C50S50-1 is 6.57 N/mm² in 7 days and 11.77 N/mm² in 28 days. By FBHF additives, the compressive strength value decreased. The compressive strength value of S50FB3 is 3.74 N/mm² in 7 days and 9.66 N/mm² in 28 days. The compressive strength value of S50FB6 is 1.32 N/mm² in 7 days and 5.51 N/mm² in 28 days. The compressive strength value of S50FB9 is 0.64 N/mm² in 7 days and 2.67 N/mm² in 28 days. It is observed that FBHF additives affect the compressive strength of the sample negatively. Moreover, S50FB9 is not suitable for even non-load bearing building materials such as brick.

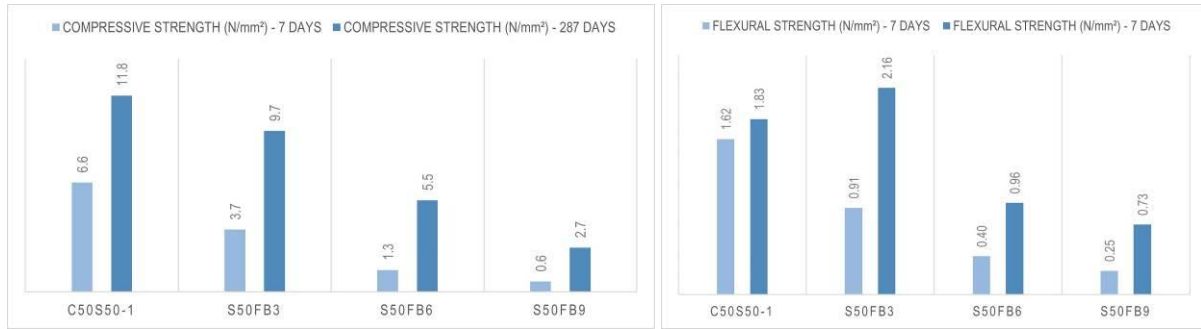


Figure 8. The compressive strength findings (left) and flexural strength findings (right) of the samples after 7 and 28 days

The samples remained intact without splitting after flexural strength tests. The flexural strength value of S50FB3 after 28 days is 2.16 N/mm² and the flexural strength value of C50S50-1 after 28 days is 1.83 N/mm². It is observed that with 3% FBHF perform better than C50S50-1 after 28 days considering flexural strength. However, 6% and 9% FBHF additives affect the flexural strength negatively. The flexural strength value of S50FB6 after 28 days is 0.96 N/mm² and the flexural strength value of S50FB9 after 28 days is 0.73 N/mm². Furthermore, it is clear that by time flexural strength of the samples with FBHF is rapidly increasing compared to C50S50-1. Figure 9 shows the load deflection curve of the samples after 7 days (above) and 28 days (below). The effects of fiber may not be observed in test results after 7 days. However, it is seen that fracture energy changes with the effects of fiber after 28 days. The results point out that 3% FBHF performed better than C50S50-1 after 28 days considering fracture energy. Therefore, it is possible to indicate that the increasing amount of fiber has not directly improved the flexural strength of the samples and fracture energy.

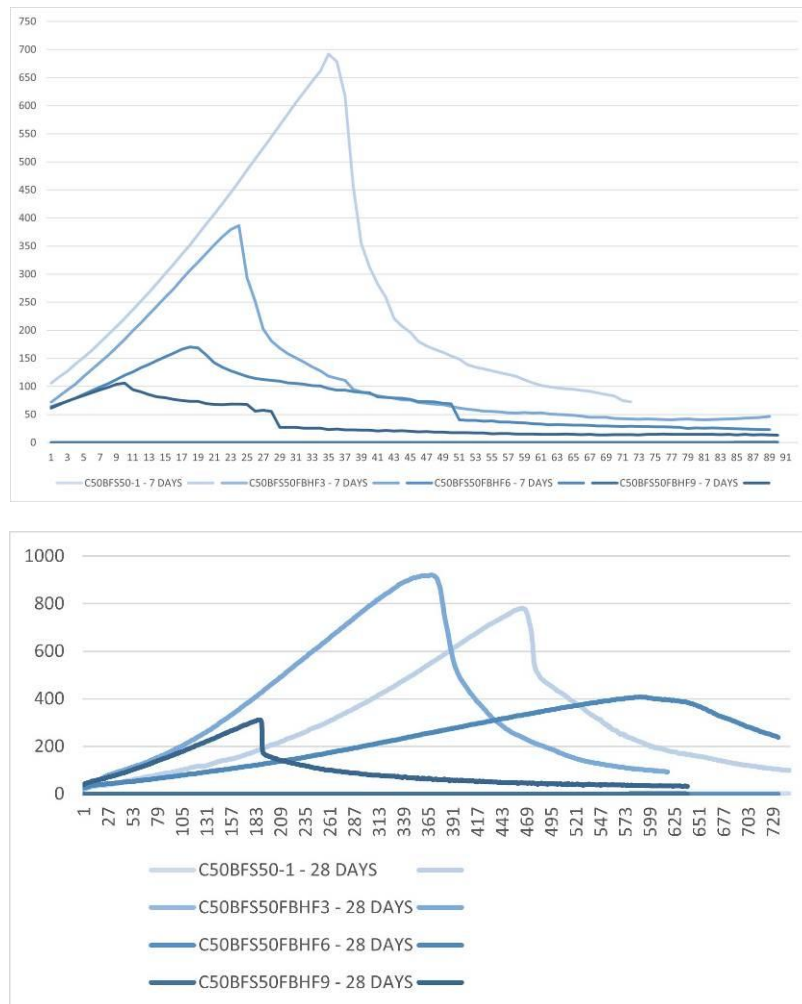


Figure 9. The load deflection curve of the samples after 7 days (above) and 28 days (below)

According to the laboratory tests results, S50FB3 may be an alternative for non-loadbearing building materials such as brick. Especially, compressive and flexural strength values of S50FB3 are close to C50S50-1.

Environmental Analysis

This study evaluates both mechanical and environmental performance of recycled aggregate concrete (RAC) mixtures incorporating fly ash (FA), blast furnace slag (BFS), and fava bean husk fibers (FBHF) using a simplified life cycle assessment (LCA) approach. The analysis adopts a cradle-to-gate system boundary, focusing on the material production and processing stages, which are known to dominate concrete's environmental impacts (Chen et al., 2010; Habert et al., 2011). The functional unit is defined as one laboratory-scale batch as specified in Tables 1 and 2, enabling direct comparison across all mix proportions. Three complementary indicators were quantified: (i) carbon footprint (kg CO₂-equivalent per batch), (ii) natural resource conservation, and (iii) waste utilization efficiency.

Emission Factors and System Boundary

Emission factors (EFs) for each constituent material were drawn from established LCA databases and peer-reviewed literature (Table 5). Portland cement was assigned an EF of 0.870 kg CO₂-eq/kg, consistent with IPCC (2006) and Habert (2011). Fly ash (FA) and ground granulated blast furnace slag (BFS) were treated as industrial by-products with markedly lower EFs of 0.027 and 0.060 kg CO₂-eq/kg, respectively, reflecting only the processing and transport burden rather than the full upstream production impact (Marceau et al., 2007). Recycled concrete aggregate (RCA) was assigned an EF of 0.015 kg CO₂-eq/kg, accounting for crushing and screening operations (Haber, 2011). Fava bean husk fibers (FBHF), being an agricultural residual, were assigned a negligible EF of approximately zero.

Table 5. Emission factors adopted for the cradle-to-gate LCA

Material	EF (kg CO ₂ -eq/kg)	References
Portland cement	0.870	IPCC, 2006; Habert (2011)
Natural fine aggregate	0.010	Marceau et al., 2007
Recycled concrete aggregate (RCA)	0.015	Serres et al., 2016
Fly ash (FA)	0.027	Chen et al., 2023
Ground granulated BFS	0.060	Habert, 2011
Water (tap)	0.000344	Wernet et al., 2016
Fava bean husk fiber (FBHF)	≈ 0.000	Agricultural waste – negligible

Carbon Footprint

The carbon footprint of each mixture was computed by summing the product of the mass of each constituent (kg) and its corresponding EF (kg CO₂-eq/kg), as expressed in formula (1):

$$CF = \sum (m_i \times EF_i)$$

where CF denotes the total carbon footprint (kg CO₂-eq), m_i is the mass of material i in the batch (kg), and EF_i is the corresponding emission factor. Results are presented in Table 6.

Table 6. Carbon footprint results for all mix designs

Sample	CO ₂ (kg/batch)	Cement CO ₂	Aggr. CO ₂	vs NA (%)
NA	0.2316	0.21750	0.01400	Baseline
RA	0.2386	0.21750	0.02100	+3.0%
C50F50	0.1332	0.10875	0.02100	-42.5%
C25F75	0.0805	0.05437	0.02100	-65.2%
C50S50	0.1373	0.10875	0.02100	-40.7%
C25S75	0.0867	0.05437	0.02100	-62.6%
S50FB3	0.1373	0.10875	0.02100	-40.7%
S50FB6	0.1373	0.10875	0.02100	-40.7%
S50FB9	0.1373	0.10875	0.02100	-40.7%

The reference mixture NA, composed entirely of Portland cement and natural fine aggregate, recorded a carbon footprint of 0.232 kg CO₂-eq per batch, with cement alone accounting for 93.9% of total emissions. Replacing natural aggregates with RCA (mixture RA) marginally increased the footprint to 0.239 kg CO₂-eq due to the energy required for RCA processing, while cement remained unchanged. Progressive substitution of cement with FA yielded substantial reductions. The C50F50 and C25F75 mixtures achieved footprint reductions of 42.5% and 65.2%, respectively, relative to NA. A comparable trend was observed for BFS-based mixtures: C50S50 and C25S75 attained reductions of 40.7% and 62.6%, respectively. The marginal difference between FA and BFS at equivalent replacement ratios (e.g., -42.5% vs. -40.7% at 50% replacement) reflects the slightly higher EF of BFS compared with FA.

The Phase 2 fiber-reinforced mixtures (S50FB3, S50FB6, S50FB9) maintained an identical carbon footprint of 0.137 kg CO₂-eq because the FBHF additive has a negligible EF. This confirms that incorporating agricultural fiber waste into the optimal BFS-substituted mixture introduces no additional carbon burden while potentially improving mechanical performance.

Natural Resource Conservation

Two dimensions of natural resource conservation were assessed. First, the substitution of natural fine aggregate with RCA was quantified in terms of avoided CO₂ emissions using the differential emission factor approach ($\Delta EF = EF_{\text{natural}} - EF_{\text{RCA}} = 0.010 - 0.015 = -0.005$ kg CO₂-eq/kg). It is noteworthy that RCA carries a slightly higher processing EF than natural aggregate in this study; consequently, the environmental benefit of RCA is realized primarily through conservation of primary mineral resources and landfill diversion rather than through direct carbon savings.

Second, cement replacement by SCMs was the primary lever for resource conservation. The C25F75 and C25S75 mixtures replaced 0.188 kg of cement per batch, yielding avoided cement-production emissions of 0.163 kg CO₂-eq per batch, equivalent to a 70.4% reduction relative to the cement-only carbon contribution in NA. At 50% replacement (C50F50, C50S50), avoided emissions amounted to 0.109 kg CO₂-eq per batch (50.0% reduction). Collectively, these results demonstrate that SCM-based cement substitution is the most impactful environmental lever available in the studied mix designs.

Waste Utilization Efficiency

Waste utilization efficiency (WUE) was defined as the mass fraction of industrial and agricultural byproducts, comprising RCA, FA, BFS, and FBHF, relative to the total batch mass in formula (2):

$$WUE (\%) = (m_{\text{waste}} / m_{\text{total}}) \times 100$$

Results are summarized in Table 7.

Table 7. Waste utilization efficiency and SCM replacement rates for all mixtures

Sample	Waste content (kg)	Total batch (kg)	WUE (%)	Cement replaced (kg)
NA	0.000	1.850	0.0%	0.000
RA	1.400	1.900	73.7%	0.000
C50F50	1.525	1.900	80.3%	0.125
C25F75	1.588	1.900	83.6%	0.188
C50BFS50	1.525	1.900	80.3%	0.125
C25BFS75	1.588	1.900	83.6%	0.188
C50BFS50FBHF3	1.529	1.904	80.3%	0.125
C50BFS50FBHF6	1.532	1.907	80.3%	0.125
C50BFS50FBHF9	1.535	1.910	80.4%	0.125

The reference mixture NA recorded a WUE of 0.0%, as no by-products were incorporated. The use of RCA alone (mixture RA) increased WUE to 73.7%, reflecting the dominant mass contribution of the aggregate fraction. Partial replacement of cement with FA or BFS at 50% (C50F50, C50S50) further increased WUE to 80.3%, while 75% replacement (C25F75, C25S75) raised it to 83.6%. The fiber-reinforced series maintained WUE values of approximately 80.3–80.4%, with a slight increase as FBHF dosage rose from 3.45 g to 10.35 g.

The convergence of high WUE values (>80%) with substantial reductions in carbon footprint (>40%) in BFS- and FA-substituted mixtures highlights their dual environmental benefit. These formulations both maximize the utilization of industrial by-products and reduce greenhouse gas emissions. The addition of FBHF extends this benefit to agricultural waste streams without incurring a measurable carbon penalty, offering a promising pathway for developing circular concrete composites suitable for non-structural applications.

This study investigated the incorporation of a bio-based additive, fava bean husk fibers (FBHF), to RCA-based concrete mixtures. The research is conducted in two phases: the first evaluated FA and BFS combinations to identify the optimum-performing concrete mixture, while the second introduced FBHF at proportions of 3%, 6%, and 9% into the selected mixture, assessing mechanical properties and environmental performance.

The experimental findings demonstrated that the C50S50 mixture exhibited the most favorable performance characteristics, making it the foundation for subsequent FBHF incorporation. Among the tested combinations, S50FB3 emerged as the most promising formulation, proving to be a viable and sustainable alternative for non-load-bearing building materials, such as brick. This outcome underscores the potential of combining industrial by-products like BFS with bio-based fiber additive to produce construction materials that are both functionally adequate and environmentally responsible.

From an environmental perspective, the integration of waste-derived materials such as BFS and naturally sourced FBHF into concrete mixtures significantly contributes to reducing the ecological burden associated with their disposal. These findings highlight a meaningful step toward circular economy principles within the construction sector, encouraging the repurpose of industrial and agricultural by-products as valuable construction resources.

Conclusion

Natural resources have become a critical global issue due to the escalating demands of uncontrolled energy consumption. Concrete, as one of the most widely utilized construction materials worldwide, exerts a remarkable impact on energy use throughout its production phases. In order to response to environmental challenges, concrete recycling has emerged as a pivotal area of research, offering pathways to reduce both energy consumption and ecological concerns. The catastrophic earthquakes of February 6, 2023, in Türkiye generated an unprecedented volume of construction and demolition waste (CDW), intensifying the urgency to develop sustainable strategies that not only address environmental risks but also harness the potential of recycled concrete aggregate (RCA).

The findings revealed that the C50S50 mixture demonstrated the most favorable performance, serving as the basis for FBHF incorporation. Among all tested formulations, S50FB3 proved to be the most promising, offering a viable and sustainable alternative for non-load-bearing building applications such as brick production.

Recommendations

The integration of industrial by-products like BFS alongside naturally sourced FBHF contributed meaningfully to reducing the ecological burden of waste disposal, reinforcing circular economy principles in the construction sector. Future research should further explore the long-term durability and scalability of these mixtures under diverse structural and climatic conditions.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Determination of the Optimum Cutting Parameters on Surface Roughness in Turning AISI 4340 Steel

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Abstract: This study investigates the effects of fundamental machining parameters including insert types on the surface roughness (R_a) obtained during finish turning of AISI 4340 steel. External turning experiments were conducted on a Spinner TC65 CNC turning centre using a Taguchi L9 orthogonal array. Three different inserts like uncoated carbide, coated carbide, and CBN, respectively, were used to find out optimal conditions. Analysis of variance was carried out and the multiple linear regression equation was established. The results indicated that measured R_a values ranged from 0.361 to 2.411 μm . Feed rate was the dominant factor affecting on R_a , followed by cutting speed/insert type, and depth of cut. The optimal conditions based on the S/N response were determined as a cutting speed of 230 m/min, a feed rate of 0.08 mm/rev, a depth of cut of 1.2 mm, and the CBN insert. The regression model explained the R_a response with $R\text{-sq} = 98.05\%$, $R\text{-sq}(\text{adj}) = 96.10\%$, and $R\text{-sq}(\text{pred}) = 90.09\%$. Moreover, ANOVA results revealed that feed rate was statistically significant ($p < 0.001$) by indicating the highest contribution to the variation of R_a values. Cutting speed was also statistically significant ($p = 0.029$), while the insert type and depth of cut were not statistically significant at the 0.05 level.

Keywords: AISI 4340, Finish turning, Surface roughness, Taguchi method, Regression analysis, Variance analysis

Introduction

Machining is one of the most widely used manufacturing methods for producing engineering components that require controlled geometry, dimensional accuracy, and functional surface quality. Among machining operations, turning is particularly important for cylindrical components such as shafts, pins, sleeves, couplings, gears, and transmission elements. In finish turning, the final surface is affected by the combined influence of cutting speed, feed rate, depth of cut, tool geometry, tool material, workpiece hardness, and chip-formation conditions. Therefore, the selection of suitable cutting parameters is directly related to production efficiency, tool life, dimensional stability, and the service performance of the machined component.

Surface roughness is one of the most important indicators used to evaluate machining performance because it affects friction, wear, fatigue strength, sealing ability, contact stiffness, lubrication behaviour, and service life. In turning studies, the arithmetic average surface roughness value, R_a , is commonly used as a practical numerical response for comparing cutting conditions and developing prediction models. Surface roughness prediction and control have therefore been widely discussed in machining literature (Benardos & Vosniakos, 2003). From a theoretical point of view, feed rate is expected to have a strong influence on R_a because ideal roughness is closely related to feed rate and tool nose radius. However, the real surface generated during cutting can also be affected by built-up edge formation, vibration, tool wear, cutting temperature, coating behaviour, and workpiece material properties (Shaw, 2005; Trent & Wright, 2000). AISI 4340 is a nickel-chromium-molybdenum low-alloy steel widely used in demanding engineering applications due to its high strength, toughness, hardenability, fatigue

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resistance, and wear resistance. In engineering material selection, the relationship between material properties, service conditions, and manufacturing route should be evaluated together because the final performance of a component depends not only on the selected material but also on how that material is processed (Sahin, 2022). AISI 4340 is commonly preferred for critical components such as crankshafts, transmission shafts, gears, couplings, pins, fasteners, and aircraft landing-gear parts. However, the same properties that make AISI 4340 attractive for structural applications also make its machining more difficult by increasing cutting forces, cutting temperature, tool wear tendency, chip-control difficulty, and surface-integrity problems.

The study on AISI 4340 and comparable hard-turning applications show that surface roughness is generally controlled mainly by feed rate, while cutting speed, depth of cut, and tool condition may have secondary effects depending on the selected range. Lima et al. (2005) examined hard turning of AISI 4340 and reported that surface finish may improve with increasing cutting speed under low feed and depth-of-cut conditions, whereas increasing feed rate generally worsens surface quality. Suresh et al. (2012a) investigated hardened AISI 4340 steel using coated carbide inserts and related surface roughness and tool wear to selected cutting parameters. In another study, Suresh et al. (2012b) evaluated multilayer coated carbide tools and emphasized that low feed rate together with suitable cutting speed is important for obtaining better surface finish. Similarly, Sahoo and Sahoo (2012) compared uncoated and multilayer-coated carbide inserts in finish hard turning of AISI 4340 and evaluated surface roughness, chip morphology, cutting forces, and tool wear.

Tool material and coating condition are also important in finish turning of AISI 4340 steel. Uncoated carbide inserts are economical and widely available, but they may be more sensitive to wear and built-up edge formation under difficult cutting conditions. Coated carbide inserts can improve thermal resistance, reduce adhesion, and provide more stable cutting performance. For demanding hard-turning conditions and high surface-quality requirements, CBN and PCBN tools have also been investigated. More et al. (2006) compared coated carbide and PCBN inserts in turning hardened AISI 4340 steel, while Coelho et al. (2007) studied tool wear in turning hardened AISI 4340 with coated PCBN tools. Caydaş (2010) also reported that tool type affects surface roughness, tool wear, tool-chip interface temperature, and microhardness in machining AISI 4340.

The Taguchi method uses orthogonal arrays and signal-to-noise ratios to determine favourable factor levels with fewer experimental trials (Taguchi, 1990). Ross (1996) explained that Taguchi designs are especially useful for identifying robust factor levels in engineering applications, while Montgomery (2017) emphasized the role of ANOVA in interpreting the statistical significance of experimental factors. For surface roughness, the smaller-is-better quality characteristic is commonly selected because the objective is to minimize Ra. ANOVA is then used to determine the contribution and significance of each factor, while regression analysis can be used to develop an empirical equation for predicting Ra within the investigated parameter range.

Statistical optimization and modelling methods are useful for converting experimental machining results into practical process knowledge. In Taguchi-based studies, feed rate is consistently reported as the most influential factor for Ra, while cutting speed generally has a secondary effect and depth of cut is often the least influential factor within finish-turning ranges. For example, Aouici et al. (2012) reported a dominant feed-rate effect in hard-turning optimization, while Khmel et al. (2012) showed that feed rate remained the dominant parameter even when tool-related effects were included in the analysis. Meddour et al. (2015) also indicated that geometric and interaction effects can be observed in expanded Taguchi designs, but the feed-rate effect remains central to surface-roughness formation. These findings are consistent with the physical mechanism of feed marks and with the theoretical roughness relationship, $R_a \approx f^2/(32r_e)$, where f is feed rate and r_e is the tool nose radius. Nalbant et al. (2007), Özel and Karpaz (2005), and Rashid et al. (2016) demonstrated the usefulness of Taguchi, regression, and statistical modelling approaches in turning and hard-turning studies.

The hardness represents a practical transition region between conventional turning and hard turning. At this level, carbide and coated carbide inserts can still be used effectively, while CBN tools may provide improved surface finish but may not always be economically necessary for general finish-turning operations. For this reason, comparing uncoated carbide, CVD-coated carbide, and CBN inserts under the same experimental design is directly related to real production decisions. Instead of evaluating only cutting parameters, the present study also considers insert condition because the selected tool affects heat generation, friction at the tool-chip interface, edge stability, wear behaviour, and the final machined surface.

Based on this background, the present study focuses on finish turning of AISI 4340 steel under different cutting conditions. The study specifically examines the effects of cutting speed, feed rate, depth of cut, and insert types on the average surface roughness Ra. Three different insert conditions, namely uncoated carbide, CVD-coated carbide, and CBN, are considered to compare conventional and high-performance tool alternatives under the same

experimental structure. Therefore, a Taguchi L9 orthogonal array is used to determine favourable factor levels for minimum Ra, and regression analysis is performed to find out the relationship between Ra and the selected input parameters. In this way, the study moves from the general problem of surface-quality control in turning to the specific optimization of AISI 4340 finish turning using different insert conditions.

Materials and Method

Workpiece Material

The workpiece material was AISI 4340 steel with a measured hardness of approximately 32 HRC. Cylindrical specimens had an initial diameter of 50 mm and a total length of 180 mm. Before the experimental cuts, the external diameter was finish turned from 50 mm to 46 mm. For each experimental condition, an 8 mm long external cylindrical region was machined and used for surface-roughness measurement. Figure 1 shows the AISI 4340 workpiece specimen used in the experiments. The nominal chemical composition of AISI 4340 steel is given as follows (wt.%): (C = 0.38-0.43; Mn = 0.60-0.80; Si = 0.15-0.35; Cr = 0.70-0.90; Ni = 1.65-2.0; Mo = 0.20-0.30; P ≤ 0.035; S ≤ 0.040).



Figure 1. AISI 4340 workpiece specimens

Machine Tool and Inserts

External finish-turning experiments were conducted on a Spinner TC65 CNC turning centre, shown in Figure 2. Three insert conditions were evaluated: uncoated carbide, CVD-coated carbide, and CBN. All inserts belonged to the 09T308 dimensional group and had a constant nose radius of 0.8 mm. Keeping the nose radius constant reduced geometric variation and allowed the comparison to focus on insert condition. The insert types, insert codes, descriptions, and corresponding insert hardness values are given in Table 1.



Figure 2. Spinner TC65 CNC turning centre

Table 1. Selected cutting tools, coding and hardnesses of the cutting tools.

Tool Condition	Insert Code	Description	Insert Hardness (HV)
Uncoated carbide	CCGT09T308-LH BU810	Uncoated cemented carbide	1600
CVD-coated carbide	CCMT09T308-P3 6325	TiN/TiCN/Al ₂ O ₃ /TiN; P20-P30	2800
CBN	CCGW09T308 S02020-2S	Brazed CBN; CBN content 70-75%	3500

The HV values in Table 1 were used to numerically represent the cutting-insert condition in the Minitab regression and Taguchi analyses. These values should not be interpreted as isolated hardness-only effects because the inserts also differ in coating structure, substrate, thermal behaviour, wear resistance, edge preparation, and tool material class. The CBN insert has a chamfered and honed edge preparation, whereas the uncoated carbide and CVD-coated carbide inserts differ mainly in coating and substrate characteristics.

Experimental Design

A Taguchi L9 (3⁴) orthogonal array was used to evaluate four experimental factors at three levels. The investigated factors were cutting speed (Vc), feed rate (f), depth of cut (ap), and insert types represented by the HV. Table 2 lists the factors selected, factor levels and their units used in the experimental design while Table 3 illustrates the experimental planning in the machining of AISI 4340 steels using various cutting tools under different conditions as pointed out above.

Table 2. Experimental factors and their levels

Factor	Level 1	Level 2	Level 3	Unit
Cutting speed, Vc	90	160	230	m/min
Feed rate, f	0.08	0.15	0.22	mm/rev
Depth of cut, ap	0.6	1.2	1.8	mm
Insert hardness, HV	1600	2800	3500	HV

Table 3. Experimental planning in the machining of AISI 4340 steels

Run	Vc (m/min)	F (mm/rev)	Ap (mm)	Hardness (HV)
1	90	0.08	0.6	1600
2	90	0.15	1.2	2800
3	90	0.22	1.8	3500
4	160	0.08	1.2	3500
5	160	0.15	1.8	1600
6	160	0.22	0.6	2800
7	230	0.08	1.8	2800
8	230	0.15	0.6	3500
9	230	0.22	1.2	1600

Surface-roughness Measurement



Figure 3. Fixed surface-roughness surface measurement system, and to be measured specimen

Surface roughness was measured using a Mitutoyo SJ-310 instrument on the 8 mm long machined region. The surface-roughness measurement system, and to be measured specimens is shown in Figure 3. The evaluation length was 5 mm. Two machining repetitions were performed for each experimental condition, and three roughness traces were obtained from each repetition. Thus, six Ra measurements were obtained for each experimental condition. A V-block fixture was used to keep the cylindrical specimens stable during measurement and to reduce possible measurement errors caused by specimen movement.

Statistical Analysis

Because the objective was to minimise Ra, the smaller-is-better signal-to-noise (S/N) quality characteristic was applied. Response tables were generated for means and S/N ratios. For the smaller-is-better criterion, the factor level with the highest S/N ratio indicates the favourable level. The S/N ratio was calculated using the following equation (1):

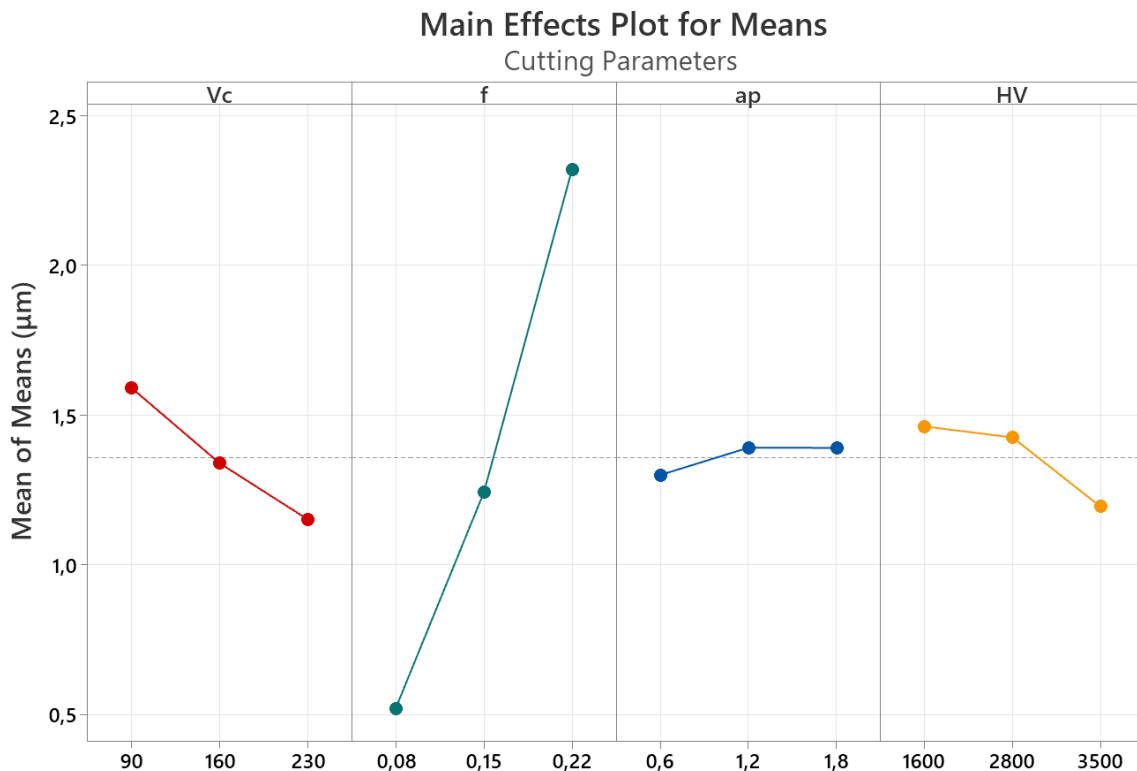
$$\frac{S}{N} = -10 \times \log_{10} \times \left[\frac{1}{n} \sum y_i^2 \right] \quad (1)$$

where n is the number of measurements and y_i is the measured response.

Results and Discussion

Experimental Results

The main-effects plots for the mean Ra values and S/N ratios obtained from the Taguchi analysis are presented in Figure 4 (a, b), respectively. -Figure 4(a) shows the main-effects plot for the mean Ra values. The plot indicates that Ra increased strongly with increasing feed rate, whereas Ra decreased with increasing cutting speed. The mean Ra value also decreased as the insert hardness level increased from 1600 HV to 3500 HV. In contrast, depth of cut showed only a very small effect on Ra within the investigated range. Based on the mean response, the favourable factor levels were Vc level 3, f level 1, ap level 1, and HV level 3, corresponding to Vc = 230 m/min, f = 0.08 mm/rev, ap = 0.6 mm, and HV = 3500.



(a) Mean Ra values

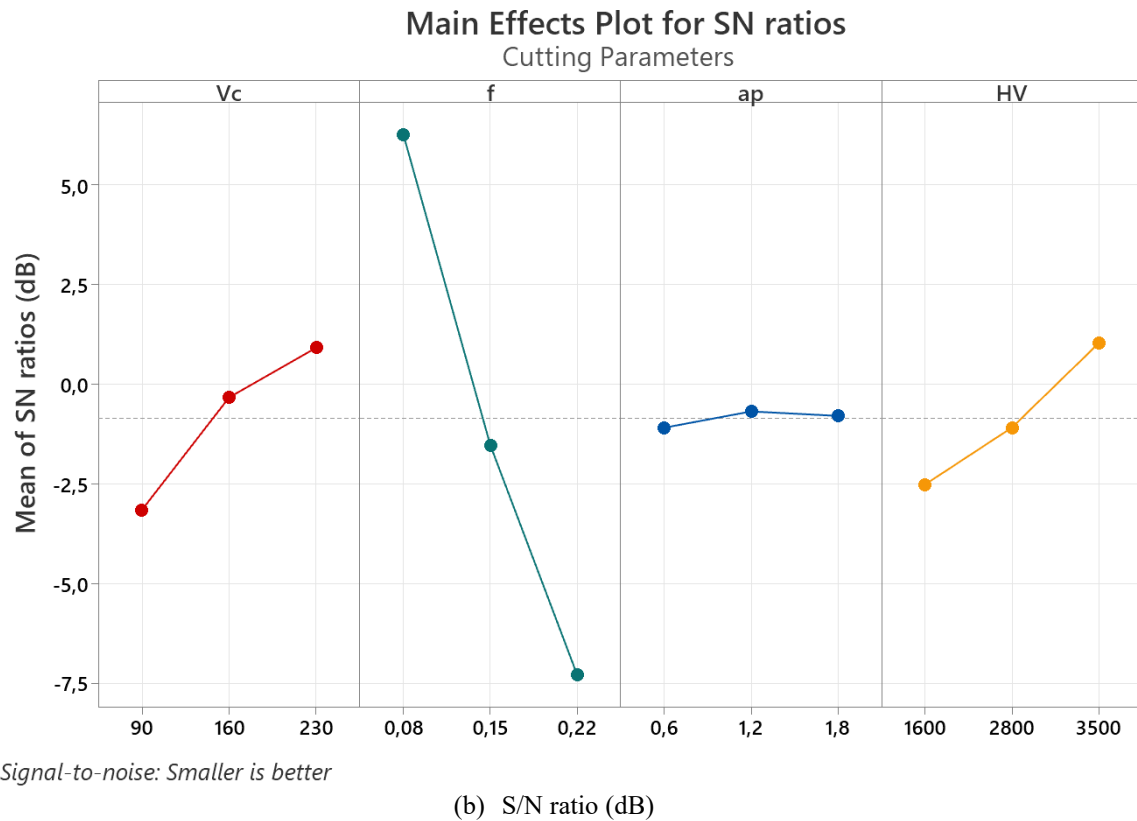


Figure 4. Main-effects plot for output like mean Ra and S/N ratios values

Figure 4 (b) shows the main-effects plot for the S/N ratios (dB). The steepest slope was obtained for feed rate, confirming that the feed rate was the most influential factor affecting on Ra, again. The cutting speed had the second effect and the HV indicates the third effect on the S/N response, but the depth of cut was no effective. These results demonstrated that surface roughness in finish turning of AISI 4340 steel was mainly controlled by feed rate, followed by cutting speed, while insert type and depth of cut has no considerable effective on the selected experimental ranges.

The experimental results indicated that the lowest feed rate generally produced the lower the Ra values, whereas, the trials performed with the highest feed rate generated the higher Ra values, which are consistent with the theoretical surface-generation mechanism in any cutting process, because increasing the feed rate leading to generated the feed marks on the machined surface. This is due to coming from theoretical back-ground of average surface roughness equation ($Ra = f^2 / (32 * r_c)$), where f = feed rate (mm/rev.), r_c = tool insert's radius (mm) that is equal to 0.8mm in present case. As results, the trial 4 gave the minimum measured Ra value among the conducted experiments. However, the optimum factor levels should be determined separately using the Taguchi S/N response analysis, which evaluates the average effect of each factor level across the experimental design.

These findings are generally consistent with previous studies on the turning and hard turning of AISI 4340 steel. Das et al. (2017) reported that feed was the most significant parameter affecting surface roughness, followed by cutting speed, while depth of cut had a comparatively lower and statistically insignificant effect. This agrees with the present ANOVA results, where feed rate had the highest contribution to Ra, cutting speed was the second most influential factor, and depth of cut had the lowest contribution. Similarly, Suresh et al. (2012a) reported that the combination of low feed rate, low depth of cut, and high cutting speed was beneficial for reducing surface roughness when machining hardened AISI 4340 steel with coated carbide inserts. Suresh et al. (2012b) also stated that low feed rate together with high cutting speed is necessary for minimizing surface roughness in hard turning of AISI 4340 steel using multilayer coated carbide tools. Therefore, the optimum Taguchi condition obtained in the present study, especially the low feed rate and high cutting speed levels, is compatible with these previous findings. The only difference is that the insert condition represented by HV showed a secondary and statistically insignificant effect in the present regression model. This can be attributed to the limited L9 experimental range and to the use of HV as a numerical representation of the overall insert condition rather than as an isolated hardness-only variable.

Taguchi Response Analysis

The Taguchi response analysis was performed using the smaller-is-better quality characteristic because the objective of this study was to minimise the average surface roughness, Ra. The response tables for the means and signal-to-noise ratios are presented in Table 4 and Table 5, respectively. In the response table for means, the factor level with the lowest mean value is considered favourable, whereas in the S/N response table based on the smaller-is-better criterion, the factor level with the highest S/N ratio is considered favourable.

Table 4. Response table for means (μm)

Level	Vc	f	ap	HV
1	1.5881	0.5186	1.2980	1.4602
2	1.3374	1.2395	1.3892	1.4233
3	1.1503	2.3177	1.3887	1.1923
Delta	0.4378	1.7992	0.0912	0.2678
Rank	2	1	4	3

As shown in Table 4, the lowest level averages were obtained at Vc level 3, f level 1, ap level 1 and HV level 3. These levels correspond to Vc = 230 m/min, f = 0.08 mm/rev, ap = 0.6 mm, and insert hardness = 3500 HV. Based on the delta values in Table 4, the factor ranking for the mean Ra values was determined as $f > Vc > \text{insert hardness (HV)} > ap$. This indicates that the feed rate had the strongest effect on the mean Ra value, while depth of cut had no effect within the investigated parameter range.

Table 5. Response table for S/N ratios: higher is better (dB)

Level	Vc	f	ap	HV
1	-3.1573	6.2477	-1.0958	-2.5197
2	-0.3366	-1.5339	-0.6878	-1.0909
3	0.9105	-7.2973	-0.7999	1.0271
Delta	4.0678	13.5450	0.4080	3.5467
Rank	2	1	4	3

As presented in Table 5, the S/N ratio results also confirmed the dominant influence of feed rate on Ra. Since the smaller-is-better criterion was used, higher S/N ratios indicate the better performance. According to Table 5, the highest S/N ratios (dB) were obtained at Vc level 3, f level 1, ap level 2, and insert hardness level 3. Therefore, the optimum factor levels predicted by the Taguchi S/N analysis were determined as Vc = 230 m/min, f = 0.08 mm/rev, ap = 1.2 mm, and insert hardness = 3500 HV. Based on the S/N delta values in Table 5, the factor ranking was $f > Vc > \text{insert hardness (HV)} > ap$. This result showed that feed rate was the most influential factor affecting Ra, followed by cutting speed and insert hardness, whereas depth of cut had the lowest influence. The favourable depth-of-cut level differed between the mean response and the S/N response. However, this difference should not be overemphasized because depth of cut had the lowest delta value in both response tables and the lowest contribution value in ANOVA.

Regression Analysis

Regression analysis was performed to develop a mathematical model for predicting the average surface roughness, Ra, as a function of cutting speed, feed rate, depth of cut, and insert hardness. In the model, cutting speed (Vc), feed rate (f), depth of cut (ap), and insert hardness (HV) were used as continuous input variables, while Ra was used as the response variable. The fitted multiple linear regression equation is given in equation (2).

$$Ra = 0.180 - 0.003127 Vc + 12.851 f + 0.076 ap - 0.0001290 HV \quad (2)$$

In Equation (2), Ra is expressed in micrometres, Vc is m/min, f is mm/rev, ap is mm, and HV is Vickers hardness. Table 6 reveals the regression coefficients for Ra output. The negative coefficient of Vc indicates that increasing cutting speed tended to reduce the Ra within the investigated parameter range. The positive coefficient of shows that increasing feed rate increased the Ra. The positive coefficient of ap indicates a slight increasing tendency in the Ra with increasing depth of cut, whereas the negative coefficient of HV suggests that higher insert hardness tended to reduce the Ra. The R-squared value of 98.05% indicates that the regression model explains a large portion of the variation in Ra. The adjusted R-squared value of 96.10% also shows that the model has a strong explanatory capability after accounting for the number of predictors. These coefficients should be interpreted together with their p-values and the ANOVA results.

Table 6. Regression coefficients for Ra values.

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.180	0.309	0.58	0.591	-
Vc	-0.003127	0.000941	-3.32	0.029	1.00
f	12.851	0.941	13.65	< 0.001	1.00
ap	0.076	0.110	0.69	0.529	1.00
HV	-0.000129	0.000069	-1.88	0.133	1.00

As shown in Table 6, feed rate was statistically significant at the 0.05 significance level, with $p < 0.001$. This confirms that the feed rate had the strongest effect on Ra among the investigated factors. The cutting speed was also statistically significant, with a p-value of 0.029, indicating that increasing the cutting speed had a measurable decreasing effect on Ra in the experimental dataset. The insert condition represented by HV had a negative coefficient, indicating a decreasing tendency in Ra with increasing HV; however, its p-value of 0.133 shows that this effect was not statistically significant at the 0.05 level. Similarly, depth of cut was not statistically significant individually, with a p-value of 0.529. Therefore, the regression results support the Taguchi response analysis by showing that the feed rate was the dominant parameter affecting surface roughness, while cutting speed had a secondary statistically significant effect.

Analysis of Variance (ANOVA)

ANOVA was carried out to determine the effective factors in the machining of the steels at different conditions and the results are shown in Table 7. In this table, p-values are about 0.029, <0.001, 0.529, 0.133 for Vc, f, d, H, respectively. Smaller p-value signifies that the regression coefficient is highly significant at 95% confidence level, which supports the results of the regression. As presented in this table, SS, Seq SS and Contribution columns were also evaluated to determine how much of the total variation was explained for each factor. The regression model explained 98.05% of the total variation in Ra, while the error contribution was only 1.95%, indicating that the selected factors explained most of the variation in the experimental dataset. Among the individual factors, feed rate had by far the highest contribution with Seq SS = 4.85550 and Contribution = 90.73%. This result confirms that feed rate was the dominant parameter controlling Ra. The cutting speed had the second-highest contribution around 5.37%, and it was statistically significant at the 0.05 level ($p = 0.029$). The insert condition represented by HV had a lower contribution of 1.72% and was not statistically significant at the 0.05 level ($p = 0.133$). The depth of cut had the lowest contribution, with only 0.23%, and was not statistically significant ($p = 0.529$). Therefore, according to the ANOVA analysis, the influence ranking was $f > Vc > HV > ap$. This ranking is consistent with the Taguchi response tables and shows that depth of cut should not be interpreted as a dominant factor for Ra in this experimental range.

Table 7. Analysis of variance for mean Ra values.

Source	DF	Seq SS	Contrib.	Adj SS	Adj MS	F-Value	P-Value
Regression	4	5.24759	98.05%	5.24759	1.31190	50.35	0.001
Vc	1	0.28753	5.37%	0.28753	0.28753	11.03	0.029
f	1	4.85550	90.73%	4.85550	4.85550	186.34	< 0.001
ap	1	0.01233	0.23%	0.01233	0.01233	0.47	0.529
HV	1	0.09222	1.72%	0.09222	0.09222	3.54	0.133
Error	4	0.10423	1.95%	0.10423	0.02606	-	-
Total	8	5.35182	100.00%	-	-	-	-

The higher HV levels tended to reduce Ra within the investigated range. However, its p-value of 0.133 indicates that this effect was not statistically significant at the 5% level in the analysis. The HV values used in this study represent the cutting-insert condition numerically; they should not be interpreted as an isolated hardness-only effect because the inserts also differ in tool material class, coating structure, substrate, wear resistance, and edge preparation.

Figure 5 indicates the residual plots used to evaluate the adequacy of the regression model. The normal probability plot indicates that the residuals approximately follow a straight-line trend, suggesting that the normality assumption is reasonably satisfied. The residuals-versus-fitted-values plot does not show a clear systematic pattern, indicating that the residuals are randomly distributed around zero. The histogram of residuals also shows an approximately balanced distribution. The residuals-versus-order plot does not indicate a strong time- or order-related trend. Therefore, the residual plots in Figure 5 support the adequacy of the regression model for interpreting Ra within the investigated experimental range.

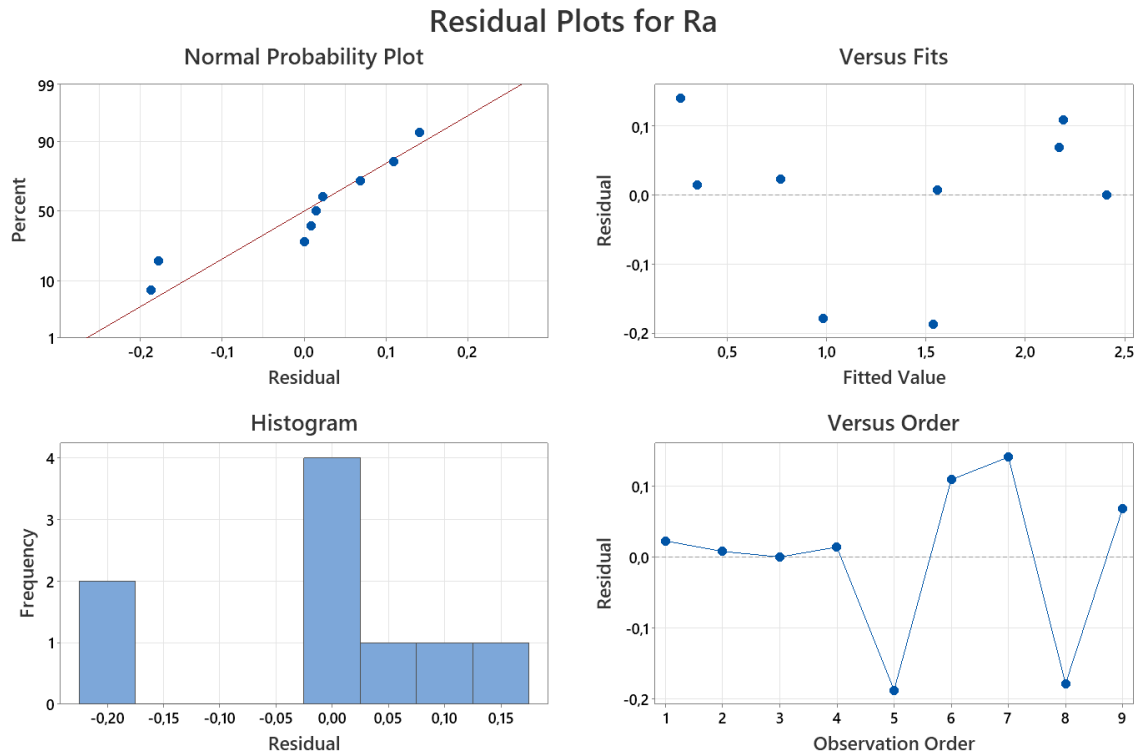


Figure 5. Residual plots for Ra regression model

Conclusion

This study investigated the effect of cutting speed, feed rate, depth of cut, and insert types on the average surface roughness, Ra, during the finish turning of AISI 4340 steel. For this purpose, a Taguchi L9 experimental design was used, and the experimental results were evaluated using Taguchi response analysis, regression analysis, ANOVA, and residual plots.

1. The measured Ra values ranged from 0.361 μm to 2.411 μm , showing that the investigated cutting parameters caused a clear variation in surface quality.
2. According to the Taguchi S/N response analysis, the optimum factor levels for minimising Ra were determined as $V_c = 230 \text{ m/min}$, $f = 0.08 \text{ mm/rev}$, $a_p = 1.2 \text{ mm}$, and insert hardness = 3500 HV, respectively.
3. Both the Taguchi response analysis and the regression results showed that feed rate was the dominant factor affecting Ra. In the variance analysis, feed rate was statistically significant at the 0.05 significance level with $p < 0.001$.
4. The regression model provided a strong explanation of the experimental data, with R-squared, adjusted R-squared, and predicted R-squared values of 98.05%, 96.10%, and 90.09%, respectively.
5. The ANOVA revealed that contribution factors also confirmed the strong effect of feed rate, which accounted for 90.73% of the total variation in Ra. Cutting speed was the second most influential factor according to contribution, with 5.37%, and it was statistically significant with a p-value of 0.029. Whereas, the insert type and the depth of cut did not show a statistically significant individual effect within the investigated experimental range.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

* This experimental machining study did not require ethics committee approval.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Impact of Energy Savings Measures in Slaughterhouse for Premium Meat, Meat Preparations and Subproducts

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Abstract: The study shows an energy audit of a slaughterhouse for the production of premium meat, meat preparations and subproducts. The distribution of energy consumed at the site by individual consumers is shown - energy consumed for refrigeration, ventilation, heating, sanitary hot water and lighting. The distribution of energy consumed for the installed technological equipment at the site is also shown - refrigeration equipment and equipment for meat processing, including for cooking processes. Analysis of energy consumption in the enterprise was carried out, energy saving measures were proposed and a technical and economic analysis was carried out. The indicators energy savings ratio, the percentage of planned energy savings and saved carbon emissions to the environment were calculated. The results of the survey show that the energy savings due to the proposed energy saving measures amount to 37099 kWh per year, the energy savings ratio is 35.5%, the percentage of planned energy savings is 33.3%, and the saved carbon emissions are 30.38 tons of CO₂/year.

Keywords: Energy efficiency, Energy audit, Energy saving measures

Introduction

Subject to mandatory energy efficiency audit in accordance with regulation act in Bulgaria are: large enterprises for the production of goods, large service providers, industrial systems whose annual energy consumption is over 3000 MWh (Ordinance №E-RD-04-3, 2016), (Ordinance №E-RD-04-05, 2016). In addition, many small and medium-sized enterprises perform energy audits in order to obtain financing for new energy-efficient equipment and to optimize and automate their production processes (Ivanov et al., 2021; Kamburova et al., 2017; Iliev et al., 2026).

In food industry enterprises, the aim is to continuously optimize and reduce energy costs, which will lead to an increase in the competitiveness of the enterprise and obtaining a final food product with the lowest possible carbon footprint (Berk, 2009; Georgiev & Kadirova, 2025). In times of uncertain fuel supplies, the rational use of electricity consumed in the enterprise becomes especially important. The peculiarity of production processes in this type of enterprises is that very often in various technological processes we have waste heat flows, the potential of which must be used before they are discharged to the environment (Genné & Derden, 2008), (Wojdalski et al, 2020).

Reducing energy costs is necessarily carried out taking into account the possibilities for supplying energy carriers to the enterprise and complying with the requirements of the cold chain. It's definitely worth it for food products subject to cold processing and cold storage (Abou Elmagd et al, 2017, Fritzson & Berntsson, 2006) . This requires the use of methods for utilizing waste heat in enterprises and the use of heat pumps for heating and hot water for technological needs.

The implementation of the described activities will guarantee the receipt of a quality final product, increasing the competitiveness of the enterprise and increase in the company's profit. The increased level of automation and robotization in production gives the enterprise the opportunity to meet requirements for various quality and

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energy management standards, which subsequently enables it to offer its products to new markets (Baev et al., 2026; Kaloyanov et al, 2026).

Method

The object of the present study for energy efficiency of an industrial system is a slaughterhouse - manufacturer of meat products in Bulgaria. The investment proposal consists of an investment project for the reconstruction of an existing slaughterhouse and the construction of a new building for cutting premium meat, meat preparations and subproducts and the creation of a yard with a shed for pre-slaughter rest of large excess cattle and a circle for pushing the animals. The main production processes are: reception of live calves, meat production and meat processing with a capacity of up to 480 cattle per year and the cutting of the same into premium meats, meat preparations and subproducts.

The products that the company produces are:

- Large cuts of meat – 26880 kg/year
- Dry-aged cuts of meat and filleted meat – 26880 kg/year
- Head cheese – 13440 kg/year
- Subproducts – 14400 kg/year

In slaughterhouse the following technological processes are carried out:

- Heating equipment;
- Ventilation equipment;
- Hot water tanks;
- Lighting equipment;
- Technological equipment.

The choice of energy-saving measures, guaranteeing the highest value energy savings in the form of energy and low carbon emissions released into the environment, requires a detailed energy analysis of the enterprise's energy costs.

Energy efficiency audit of the industrial system is related to the implementation of the following activities:

- inspection of the industrial system;
- collection and processing of primary information on the functioning of the industrial system and energy costs;
- analysis of the existing state and energy consumption;
- determination of the baseline of energy consumption;
- analysis of energy use systems;
- development of energy-saving measures to increase energy efficiency;
- valuation of each of the measures;
- analysis and assessment of the annual amount of CO₂ emissions saved as a result of developing measures to increase energy efficiency.

The determination of specific electrical energy consumption (SEEC) is determined by the formula:

$$SEEC = \frac{EEC}{M}$$

where: EEC is electrical energy consumption, kWh/ year and M is manufactured output, kg/ year.

The net present value (NPV) of energy saving measure is calculated by the formula:

$$NPV = \sum_{i=1}^n \frac{B}{(1+r)^i} - I_0$$

$$NPV = B \cdot \frac{1 - (1 + r)^{-n}}{r} - I_0$$

where: n – technical/ economic life of the facility, years, r - real interest rate, % and I_0 – investment costs, €. Coefficient of net present value (NPVQ) is calculated according to the formula:

$$NPVQ = \frac{NPV}{I_0}$$

The pay back period (PB) of energy saving measure is determined by the formula:

$$PB = \frac{I_0}{B}$$

Energy savings ratio (ESR) is determined by the formula:

$$ESR = \frac{TES}{TC} \cdot 100, \%$$

where: TES = B – net annual energy savings, kWh/year, TC - energy consumption of equipment covered by energy saving measures, kWh/year.

Energy savings potential (ESP) is calculated by the formula:

$$ESP = \frac{TES}{TC^*} \cdot 100, \%$$

where: TES = B – net annual energy savings, kWh/year, TC^* - energy consumption of all equipment installed at the slaughterhouse, kWh/year. The parameters of the energy efficiency measures are calculated based on the following data:

- Carbon dioxide (CO₂) emissions of electricity are 0.819 kgCO₂/kWh;
- Price of electricity supply – 0.22 €/kWh;
- Duration of technical/economic life of the facility is n = 15 years;
- Real interest rate, r = 3.00 %.

The purpose of the study is to propose specific energy-saving measures for the slaughterhouse, and to assess the saving effect and the ecological impact of the energy-saving measures on the environment.

Results and Discussion

General Characteristics of the Slaughterhouse

General Information

The data from the energy audit will serve for the complete reconstruction and modernization of an existing slaughterhouse, the construction of new premises for cutting premium meat and the separation of a yard with a shed for pre-slaughter rest of large ruminants, a circle-type device for painlessly pushing the animals and a ramp with a scale.

For the proper functioning of the technological process, the project provides the following premises: main room, waste processing room and meat cutting room, rest room with toilet and shower system. The main working room is conditionally divided into two zones - dirty and clean, equipped with a pipeline with positions for sequential processing of the animal carcass. Sterilizers for knives and a contactless hand sink are provided, as well as a sink for washing internal packaging necessary for the production process.

1) The dirty area consists of:

- calf stunning position;
- bleeding position – bath;
- skinning position;
- skinning position – mechanical with a hoist up to 1.5 tons;
- head and leg separation position;
- gutting position with gut contents – trolley;

2) The clean area consist of:

- liver separation position;
- carcass halving position;
- liver veterinary inspection position;
- sample taking position for testing;
- calf carcass halving position;
- corner for washing inner packaging in a three-well sink;
- corner for washing hands with a contactless sink;

3) Room for processing of viscera with ventilation and corners used for:

- gut processing with a workbench and sink;
- corner for processing calf heads, legs with a workbench and sink;
- a corner for processing tripe – machine;
- a corner for washing trolleys with a water tap.

4) Warehouse used for packaging, trays, foil, labels, spices and edible intestines, equipped with racks – a rack for packaging, trays, labels, foil and a rack for spices;

5) A room for slicing and producing minced meat and meat preparations;

A pipe route is provided in it, which comes from cold room for cooling the carcass. A work table for slicing the carcass, a work table for packaging in trays, as well as a wolf machine, a mixer and a molding machine are provided.

6) Auxiliary premises:

A cold room for cooling and storing carcass meat, heads, legs and waste, equipped with a pipe path and racks for separate storage of packaged waste;

Dry agers for ripening carcass meat;

A cold room for storing cuts, minced meat and meat preparations;

A veterinarian's office;

A dispatch room where the pipe path ends.

A position is designated for manual foiling of carcass meat. The carcass meat is weighed on an electronic scale.

Meat intended for canning is processed in a separate room, where dosing, mixing with spices and vegetables, heat treatment, filling into jars and sealing take place. An autoclave compartment is also provided, where sterilization of closed jars takes place, and there is also a separate area for blown jars. A packing room /stretching of jars/ and labeling is provided. For the finished canned products, a finished product warehouse, warehouses for jars, caps, labels, a room for inspection and rinsing of jars are provided. A protective sleeve is installed at the exit to protect the meat from contamination when loading into specialized transport. A storage area is formed, located under a canopy on a concrete platform with a channel grid and a water tap.

Two sanitary and household units of the sanitary filter type will be built with a changing room for outer clothing, showers, a changing room for work clothes, a rest room and toilets. The sanitary filter for workers in the dirty area of the slaughterhouse is separate from the one for the clean area and processing. In order to improve the personal hygiene of the staff, a foot disinfection bath and hand sanitizer are provided before entering the work premises. The sinks in the production premises will be contactless.

Water Supply and Sewage

The water supply of the enterprise will be carried out by an existing water supply system of the local water supply company, for which there is an open lot and an existing water supply system, and water suitable for drinking will be used. The necessary water will be for watering the animals, servicing the slaughterhouse, the cutting room for premium meat and sanitary and household needs. There is no need to build new water facilities. No treatment is planned for household waste. Waste from the production process will be stored in a refrigerator until it is handed over to a manure truck, and some of it, which is suitable for food for rare birds of prey, will be provided to environmental protection organizations caring for eagles, vultures, etc. Animal manure will be transported for storage and composting in an existing manure pit located within the farm. After composting, it will be used to fertilize fields and pastures, meadows and meadows managed by the client of the investment proposal.

Power Supply

The equipment of the enterprise envisaged in the project operates only with electricity. The electricity will be supplied from a substation located near the property.

Description of Production Process

The products produced by the enterprise are:

- Large local cuts;
- Meat cuts for dry aging and filleted meat in vacuum packaging;
- Meat preparations /minced meat, burgers, beef sausage, by-product sausage/;
- Canned meat in jars 0.700 kg. with twist-off caps.

The technological process in the enterprise is as follows:

Live cattle are brought by self-propelled and special truck to a pre-slaughter box from the farm owned by the investor or from partner farms, having previously been weighed on an animal scale. An isolation box is provided for cattle in case of doubts regarding the health condition of the animals. Large ruminants /in this case cattle/ are kept in a yard with a shed for pre-slaughter rest at the slaughterhouse 24 hours before slaughter, without feeding, but are watered regularly. Cattle from the pre-slaughter box enter a calf stunning box. Here, using a stunning gun with an unattached bolt, they are stunned, with the gun's stinger directed into the frontal skull bone. The bleeding of the cattle occurs immediately after stunning the animal and no later than 1-2 minutes after stunning. The following technological scheme of meat production is established:

- a/ Termination of life: stunning before slaughter, slaughter and bleeding;
- b/ Separation of the head and removal of the skin;
- c/ Removal of internal organs;
- d/ Cutting the carcass into quarters;
- e/ Dressing.

The receipt of products will be subject to systematic quality control. The full quality management system will ensure compliance with the norms regarding origin and production. The control system will cover the entire production chain, thus ensuring the traceability of the products. The enterprise will process premium meat, meat preparations and subproducts in a five-day working week. The production base is planned to operate in a single-shift mode with an 8-hour working day. The number of personnel employed in the enterprise is 10 people.

Energy Consumption Analysis

The enterprise will use one energy carrier – electricity.

Electricity

The power supply of the enterprise will be carried out from the transformer station located to the north in the former farmyard.

Heating

For the heating needs of the building, convector units operating on electricity have been proposed and selected, operating with a mechanical thermostat for temperature control in the rooms. Heating units are provided in the premises for meat production, sanitary and household premises and offices of the enterprise.

Table 1. Installed electrical power of the facilities in the slaughterhouse

Name	Value	Power, kW	Total kW	power, power,	Operating hours, hours/year	Annual consumption, kWh/ year
Technological equipment						
Refrigeration unit 1 Qo=1.45 kW	1	0.93	0.93		2925	2720
Refrigeration unit 2 Qo=1.8kW	1	1.40	1.40		2925	4095
Refrigeration unit 3 Qo=2.6kW	1	2.00	2.00		2925	5850
Trip cleaning machine	1	0.85	0.85		1040	884
Bone chest freezer	1	0.35	0.35		1040	364
Salmon chest freezer	1	0.35	0.35		1040	364
Blood refrigerator	1	0.18	0.18		1039	187
Knife sterilizer	3	0.75	2.25		1040	2340
Half-cutting saw	1	1.20	1.20		520	624
Electric hoist	1	2.50	2.50		1040	2600
Stun gun	1	0.50	0.50		520	260
Chilled carcass meat scale	1	0.15	0.15		393	59
Warm carcass meat scale	1	0.15	0.15		393	59
Undercounter refrigerator	1	0.33	0.33		1039	343
Spice grinder	1	0.50	0.50		390	195
Filler	1	1.50	1.50		1040	1560
Shaping machine for meat blanks	1	1.00	1.00		1040	1040
Mixer	1	0.75	0.75		1040	780
Wolf machine	1	0.36	0.36		1039	374
Bone chest freezer	1	0.68	0.68		1040	707
Cooking pot	1	24.00	24.00		1300	31200
Bone saw	1	1.50	1.50		1300	1950
Total usable power			43.43			58555
Heating equipment						
Electric convector 2000W	10	2.00	20.00		1300	26000
Total usable power			20.00			26000
Ventilation equipment						
Fans for sanitary premises	4	0.06	0.24		521	125
General exchange ventilation fans	2	0.15	0.30		2600	910
Exhaust ventilation fans	1	0.35	0.35		2600	780
Total usable power			0.89			1815
Hot water						
Hot water boiler V= 150 l, Nel=2.5kW/220V	2	2.50	5.00		4000	20000
Total usable power						20000
Lighting equipment						
LED lighting fixtures 2x36W for open ceiling mounting, IP44	28	0.072	2.02		1000	2020
Evacuation lighting fixtures - illuminated arrows with power LL 2x8W	8	0.016	0.13		1000	130
Lighting fixture type spotlight with MHL 100W, IP65, wall mounting	10	0.100	1.00		3000	3000
Total usable power			3.15			5150
Total power			72.47			111520

Ventilation

For the ventilation needs of the premises in the building, general exchange ventilation is provided. The released harmful substances – vapors, odors, etc. are removed from the premises by local exhaust ventilation. For the sanitary units, independent exhaust ventilation with a check valve, wall or ceiling mounting is provided. The exhaust air is taken to the roof of the building through ventilation verticals made of round PVC pipes.

Hot Water

For the preparation of hot water for technological and sanitary needs, two volumetric hot water tanks with a single capacity of 150 liters (total volume 300 liters), equipped with an electric heater, are planned.

Technological Processes

The equipment used to carry out all technological processes consumes electrical energy. According to the technology of the processes taking place in the enterprise, the corresponding number of working hours has been determined for the different groups of equipment, with 249 working days per year (5 days/ week). In Table 1 installed electrical power and annual consumption of the facilities in the slaughterhouse are shown. According to the data from Table 1, the annual electricity consumption of the enterprise is determined to be 111520 kWh/year. On Figure 1 a percentage distribution of electrical energy consumed in slaughterhouse is shown in Figure 1..

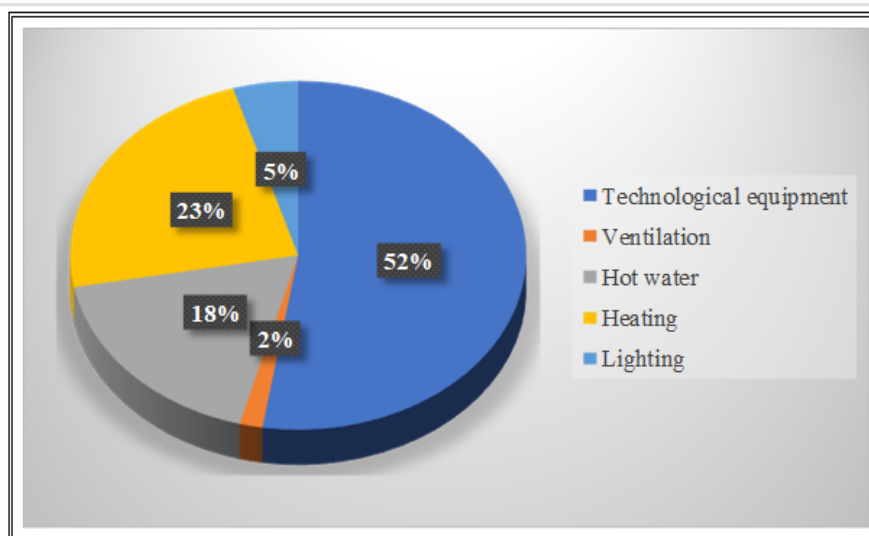


Figure 1. Distribution of electrical energy consumed in slaughterhouse

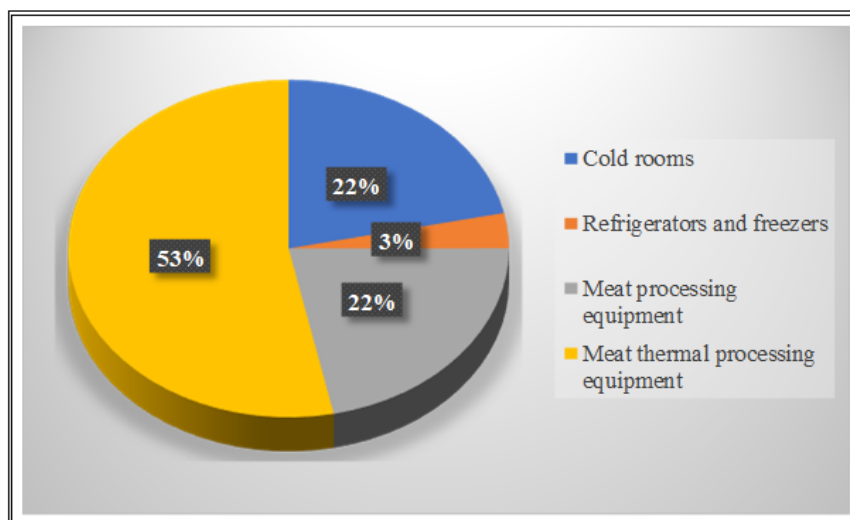


Figure 2. Distribution of electrical energy consumed by technological equipment

The data shows that 52 % of electrical energy in slaughterhouse are consumed by technological equipment - refrigeration equipment, cooking pot, etc. On Figure 2 a percentage distribution of electrical energy consumed by technological equipment is shown in Figure 2. The data shows most of electrical energy for technological equipment is consumed by meat thermal processing equipment (cooking pot) and refrigeration installation for cold rooms.

Proposed Energy Saving Measures

After analyzing the energy consumption of the slaughterhouse, we must focus our attention on taking energy-saving measures in the following areas:

- implementation of measures reducing the consumption of electrical energy of the technological equipment - equipment for cooking processes (cooking pot for head cheese);
- implementation of measures reducing the consumption of electrical energy for heating the premises;
- implementation of measures reducing the consumption of electrical energy for heating hot water for sanitary and technological needs;

The following conclusions can be made:

- For heating the premises of the meat production premises, sanitary and household premises and offices, electric convectors are used, which generate high energy costs;
- To provide hot water for sanitary and technological needs, a conventional system operating with electrical energy has been selected, which generates high energy costs for water heating;
- There is a possibility of using waste heat from the refrigeration machines, serving cold rooms.

The following energy saving measures (ESM) are proposed:

ESM 1: Installation of inverter air conditioning installations (split systems) of high energy class, operating on principle of a refrigeration cycle with direct evaporation of the refrigerant in the meat production premises, sanitary and household premises and offices. According to expert assessment and manufacturers' data, air conditioning installations of this type can achieve 60% electricity savings compared to electric convectors;

ESM 2: Installation of a heat pump hot water tank with a capacity of 300 l., operating on the principle of a refrigeration cycle with direct evaporation of refrigerant. The heat pump tank is a volumetric tank with a capacity of 300 l. with a built-in coil, which is a condenser of the integrated heat pump system. The refrigerant transfers heat to the water in the tank at the cost of low energy costs. According to expert assessment and manufacturer data, air conditioning systems of this type can achieve 60% electricity savings compared to the electricity consumed by a standard volumetric tank with an electric heater of the same capacity;

ESM 3: Installation of hydraulic modules for utilizing waste heat from the condensers of the refrigeration machines for cold rooms. The hydraulic modules are a plate heat exchanger refrigerant - water with a pump and automation. The module is connected to the refrigeration system of the respective cold room, by being connected between the refrigeration compressor and the air-cooled condenser of the refrigeration system. The hot vapors from the refrigeration compressor enter the plate heat exchanger, where they are cooled by water, which is heated to a temperature of about 60 °C and can be used as hot water for the cooking processes (for a cooking pot for head cheese). When hot water is needed, the refrigeration installation works with the water-cooled plate heat exchanger, and when there is no need for it, the air-cooled condenser fan of the refrigeration installation is turned on and the heat is released to the environment. According to expert assessment and manufacturers' data, 50% of the waste heat from the refrigeration condensers can be utilized through hydro modules for waste heat utilization. Utilization of waste heat leads to savings of the same amount of electrical energy consumed by the refrigeration machines for cold rooms. This is equivalent to 16% savings of electrical energy consumed by the refrigeration machines.

Technical and Economic Analysis of Energy Saving Measures

A comparison of specific energy consumption before and after energy saving measures is shown in Table 2.

Table 2. Comparison of specific costs before and after energy saving measures

	Before ESM			After ESM			
	Energy consumption for related with measures activities	Produced output	Specific energy consumption	Corrected energy consumption for related with measures activities	Energy consumption for related with measures activities	Produced output	Specific energy consumption
	kWh/year	kg/year	kWh/kg	kWh/year	kWh/year	kg/year	kWh/kg
ESM 1	26000	81600	0.32	26000	10400	81600	0.13
ESM 2	20000	81600	0.25	20000	8000	81600	0.10
ESM 3	58555	81600	0.72	58555	49056	81600	0.60
Total:	104555	81600	1.28	104555	67456	81600	0.83

Calculation whether the measures are cost-effective (values of NPV, NPVQ) and their payback period (PB) are presented in Table 3.

Table 3. Assessment of the economic effectiveness of energy saving measures

	B, kWh/year	B, €/year	I ₀ , €	PB, years	NPV, €	NPVQ, -
ESM 1	15600	3432.00	6300.00	1.83	+ 34 670.99	5.50
ESM 2	12000	2640.00	3800.00	1.44	+ 27 716.15	7.29
ESM 3	9499	2089.78	6250.00	2.99	+ 18 697.66	2.99
Total:	37099	8161.78	16350.00	2.00	-	-

The values of energy saving ratio (ESR), energy saving potential (ESP) and ecological equivalent (t CO₂/ year) of energy saving measures are shown in Table 4.

Table 4. ESR, ESP and ecological equivalent of energy saving measures

Energy saving measures	Energy carrier	Energy savings			Ecological equivalent t CO ₂ / year
		TES, kWh/year	ESR, %	ESP, %	
ESM 1	electricity	15600	60.0	-	12.77
ESM 2	electricity	12000	60.0	-	9.83
ESM 3	electricity	9499	16.0	-	7.78
Total:	-	37099	35.5	33.3	30.38

Conclusion

The energy audit of the slaughterhouse showed the following results:

- After implementing the described measures, annual savings of 37099 kWh of electricity are expected, with an ecological equivalent of 30.38 tons of CO₂ emissions saved. The total annual savings from the reduced consumption of electricity are in the amount of 8161.78 €;
- Energy savings ratio ESR is 35.5%, the percentage of planned energy savings PES is 33.3%;
- The payback periods of the measures PB vary from 1.44 to 2.99 years, and for the entire package of energy-saving measures the payback period is 2.00 years;
- The net present value NPV of each of the measures is a positive value, this means that all energy-saving measures are economically profitable;
- The sequence for implementing the measures according to the values of the net present value coefficient NPVQ should be: first implemented measure is ESM 2 (NPVQ = 7.29), followed by ESM 1 (NPVQ = 5.50) and ESM 3 (NPVQ = 2.99);

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Conflict of Interest

* The author declares that there is no conflict of interest

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Biomedical Engineering and Biomedical Technologies for Effective Prevention, Detection and Elimination of Choledocholithiasis

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Abstract: Currently, the issues of effective prevention, detection and high-quality elimination of choledocholithiasis remain open. These issues have changed radically over the past 30 years after the significant spread of visualization using endoscopic ultrasound and magnetic resonance cholangiography, endoscopy and laparoscopy, but still require additional clarification. We studied the possibilities of modern approaches and developments in biomedical engineering and biomedical technologies in patients with choledocholithiasis on the basis of the Department of Surgery and Urology of Dnipro State Medical University and the surgical departments of Clinical Hospital No. 6 of Dnipro (Ukraine). To detect choledocholithiasis, a whole arsenal of biomedical engineering and biomedical technologies is used: clinical and laboratory, biochemical, radiation and endoscopic research methods. The most informative diagnostic methods are ultrasound in combination with computed tomography or magnetic resonance imaging, which are non-invasive, and endoscopic retrograde cholangiopancreatography. Along with the generally accepted method of eliminating the problem, where laparoscopic cholecystectomy was performed, we used intraoperative fibrocholedochoscopy as a component of biomedical engineering and an auxiliary component of biomedical technologies in the effective elimination of choledocholithiasis. The result of using biomedical engineering components with biomedical technologies in our work, which was carried out for the period from 2018 to 2024, is: the duration of treatment when using modern diagnostic and minimally invasive technologies was 6.8 ± 0.52 bed-days, mortality - 0.2%, while with open operations - 12.8 ± 3.3 bed-days, mortality — 5.2%. The use of minimally invasive interventions allowed to reduce the number of traditional - "open" - operations for choledocholithiasis and significantly reduce the number of complications, mortality, and the duration of patient hospitalization, which emphasizes the great importance of using biomedical engineering developments together with biomedical technologies in the detection, prevention and elimination of choledocholithiasis in patients.

Keywords: Biomedical, Engineering, Technologies, Choledocholithiasis

Introduction

With the introduction of choledocholithiasis biomedical minimally invasive and endoscopic technologies, the diagnostic capabilities in the detection of are expanding, but often this complication is not diagnosed before cholecystectomy. Choledocholithiasis is the presence of gallstones in the common bile duct (CBD), causing bile obstruction. It often causes upper right abdominal pain, jaundice, nausea, and vomiting. Caused by stone

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migration from the gallbladder (secondary) or formation within the ducts (primary), it is treated via ERCP for stone removal. Despite the wide range of biophysical diagnostic methods available today, none of them is a completely reliable method for detecting stones in the bile ducts, so the question of effective diagnosis of choledocholithiasis remains open (Girón, et al., 2023). This complication requires general surgical intervention, and due to the rapid development of biomedical technologies, its diagnosis and treatment are gradually improving.

Diagnosis and treatment of choledocholithiasis have changed radically in recent years after the significant spread of visualization using biophysical endoscopic ultrasound and magnetic resonance cholangiography, "RendeVouz" procedure, endoscopy and laparoscopy (Costi et al., 2014). Discussions are ongoing regarding the selection of the most informative, less invasive and cost-effective methods for detecting different forms of choledocholithiasis. It is also important to determine the most effective treatment for this condition. Modern biophysical technologies in the diagnosis and treatment of choledocholithiasis and its complications may rely on various imaging techniques and minimally invasive treatment methods, but there is no consensus on the best treatment for choledocholithiasis and its complications. New questions arise regarding the most effective treatment of complex cases requiring conversion to open surgery when intraoperative complications arise during laparoscopic choledocholithotomy (Alkarboly, et al., 2016; Cianci et al., 2021).

The American Society of Gastrointestinal Endoscopy (ASGE) has proposed risk criteria for choledocholithiasis that are used worldwide. According to ASGE guidelines, patients are routinely classified according to their likelihood of developing choledocholithiasis as low risk (<10%), intermediate risk (10%-50%), and high risk (>50%). The risk of choledocholithiasis should be assessed in every patient who requires cholecystectomy to determine the appropriate treatment strategy (Maple et al., 2010; Buxbaum et al. 2019). Accurate risk assessment of choledocholithiasis before laparoscopic cholecystectomy is essential to determine the optimal treatment strategy. Over the past 30 years, a number of biophysical and technological strategies have been introduced to treat even the most complex bile duct stones, including large balloon papillary dilatation and intraductal laser and electrohydraulic lithotripsy under cholangioscopy guidance (Khoury et al., 2019). Diagnosis of choledocholithiasis includes the consistent use of modern biomedical technologies: transabdominal ultrasound, direct contrast methods of the biliary tract and the use of polarization microscopy of bile (Wei et al., 2020).

The presence of crystals in bile is a marker of choledocholithiasis, which, in the absence of pathognomonic signs, requires a thorough instrumental examination of patients, taking into account different informative and invasive methods of research, which will complete the diagnostic stage before surgical treatment (Baiu &Hawn, 2018) The results of microscopic examination of bile can be used as an important criterion for determining indications for endoscopic transpapillary intervention. According to literature data, the most common surgical intervention (up to 70%) in patients over 50 years of age was laparoscopic cholecystectomy with laparoscopic choledocholithotomy and T-tube drainage or primary closure.

The aim of the article is to identify a quantitative assessment of the prevalence of choledocholithiasis, identify reliable preoperative biophysical and technological factors for predicting choledocholithiasis, and improve the results of surgical treatment of patients with choledocholithiasis through the use of comprehensive effective preoperative and intraoperative diagnostics (Cai et al., 2017).

Method

In 2108 patients with gallstone disease who were treated in a surgical clinic of Dnipro City Hospital #6 from 2018 to 2024. Of these, 565 (26.8%) were diagnosed with choledocholithiasis. Including 193 (34.2%) were diagnosed with microcholedocholithiasis, and 147 (26%) of them required repeated operations for residual choledocholithiasis. Of the 565 patients with choledocholithiasis, 465 (82.3%) were women and 100 (17.7%) were men. Age over 50 years was observed in 502 (89%) patients. Clinical manifestations of choledocholithiasis were distinguished by the inconstancy of individual symptoms. In 78.7%, the absence of cholangitis was noted, in 26.5% - mechanical jaundice, in 28.9% choledocholithiasis proceeded without expansion of the diameter of the duct, in 17.2% without pronounced pain syndrome. Further, in all 565 patients with choledocholithiasis, during a comprehensive preoperative examination, calculi were found in the lumen of the bile ducts (Meeralam et al., 2017; Sebghatollahi et al., 2023). For the purpose of preoperative diagnostics to identify the risk of carrying choledocholithiasis, serological studies of the liver/pancreas, biomedical engineering instrumental methods were used: ultrasound examination, fibrogastroscopy, X-ray computed tomography of the bile ducts, M-retrograde cholecystopancreatography, E-retrograde cholecystopancreatography (Mandelia et al., 2013).

The complexity of preoperative diagnosis of choledocholithiasis lies in the diversity of clinical manifestations, the absence of a pathognomonic symptom complex, the presence of asymptomatic forms. Choledocholithiasis can be masked as other diseases. Methods of preoperative diagnosis of choledocholithiasis should be carried out according to the principle of "from simple to most complex" method.

Results and Discussion

In serological tests in choledocholithiasis, the direct fraction of total bilirubin was increased by 25 and 30.8 times, total cholesterol by 1.8 and 1.9 times, γ -glutamyl transpeptidase by 1.3 and 1.2 times, alkaline phosphatase by 3.9 and 4 times, and glutamate dehydrogenase by 1.2 and 1.3 times. Alkaline phosphatase had a sensitivity of 74.8%, total bilirubin had a sensitivity of 73.7%. (Isherwood et al., 2014). Thus, choledocholithiasis can be suspected based on markers of bile lithogenicity: $\uparrow$ cholesterol, $\downarrow$ cholatocholesterol coefficient, presence of $\uparrow$ level of direct bilirubin fraction in bile, $\uparrow\gamma$ glutamyl transpeptidase in blood serum. The presence of these markers of choledocholithiasis requires a thorough biotechnological instrumental examination and affects the choice of further treatment tactics (Toro-Calle et al., 2020; Kokoroskos et al., 2021).

Ultrasound was used as the initial imaging test for screening patients with suspected choledocholithiasis in 100% of patients. Of these, direct and indirect signs of choledocholithiasis were detected in 75%, and pseudo-negative results were obtained in 13%, and were explained by the severity of infiltrative changes in the hepatoduodenal ligament, which caused distortion of the echo signal, especially after repeated operations. No ultrasound signs of choledocholithiasis were detected in 193 (34.31%), in 107 (19%) patients, single stones from 2 to 4 mm were detected, and the diameter of the common bile duct was 0.7-0.8 cm. A direct sign of choledocholithiasis was considered to be the presence of a hyperechoic acoustic shadow in the lumen of the common bile duct. The acoustic shadow was detected in 176 (31.3%) patients. Indirect signs include the spread of intra- and extrahepatic bile ducts. According to ultrasound, it was found in 372 (65.9%) patients. The accuracy of preoperative ultrasound for the diagnosis of choledocholithiasis is low, however, an elevated level of alanine aminotransferase, concomitant acute cholecystitis, and an increased diameter of the common bile duct were identified as key factors affecting the accuracy of the diagnosis. Computed tomography, as one of the modern biomedical technological methods, was performed on 39 patients (28 women, 11 men) with choledocholithiasis. In 29 of them, choledocholithiasis was combined with chronic calculous cholecystitis, in 14 - with obstructive jaundice and cholangitis.

The combination of ultrasound examination with computed tomography increases the accuracy of choledocholithiasis diagnosis to 97.4%. In severe cases with the development of complications, with suspected infection, computed tomography allowed to diagnose the presence of pancreatic necrosis and the volume of organ damage, as well as to determine the presence of infiltration of adjacent tissues and fluid accumulations, their distribution in anatomical spaces. Computed tomography with bolus contrast, unlike ultrasound, allowed to more accurately assess the extrapancreatic spread of the inflammatory process.

Fibrogastroduodenoscopy was performed on a mandatory basis in all 565 patients with suspected choledocholithiasis. This technique helped to detect bedsores in the area of the major duodenal papilla, due to the impaction of concretions in 8 patients, in 8 patients after fibrogastroduodenoscopy, spontaneous passage of concretions into the duodenum was observed and, as a result, mechanical jaundice decreased and urine color lightened.

As a biomedical engineering technology, direct contrast of the extrahepatic bile ducts before surgery was used, and it was carried out using E-retrograde cholecystopancreatography, which was performed in 198 (35%) patients. The indications for its implementation were: 1) suspicion of choledocholithiasis according to ultrasound; 2) biochemical disorders (increased bilirubin and other indicators); 3) the need to remove common bile duct stones. The informativeness of E-retrograde cholecystopancreatography in choledocholithiasis was 96.7%. The data obtained indicate the presence of choledocholithiasis in 28%, however, in 5% only the pancreatic duct was contrasted, and in 2% pseudo-negative results of the study were obtained.

In 83 patients, M-retrograde cholecystopancreatography was used to diagnose choledocholithiasis. Common bile duct stones were visualized on MR images as single or multiple filling defects with loss of MR signal from them against the background of a bright signal from the surrounding bile. The common bile duct was more than 0.8 cm in 61 patients and 0.7-0.8 cm in 22 patients. In 15, single small stones were located in the ampullary part of the common bile duct, in 30 choledocholithiasis was combined with stenosis of the major duodenal papilla (Polistina et al., 2015).

Our results showed the informativeness of M-retrograde cholecystopancreatography in the diagnosis of various forms of choledocholithiasis. This study is a non-invasive diagnostic method for visualization of the bile ducts. The technique does not require the administration of contrast agents, does not involve intervention in the biliary system, and does not involve radiation exposure. The informativeness of M-retrograde cholecystopancreatography in choledocholithiasis was 93% (Qiu et al., 2015; Giljaca et al., 2015; Reid et al., 2017).

There were 1 false-positive and 1 false-negative results. The reason for the false positive result of M-retrograde cholecystopancreatography was the mistaken perception of edema of the ampullary sphincter for a stone of the distal common bile duct. False negative diagnosis associated with the lack of contrast between multiple small intrahepatic duct stones and the surrounding liver, without high signal of bile, which outlines the stones. Stones with a diameter of <5 mm are almost not visualized on M-retrograde cholecystopancreatography. Choledocholithiasis diagnosed by M-retrograde cholecystopancreatography in this category of patients is an indication for laparoscopic, endoscopic, or other surgical intervention, to prevent repeated surgical interventions on the biliary tract.

This biomedical technological method should not be used as a screening method due to the high cost and the need for hardware, but it is very necessary when ultrasound examination does not provide sufficient diagnostic information. The lack of invasiveness, visualization of the bile ducts above or below the intersection allows in many cases to replace invasive E-retrograde cholecystopancreatography. Preoperative diagnostic methods together with clinical, laboratory and functional examination results allow to justify indications for surgery. However, it is possible to determine all the subtleties of the nature and extent of the pathological process only when conducting a comprehensive intraoperative examination.

The main method of treatment of choledocholithiasis and its complications was surgery. Preoperative conservative therapy began with intensive infusion therapy in combination with antisecretory therapy. All patients received standard infusion therapy, which included antispasmodic, antisecretory, detoxification, anticoagulant therapy, correction of water and electrolyte imbalance and, if necessary, antibacterial therapy.

In primary choledocholithiasis, 408 (72.2%) underwent one-stage treatment using the necessary modern biomedical engineering and technological complex: laparoscopic cholecystectomy, intraoperative fibrocholedochoscopy, choledochotomy, choledocholithotomy, external drainage of the common bile duct with T-tube drainage. We believe that drainage of the bile duct is mandatory because manipulations on the bile ducts can cause the development of severe pancreatitis, which is more common in women (Tan et al., 2023).

In secondary choledocholithiasis, 143 (25.3%) underwent intraoperative fibrocholedochoscopy, choledochotomy, choledocholithotomy, and external drainage of the common bile duct. Intraoperative fibrocholedochoscopy was performed in 408 (72.2%) patients with primary choledocholithiasis and in 143 (25.3%) with secondary choledocholithiasis. Choledochoscopy was performed using a new generation thin endoscope from Cirkon (USA) with an external diameter of 9.8F and a working channel diameter of 3.6F. The fibrocholedochoscope was inserted into the lumen of the common bile duct through the cystic duct in 121 (22%) and through the choledochotomy opening in 430 (78%) (Virzi et al., 2018).

After that, the distal parts of the common bile duct, the internal canal of the major duodenal papilla were examined and its patency was checked. Then, the proximal part of the hepaticocholedochus and intrahepatic ducts were revised. The detected stones were removed using Dormia baskets manufactured by Cirkon (USA). Fogarty catheters of various diameters were also used to remove stones. Signs of cholangitis (fibrin flakes, edema, hyperemia, erosion of the duct mucosa) were detected in 120 (20%) patients, and these patients underwent biopsy with histology and bacteriological examination. According to our data, intraoperative fibrocholedochoscopy is the most informative method of intraoperative diagnosis of choledocholithiasis and its complications (Badger et al., 2014).

The diagnostic value of choledochoscopy performed through the cystic duct stump is 89.8%. The diagnostic value of choledochoscopy through the choledochotomy opening is 100% and allows for a detailed examination of the proximal and distal parts of the bile ducts. The completeness of stone removal was assessed by control fibrocholedochoscopy. According to its data, fragments of stones with a diameter of 4 to 6 mm were detected in 3 (16%) patients, which prevented the development of residual choledocholithiasis. The special importance of fibrocholedochoscopy in the diagnosis of intrahepatic lithiasis. According to its data, intrahepatic lithiasis was detected in 20 (3.7%) patients. These patients had no data on intrahepatic lithiasis before choledochoscopy. The

found concrements were removed using Dormia baskets, Fogarty catheters under the control of a fibrocholedochoscope.

After the surgical intervention, patients experienced a decrease in pain syndrome, intoxication, improvement in general condition, and disappearance of symptoms of mechanical jaundice. All patients underwent early activation. Simultaneous elimination of complications of choledocholithiasis allows reducing the severity and duration of organ and multiorgan failure and avoiding probable death in the elderly and senile age with severe concomitant pathology (Aleknaitė et al., 2018). The drain was removed 14–21 days after surgery based on the results of E-retrograde cholecystopancreatography or fistulography. One patient died after surgery, with a mortality rate of 0.6%. Minimally invasive interventions (as primary surgery) were performed in 418 (74%) patients - in 408 (72.2%) laparoscopic cholecystectomy, intraoperative fibrocholedochoscopy, choledochotomy, choledocholithotomy and 10 patients (1.8%) underwent endoscopic papillosphincterotomy during E-retrograde cholecystopancreatography. They proved to be an effective and sufficient method of surgical intervention in 74% of patients. The duration of treatment when using minimally invasive technologies was 6.8 ± 0.52 bed-days, mortality – 2.6%, with open operations – 12.8 ± 3.3 bed-days, mortality – 5.2% (Bergeron, et al., 2021).

Conclusion

1. Choledocholithiasis occurs, according to our data, in 26.8% of patients with gallbladder diseases.
2. Predictors of choledocholithiasis were: age over 50 years in 89% of patients, female gender in 82.3%, markers of bile lithogenicity: $\uparrow$ cholesterol, $\downarrow$ cholatocholesterol coefficient, $\uparrow$ level of direct bilirubin fraction, $\uparrow$ level of alkaline phosphatase in blood serum, diameter of the common bile duct (0.7 cm and $\uparrow$).
3. For the diagnosis of choledocholithiasis, it is advisable to use modern biomedical engineering and technological transabdominal ultrasound examination in combination with E-retrograde cholecystopancreatography or M-retrograde cholecystopancreatography.
4. The final decision is made during a comprehensive intraoperative examination.
5. An effective and sufficient method of surgical treatment of primary choledocholithiasis is laparoscopic cholecystectomy, intraoperative fibrocholedochoscopy, choledochotomy, choledocholithotomy, external drainage of the common bile duct with T-tube drainage.
6. Intraoperative fibrocholedochoscopy is the most informative method of diagnosing choledocholithiasis and its complications. The diagnostic value of choledochoscopy performed through the cystic duct stump is 89.8%. The diagnostic value of choledochoscopy through the choledochotomy opening is 100%.
7. Intraoperative fibrocholedochoscopy allows for the detection of intrahepatic lithiasis, and makes it possible to specifically remove calculi located in the segment and lobar ducts of the liver.
8. An effective and sufficient method of surgical treatment of secondary choledocholithiasis is intraoperative fibrocholedochoscopy, choledochotomy, choledocholithotomy, and external drainage of the common bile duct with T-tube drainage.

Recommendations

In the future, the application of the proposed complex-combined method of prevention, detection, correct diagnosis and effective treatment of choledocholithiasis using biophysical and biotechnological means can objectify and accelerate the determination of this pathological condition, and an in-depth study of these results can become the basis for successful surgical treatment of specialized patients.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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***Clausena excavata*: In Vitro Inhibitory Activity Against α -Glucosidase and Pancreatic Lipase**

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Abstract: *Clausena excavata* Burm.f. is a tropical medicinal plant that has been used in traditional practice for a range of health conditions. In this study, leaf fractions of *C. excavata* prepared using methanol (MOH), ethyl acetate (EA), chloroform (CH), and petroleum ether (PT) were screened for their ability to inhibit two clinically relevant enzymes: α -glucosidase, which is associated with postprandial glucose control, and pancreatic lipase, which is involved in intestinal fat digestion. Among the fractions tested, the CH fraction produced the strongest inhibition against both α -glucosidase and porcine pancreatic lipase, with IC_{50} values of 53.5 ± 1.08 μ g/mL and 177.3 ± 0.43 μ g/mL, respectively. These findings suggest that the chloroform-soluble constituents of *C. excavata* leaves may contain compounds of interest for further anti-diabetic and anti-obesity investigation. Further chemical profiling and mechanism-based studies are required before therapeutic claims can be made to position it as a promising candidate for anti-diabetic, and anti-obesity drug development.

Keywords: Clausena, Enzyme inhibition, Leaf fractions

Introduction

Enzymes regulate many biochemical reactions in the body, and for this reason, several enzymes have become useful targets in drug discovery. Two examples that are relevant to metabolic disorders are α -glucosidase and pancreatic lipase (Aslan et al., 2019). Ty Human body's inability to maintain normal glucose concentration and insulin resistance will eventually lead to type II diabetes mellitus. Controlling post-meal elevation in glucose levels is achieved by slowing the carbohydrates digestion in the intestines. Enzymes inhibitors especially α -glucosidase, are the main players in this reaction through decreasing disaccharides conversion into monosaccharides, resulting in preventing the rapid spike in blood glucose levels after meals. That's clarifies the increasing demand α -glucosidase plant derived inhibitors (Papoutsis et al., 2021; Proença et al., 2022).

Sedentary lifestyle and imbalanced unhealthy diet causing dramatic increase in obesity levels in the communities, thus directly resulting in abnormal lipid profile (hyperlipidemia) with high-risk cardiovascular associated endocrine disorders. Reducing pancreatic lipase will decrease the amount of fat absorbed in the digestive system as this enzyme is responsible for hydrolyzing dietary triglycerides before absorption occurs. These clarify that naturally occurring product with pancreatic lipase inhibitory activity remains rich area of research concerning anti-obesity (Albaayit et al., 2025; Jaradat et al., 2017).

Clausena excavata is widely reported in folk/ traditional medicine. Its phytochemicals rich profile has attracted the research interests in many aspects (Sharifi-Rad et al., 2020; Atanasov et al., 2021), whilst its leaf

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fraction inhibitory activity against α -glucosidase and pancreatic lipase remains poor. The present study therefore examined the *in vitro* inhibitory effects of *C. excavata* leaf fractions against these two enzymes as an early screening step for potential metabolic health applications.

Method

Plant Preparation

Fresh *C. excavata* leaves were processed and extracted according to the method described by Albaayit, 2023.

Alpha-Glucosidase Inhibition Assay

The α -glucosidase assay was performed in 96-well plates. MOH, EA, CH, and PT fractions were tested at concentrations ranging from 31.25 to 250 μ g/mL. Each fraction was mixed with α -glucosidase solution (0.2 U/mL) and phosphate-buffered saline (0.1 M, pH 6.8), followed by incubation at 37 °C for 15 minutes. Absorbance was recorded before the addition of p-nitrophenyl- α -D-glucopyranoside (PNP-G), and the reaction was monitored for 30 minutes at 400 nm. Acarbose was used as the positive control (Kumar et al., 2021; Limcharoen et al., 2022).

In vitro Pancreatic Lipase Inhibition Assay

Pancreatic lipase inhibition was assessed using a spectrophotometric method. The reaction mixture contained Tris-HCl buffer, test fractions of MOH, EA, CH, and PT (0.025-0.2 mg/mL), porcine pancreatic lipase (PPL), and p-nitrophenyl butyrate (pNPB) as the substrate. After incubation at 37 °C for 5 minutes, absorbance was measured at 410 nm. Percentage inhibition was calculated relative to the control, and IC₅₀ values were estimated from the concentration-response data ((Limcharoen et al., 2022; Buchholz & Melzig, 2021).

$$\text{Enzyme inhibition (\%)} = [(A \text{ control} - A \text{ sample}) / A \text{ control}] \times 100 = \frac{\text{O.D of enzyme with inhibitor}}{\text{O.D of enzyme without inhibitor}} \times 100$$

Results and Discussion

The starting point for identifying bioactive compounds is medicinal plants especially when these plants have been traditionally widely used and this usage is supported by experimental screening. *Clausena excavata* has been reported to contain flavonoids, carbazole alkaloids and coumarins in their leaves (Seca & Pinto, 2021; Arbab et al., 2020; Thant et al., 2019). Enzyme inhibitory effect observed in this study is mostly due to the contribution of these compounds even though the specific active constituents were not isolated.

Health and economic burden of chronic metabolic diseases give high relevancy to this study. Global large proportion mortalities have been reported by the world health organization mainly due non-communicable diseases such as diabetes, it is considered the major risk factor for cardiovascular, neurological, renal complications (WHO, 2021; 30). Postprandial glucose rise moderation agents are still of interest, especially at the early detection stage. Pancreatic lipase considered one of the main experimental targets in obesity screening as it controls a pivotal step in fat digestion. Pancreatic lipase hydrolyses triacylglycerols into fatty acids and 2-monacylglycerols. Intestinal fat absorption may decrease when the lipase activity is reduced, thus explains the wide usage of pancreatic lipase inhibition as an *in vitro* model in natural product research (Ado et al., 2013).

Clausena excavata chloroform leaves fraction in this study showed the highest inhibitory activity among the tested fractions. The IC₅₀ values of 177.3 $\pm$ 0.43 μ g/mL against pancreatic lipase and 53.5 $\pm$ 1.08 μ g/mL against α -glucosidase (Table 1). These findings are consistent with the previous findings confirming the higher flavonoid content in the CH fraction in *Clausena excavata* leaves (Kashyap et al., 2022; Tchamgoue et al., 2020)). Flavonoids have been associated with enzyme inhibition through non-covalent binding and, in some cases, competitive interactions with digestive enzymes (He et al., 2019; Rahim et al., 2015). Taken together, the results support further phytochemical and mechanistic evaluation of the CH fraction.

Table 1. *In vitro* enzyme inhibitory activity of the different extract of *C. excavata* leaves

	Enzyme Inhibition (IC ₅₀)				
	Methanol (MOH)	Ethyl acetate (EA)	Chloroform (CH)	Petroleum ether (PT)	^a standard
α -glucosidase	137.1 $\pm$ 7.01	113.3 $\pm$ 3.01	53.5 $\pm$ 1.08	187.7 $\pm$ 5.03	875.75 $\pm$ 2.08 μ M
Pancreatic lipase	>200	>200	177.3 $\pm$ 0.43	>200	12.7 $\pm$ 1.27 μ g/mL

^a The standard drug Acarbose was used in α -glucosidase assays, Orlistat in pancreatic lipase

Conclusion

The study concludes that *C. excavata* exhibits inhibition activity against α -glucosidase and pancreatic lipase enzyme, making a valuable insight for future therapeutic development, but the current findings should be interpreted as preliminary *in vitro* evidence rather than proof of clinical efficacy.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare no conflict of interest.

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Strategic Management of Sector-Specific ESG KPIs in Technology-Intensive Industries

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Abstract: The mining industry is characterized by high technological intensity, capital-intensive operations and significant environmental and social impacts. As a result, Environmental, Social and Governance (ESG) performance measurement in the sector requires indicators that reflect industry-specific technologies and operational realities. This paper examines the strategic management of sector-specific ESG KPIs in the mining industry and their role in achieving sustainable competitive advantage. Adopting a management-oriented perspective, the study analyses how mining companies align ESG KPIs with extraction and processing technologies, operational risks and strategic objectives. A conceptual framework is developed to illustrate the relationship between mining technologies, ESG KPI selection and strategic management practices. The analysis demonstrates that mining companies that effectively manage sector-specific ESG KPIs are better positioned to improve operational transparency, manage environmental and social risks and integrate sustainability into core decision-making processes. The findings suggest that sector-specific ESG KPIs function as strategic management tools in the mining industry, enabling firms to move beyond compliance and leverage sustainability as a driver of long-term competitiveness. The study contributes to the management of technology literature by addressing performance measurement and strategic control in complex, technology-intensive industrial systems.

Keywords: ESG KPIs, Mining industry, Strategic performance management, Management of technology, Technology-intensive industries.

Introduction

ESG Challenges in the Mining Industry

The mining industry occupies a structurally complex position within the sustainability discourse, as it simultaneously underpins economic development and the green transition while generating significant environmental and social externalities. Mining activities are inherently technology-intensive, capital-intensive, and site-specific, resulting in material impacts that include land disturbance, biodiversity loss, high water and energy consumption, greenhouse gas emissions, tailings generation, and elevated occupational health and safety risks. (Dimov et al, 2020) These impacts are not incidental but are intrinsically linked to extraction and processing technologies, ore characteristics, and operational scale, making sustainability performance in mining fundamentally different from that in less resource-intensive sectors (Azapagic, 2004; Hilson, 2012).

Over the past decade, stakeholder expectations toward the mining industry have intensified considerably. Regulators, investors, financial institutions, downstream manufacturers, and local communities increasingly demand transparent, credible, and decision-useful information on how mining companies identify, manage, and mitigate ESG-related risks. This shift reflects a broader transformation in corporate sustainability governance, whereby ESG considerations are no longer treated as peripheral reputational concerns but as determinants of

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operational continuity, access to finance, and long-term competitiveness (Eccles et al., 2014; Friede et al., 2015). In mining, this transformation is particularly pronounced due to the sector's exposure to high-consequence environmental and social risks and its reliance on long-lived assets with irreversible impacts. Good practices and approaches aimed at enhancing innovation potential contribute to the more efficient use of natural resources and to reducing resource depletion. They are included in the policies for social, corporate and environmental responsibility of the mining companies (Galabova & Trifonova, 2018).

The institutionalization of ESG expectations has further accelerated through the expansion and consolidation of sustainability reporting and disclosure frameworks. At the global level, the emergence of investor-oriented standards such as the IFRS Sustainability Disclosure Standards has reinforced the integration of ESG considerations into corporate governance, strategy, and risk management, while explicitly encouraging the use of industry-based guidance to enhance relevance and comparability (IFRS Foundation, 2023). In parallel, the European Union has introduced an extensive regulatory architecture through the Corporate Sustainability Reporting Directive and the European Sustainability Reporting Standards, which require companies to disclose sustainability information based on a double materiality perspective, linking impact materiality with financial materiality (European Commission, 2023; European Union, 2023).

For the mining industry, these developments have profound implications. Sector-specific sustainability standards, most notably the GRI 14: Mining Sector 2024 standard, explicitly acknowledge that generic sustainability disclosures are insufficient to capture the industry's impact profile. Instead, they emphasize the need for disclosures and indicators that reflect mining-specific technologies, operational risks, and lifecycle considerations, including site-level impacts and long-term liabilities (Global Reporting Initiative, 2024). This recognition aligns with earlier scholarship highlighting that sustainability challenges in mining are best understood as sociotechnical systems in which environmental, social, and governance outcomes are co-produced by engineering design, operational practices, and institutional arrangements (Azapagic & Perdan, 2000; Jenkins & Yakovleva, 2006).

A particularly illustrative example is tailings management, which has emerged as a critical ESG issue following several high-profile failures with catastrophic environmental and social consequences. The Global Industry Standard on Tailings Management frames tailings governance as a zero-harm aspiration supported by integrated technical, environmental, and social requirements throughout the facility lifecycle (UNEP, 2020). The existence of such sector-specific standards underscores a central argument of this study: in mining, ESG performance is inseparable from technological choices and operational controls, and therefore requires measurement systems that are explicitly aligned with these determinants.

Why Universal KPIs Do Not Work

Despite growing recognition of sectoral specificities, ESG measurement in practice continues to rely heavily on universal, cross-sector key performance indicators. These indicators are often designed to facilitate comparability across industries and geographies, yet their applicability to mining is increasingly contested. Research on ESG metrics and ratings consistently demonstrates substantial heterogeneity in indicator selection, weighting, and aggregation methods, leading to divergent assessments of corporate ESG performance even for the same firm (Berg et al., 2022; OECD, 2020). Such divergence reflects deeper methodological tensions between financially oriented ESG metrics and impact-oriented sustainability measurement, with significant implications for managerial decision-making.

In the mining industry, the limitations of universal ESG KPIs are particularly acute for several reasons. First, mining impacts are technologically mediated and highly site-specific. Universal indicators often obscure critical differences arising from extraction methods, processing technologies, ore grades, and local environmental conditions. For example, a single water-use or emissions intensity metric may fail to distinguish between operations facing fundamentally different hydrological constraints or energy systems, thereby providing limited insight into actual environmental risk exposure or improvement potential (Azapagic, 2004).

Second, material ESG issues in mining are unevenly distributed across environmental, social, and governance dimensions and vary significantly across commodities, jurisdictions, and project lifecycles. Sector-focused standards such as GRI 14 explicitly reflect this logic by prioritizing material topics that are likely to be significant for mining organizations and their stakeholders, rather than prescribing a uniform set of indicators applicable to all sectors (Global Reporting Initiative, 2024). The very existence of such standards constitutes an implicit critique of universal KPI approaches, suggesting that sectoral impact logic must precede indicator selection.

Third, mining operates under a pronounced legitimacy constraint shaped by social license to operate considerations. Community acceptance, trust in risk management practices, and perceptions of procedural fairness play a decisive role in project viability and operational continuity. While these dimensions are difficult to quantify, their strategic relevance is well documented in the mining and development literature (Prno & Slocombe, 2012; Owen & Kemp, 2013). Universal ESG KPIs frequently underrepresent these relational and process-oriented aspects, focusing instead on simplified output metrics that may inadequately capture social risk dynamics.

Fourth, and most critically from a management perspective, universal ESG KPIs often fail to support strategic decision-making. While such indicators may satisfy external disclosure requirements, they are not necessarily designed to guide internal resource allocation, technology selection, or risk governance. Empirical studies of ESG ratings in the mining sector indicate weak or inconsistent relationships between aggregated ESG scores and financial performance, suggesting that these metrics may reflect disclosure intensity or firm size rather than underlying operational performance (Fikru, 2021). This disconnect undermines the utility of universal KPIs as instruments of strategic management in technology-intensive industries.

Motivation and Contribution of the Study

Against this backdrop, this paper advances the argument that ESG KPIs in the mining industry should be conceptualized primarily as strategic management instruments, rather than as standardized reporting artifacts. While contemporary regulatory and voluntary frameworks increasingly acknowledge the importance of industry-based disclosures, a gap remains between disclosure-oriented indicator systems and KPI frameworks explicitly designed for strategic integration into mining governance, investment decisions, and operational control.

This study addresses this gap by proposing a sector-specific, management-oriented perspective on ESG KPIs grounded in the technological characteristics of mining operations. It contends that mining technologies constitute first-order determinants of ESG materiality and performance and must therefore serve as the starting point for KPI design and strategic management. By articulating a conceptual framework that links mining technologies, sector-specific ESG KPI design, and strategic management practices, the paper contributes to the literature on management of technology and sustainability by demonstrating how ESG KPIs can support sustainable competitive advantage in a sector increasingly defined by sustainability constraints and stakeholder scrutiny.

This Study Makes Three Distinct Contributions to Literature

First, it reframes ESG KPIs in the mining industry from disclosure-oriented metrics to *strategic management instruments* explicitly shaped by extraction and processing technologies. Second, it advances the management of technology literature by conceptualizing ESG KPIs as mediating mechanisms between technological systems and competitive outcomes in high-risk industrial environments. Third, the paper develops a sector-specific framework that links technological determinants, ESG KPI design, and strategic performance management, thereby addressing a gap between sustainability measurement and strategic decision-making in technology-intensive industries.

Literature Review

ESG KPIs in the Mining Sector

The academic literature on ESG performance in the mining sector consistently emphasizes the inadequacy of generic sustainability indicators to capture the sector's distinctive impact profile. Early contributions in the field of sustainability assessment in mining already highlighted that environmental and social impacts are deeply embedded in extraction and processing technologies, site-specific geological conditions, and long project lifecycles (Azapagic, 2004; Azapagic & Perdan, 2000). As a result, ESG performance measurement in mining has long been recognized as fundamentally different from that in manufacturing or service-oriented industries.

Subsequent research has expanded this perspective by examining how ESG indicators are operationalized through corporate reporting and performance management systems. Studies on sustainability disclosure in the mining industry reveal significant variation in the scope, depth, and consistency of ESG metrics used by firms, even within the same commodity group or jurisdiction (Jenkins & Yakovleva, 2006; Fonseca et al., 2014). This variation is often attributed to differences in operational technologies, regulatory environments, and stakeholder

pressures, suggesting that ESG KPIs in mining are shaped as much by technological and institutional contexts as by managerial intent.

More recent literature has focused on the growing formalization of ESG measurement through sector-specific standards and guidance. The introduction of mining-focused disclosure frameworks reflects a recognition that sectoral materiality must precede indicator selection. These frameworks emphasize ESG topics such as tailings management, water stewardship, occupational health and safety, community engagement, and mine closure, which are directly linked to mining technologies and operational risks (Global Reporting Initiative, 2024). Academic analyses interpret this sectoral turn as an attempt to enhance the decision-usefulness of ESG information by aligning indicators with the underlying drivers of impact and risk (Sullivan & Gouldson, 2017).

Despite these advances, a recurring critique in the literature is that ESG KPIs in mining remain predominantly disclosure-oriented. Empirical studies show that many indicators are selected to satisfy external reporting expectations rather than to support internal decision-making, resulting in limited integration of ESG KPIs into strategic planning and operational control (Lodhia & Hess, 2014; Fonseca, 2010). This critique is reinforced by research on ESG ratings in the mining sector, which demonstrates weak correlations between aggregated ESG scores and financial or operational performance, raising questions about the managerial relevance of widely used metrics (Fikru, 2021; Berg et al., 2022).

Collectively, the literature suggests that while ESG KPIs are increasingly institutionalized in the mining sector, their strategic potential remains underdeveloped. Existing studies tend to focus on what is disclosed rather than on how ESG indicators are managed, governed, and used as instruments of strategic control. This gap provides a critical entry point for research that repositions ESG KPIs as elements of strategic management rather than as static reporting artifacts.

Technology-Intensive Industries and Sustainability Measurement

The concept of technology-intensive industries is well established in the management and industrial economics literature, where such industries are characterized by high capital intensity, complex production systems, long asset lifecycles, and strong path dependencies shaped by technological choices (Pavitt, 1984; Tidd & Bessant, 2018). Mining is frequently cited as a paradigmatic example of a technology-intensive industry, given its reliance on specialized extraction and processing technologies, large-scale infrastructure, and irreversible environmental interventions.

Within this body of literature, technology is not treated merely as an operational input but as a structural determinant of organizational behavior, risk exposure, and performance outcomes. Research on management of technology emphasizes that technological systems constrain and enable strategic choices, influencing cost structures, flexibility, learning trajectories, and competitive positioning (Grant, 2016). From this perspective, sustainability performance in technology-intensive industries cannot be decoupled from the technological architectures through which value is created.

Studies examining sustainability in technology-intensive sectors highlight that environmental and social impacts are often non-linear, cumulative, and characterized by high uncertainty. In mining, these characteristics are evident in areas such as tailings storage, groundwater interactions, and occupational safety, where technological failures can result in disproportionate consequences (Prior et al., 2012). As a result, performance measurement systems in such industries must be capable of capturing risk dynamics and long-term liabilities, rather than relying solely on short-term efficiency indicators.

The literature further indicates that technology-intensive industries face heightened scrutiny from regulators and investors precisely because of these risk characteristics. This has contributed to the proliferation of sector-based sustainability standards and the increasing expectation that firms demonstrate robust governance of technology-related ESG risks (UNEP, 2020; OECD, 2020). However, scholars note that the translation of these expectations into effective performance measurement remains uneven, with many firms struggling to align sustainability metrics with technological realities (Schaltegger et al., 2017).

Importantly, research on technology-intensive industries underscores the limits of cross-sector comparability in performance measurement. Indicators designed for broad applicability often obscure critical differences in technological risk profiles and impact pathways, thereby reducing their explanatory and managerial value (Kaplan

& Norton, 2001). This insight reinforces the argument that ESG KPIs in mining must be explicitly grounded in sector-specific technologies if they are to support meaningful management decisions.

Strategic Performance Management and ESG Integration

Strategic performance management (SPM) literature provides a critical lens for understanding how ESG KPIs can move beyond disclosure to become instruments of strategic control. Classical contributions to SPM conceptualize performance measurement systems as mechanisms for translating strategy into operational terms, aligning organizational behavior with strategic objectives, and enabling feedback and learning (Kaplan & Norton, 1996; Neely et al., 2005). Within this framework, KPIs are not neutral metrics but selective representations of what organizations choose to value and manage.

Recent extensions of SPM theory explicitly incorporate sustainability considerations, arguing that environmental and social performance must be integrated into core management systems to achieve long-term value creation (Schaltegger & Wagner, 2011; Gond et al., 2012). This stream of literature emphasizes that sustainability-oriented KPIs should be embedded in strategic planning, capital allocation, and risk management processes, rather than treated as parallel or supplementary reporting tools.

However, empirical evidence suggests that such integration remains limited, particularly in technology-intensive industries. Studies examining ESG integration into performance management systems find that while firms increasingly monitor ESG indicators, these metrics are often decoupled from strategic decision-making and incentive structures (Crutzen et al., 2017). In mining, this decoupling is exacerbated by the dominance of externally driven ESG requirements, which prioritize comparability and disclosure over internal controllability and strategic relevance.

The strategic management literature also highlights the importance of context-specific KPIs in environments characterized by high uncertainty and irreversible investments. In such settings, performance indicators must support risk-informed decision-making and long-term planning, rather than short-term optimization (Simons, 1995; Grant, 2016). Applied to mining, this implies that ESG KPIs should reflect technological risk profiles, lifecycle considerations, and stakeholder dependencies, enabling managers to anticipate and mitigate sustainability-related constraints on competitiveness.

Taken together, the literature on strategic performance management suggests that ESG KPIs can contribute to sustainable competitive advantage only when they are strategically designed, contextually grounded, and actively managed. Yet, existing research rarely examines how these principles apply in the mining industry, where technological intensity and sustainability risks intersect most strongly. This gap underscores the need for a sector-specific, management-oriented framework that connects mining technologies, ESG KPI design, and strategic performance management—an objective directly addressed by the present study.

Methodology

Research Design and Conceptual Orientation

This study adopts a conceptual and qualitative research design, appropriate for addressing research questions that are exploratory, theory-building, and integrative in nature. The objective is not to test predefined hypotheses or quantify causal effects, but to develop a theoretically grounded framework that explains how sector-specific ESG KPIs can be strategically managed in the mining industry, given its technology-intensive characteristics. Such an approach is well established in the management and sustainability literature, particularly where existing empirical evidence is fragmented and where conceptual clarification is required to advance understanding (Eisenhardt, 1989; Meredith, 1993; Jaakkola, 2020).

Conceptual research is especially relevant in the context of ESG KPIs in mining for two reasons. First, the rapid evolution of ESG-related standards, regulations, and practices has outpaced the development of stable, cumulative theory, resulting in a body of literature that is rich in descriptive insights but limited in integrative frameworks. Second, ESG KPIs operate at the intersection of technology, governance, and strategy, making them difficult to analyze through single-method empirical designs without prior conceptual structuring. Accordingly, this study positions conceptual development as a necessary precursor to future empirical testing and model refinement.

Development of the Conceptual Framework

The conceptual framework proposed in this study was developed through an iterative process of analytical abstraction and synthesis of insights from three interrelated bodies of literature:

1. ESG measurement and reporting in the mining sector,
2. management of technology and technology-intensive industries, and
3. strategic performance management.

Following established principles of conceptual framework development, the process involved identifying key constructs, clarifying their boundaries, and specifying theoretically plausible relationships among them (Whetten, 1989; Miles et al., 2014). Rather than aggregating variables in a statistical sense, the framework organizes analytical layers that reflect different levels of decision-making and causality: technological determinants, ESG KPI design, strategic management practices, and competitive outcomes.

Mining technologies are positioned as the foundational layer of the framework, reflecting insights from technology management theory that technological systems shape organizational constraints, risk profiles, and strategic options (Grant, 2016; Tidd & Bessant, 2018). ESG KPIs are conceptualized as a translation mechanism that converts technology-driven impacts and risks into measurable indicators suitable for managerial use. Strategic management practices constitute the central mediating layer, where ESG KPIs are integrated into planning, investment appraisal, and risk governance processes. The framework culminates in sustainable competitive advantage as an outcome, consistent with strategic management literature that links performance measurement systems to long-term value creation when they are aligned with organizational context and strategy (Kaplan & Norton, 1996; Neely et al., 2005).

Importantly, the framework is analytical rather than prescriptive. It does not propose a universal set of KPIs or managerial actions, but instead provides a structured logic for understanding how ESG KPIs can be designed and managed in a sector where technology is a primary driver of sustainability performance. This orientation aligns with calls in the sustainability and management literature for theory-building approaches that respect sectoral heterogeneity and contextual specificity (Schaltegger et al., 2017; Jaakkola, 2020).

Qualitative Analysis of Standards, Reports, and Sectoral Practices

To ground the conceptual framework in real-world practices and enhance its analytical robustness, the study employs a qualitative document-based analysis of selected standards, sustainability reports, and sectoral practices relevant to the mining industry. Qualitative analysis of documentary sources is a well-established method in sustainability and management research, particularly where the objective is to interpret institutional logics, governance arrangements, and performance measurement practices rather than to generate statistically generalizable results (Bowen, 2009; O'Dwyer, 2004). The analysis focuses on three categories of sources.

First, sustainability standards and regulatory frameworks relevant to ESG measurement in mining were examined. These include global and sector-specific standards that articulate material ESG topics, disclosure expectations, and performance indicators for the mining industry. Such standards are treated as institutionalized expressions of collective expectations regarding what constitutes relevant and credible ESG performance in the sector (Global Reporting Initiative, 2024; IFRS Foundation, 2023). The analysis concentrates on how these frameworks address sector specificity, technological impacts, and the role of KPIs in governance and risk management, rather than on detailed compliance requirements.

Second, corporate sustainability reports of mining companies were reviewed to identify prevailing practices in ESG KPI selection and presentation. Sustainability reports are widely recognized as key artifacts through which organizations communicate their sustainability priorities and performance, while simultaneously revealing internal measurement logics and managerial emphases (Jenkins & Yakovleva, 2006; Fonseca, 2010). The analysis does not seek to evaluate the credibility or completeness of individual reports, but rather to observe patterns in how ESG KPIs are framed, linked to operations, and embedded (or not embedded) in strategic narratives.

Third, sectoral practices and industry initiatives were analyzed to capture how ESG risks and performance are addressed beyond formal reporting. This includes industry-level guidance on critical issues such as tailings management, occupational health and safety, and community engagement, which often reflect tacit knowledge and shared norms within the sector (UNEP, 2020; Owen & Kemp, 2013). These sources provide insight into how

ESG KPIs are implicitly shaped by technological risk domains and operational priorities, even when not explicitly labeled as “KPIs” in corporate disclosures.

The qualitative analysis followed a structured interpretive approach, involving iterative reading, thematic coding, and comparison across different categories of documentary sources (Miles et al., 2014). The analysis focused on identifying recurring patterns in how ESG KPIs are linked to technological processes, risk management structures, and strategic narratives within the mining sector. Particular attention was paid to cross-document consistency and divergence, as well as to the stated purposes of ESG KPIs, including reporting, risk management, and performance improvement. The insights derived from this analysis informed the specification of KPI categories and managerial linkages presented in Table 1, ensuring that the proposed conceptual framework is grounded in observed sectoral practices rather than normative or abstract assumptions.

Methodological Rigor and Limitations

The methodological rigor of the study is ensured through theoretical triangulation and transparent articulation of analytical assumptions. By integrating insights from multiple literature streams and documentary sources, the study reduces the risk of overreliance on a single perspective or normative framework. At the same time, the conceptual and qualitative nature of the research entails inherent limitations. The proposed framework is not empirically tested and does not claim statistical generalizability. Instead, it is intended as a theory-building and sense-making device, suitable for guiding future empirical research and informing managerial practice in the mining industry.

Such limitations are consistent with the aims of conceptual research in management and sustainability studies, where the development of coherent explanatory frameworks is recognized as a valuable scholarly contribution in its own right (Whetten, 1989; Jaakkola, 2020). Future research may build on this study by empirically testing the framework through case studies, surveys, or mixed-method designs across different mining contexts and commodities.

Strategic Management of ESG KPIs in the Mining Industry

The strategic management of ESG KPIs in the mining industry requires a deliberate shift from disclosure-oriented measurement toward decision-oriented performance management. In technology-intensive sectors such as mining, ESG KPIs acquire strategic relevance only when they are explicitly linked to operational processes, technological constraints, and governance mechanisms. This section operationalizes the proposed conceptual framework by examining how environmental, social, and governance KPIs function as strategic management instruments in the mining context, rather than as isolated reporting metrics. To operationalize the proposed conceptual framework and to illustrate the strategic role of ESG KPIs in the mining industry, Table 1 presents a set of sector-specific ESG KPIs aligned with key technological drivers, managerial relevance, and potential contributions to sustainable competitive advantage. The table provides an integrative overview of how environmental, social, and governance KPIs translate technology-driven impacts into strategic management instruments, which are subsequently discussed in detail in the following subsections.

Illustrative Application of Strategic ESG KPIs in a Mining Context

Consider a large-scale copper mining operation characterized by energy-intensive comminution processes and long-life tailings facilities. In this context, energy intensity per unit of output functions not only as an environmental indicator but as a strategic KPI informing investment decisions related to equipment modernization and energy sourcing. Simultaneously, tailings management efficiency operates as a governance-critical KPI, supporting board-level oversight of long-term environmental liabilities and risk exposure. Social KPIs related to occupational health and safety further interact with technological choices, as higher levels of mechanization reduce accident rates while altering workforce skill requirements. This illustrative example demonstrates how sector-specific ESG KPIs translate technological characteristics into strategic management signals, reinforcing the framework proposed in this study.

Strategic Management of Environmental KPIs

Table 1. Strategic ESG KPIs in mining

<i>ESG Dimension</i>	<i>Strategic KPI</i>	<i>ESG</i>	<i>Technological Driver</i>	<i>Managerial Relevance</i>	<i>Contribution to Competitive Advantage</i>
<i>Environmental</i>	Energy intensity of extraction and processing		Extraction method; processing technology; equipment efficiency	Supports strategic decisions on technology upgrades and energy sourcing	Cost efficiency; reduced exposure to energy price volatility
	Water use efficiency		Ore processing technology; water recycling systems	Guides investment in water-saving technologies and operational planning	Reduced operational risk; improved license to operate
	Tailings and waste management efficiency		Tailings storage technology; waste treatment systems	Enables proactive risk management and long-term liability control	Lower environmental risk; enhanced stakeholder trust
	Emissions intensity per unit of output		Fuel mix; processing routes; operational scale	Informs decarbonization strategies and compliance planning	Regulatory resilience; improved market positioning
	Occupational health and safety performance		Level of mechanization; automation; workplace technology	Supports workforce safety strategies and technology adoption	Reduced downtime; higher productivity
<i>Social</i>	Workforce stability and skills intensity		Technological complexity; training requirements	Informs human capital planning and skills development	Knowledge retention; operational continuity
	Community impact intensity (e.g., grievance rate; local employment share; land-use footprint)		Scale of operations; land use technologies	Guides stakeholder engagement and community investment strategies	Social acceptance; reduced project delays
	ESG risk integration into strategic planning		Technological risk profile; operational complexity	Supports board-level oversight and risk governance	Improved decision quality; long-term resilience
<i>Governance</i>	Transparency of ESG performance management		Monitoring and reporting systems	Enhances internal control and accountability	Investor confidence; reputational advantage
	Alignment of ESG KPIs with investment decisions		Capital allocation processes; technology lifecycle	Enables capital prioritization based on ESG performance	Efficient capital deployment; sustainable growth

Environmental performance constitutes the most visible and technologically mediated dimension of ESG in the mining industry. Environmental KPIs are directly shaped by extraction and processing technologies and therefore offer significant potential for strategic intervention when integrated into managerial decision-making.

Energy Intensity

Energy intensity—typically measured as energy consumption per unit of output—represents a critical environmental KPI in mining due to the sector’s reliance on energy-intensive extraction, hauling, crushing, and processing activities. The literature consistently identifies energy use as a major driver of both operating costs and greenhouse gas emissions in mining operations (Azapagic, 2004; Prior et al., 2012). From a strategic management perspective, energy intensity is not merely an efficiency indicator but a technology-contingent KPI that reflects choices regarding mining methods, equipment configuration, and processing routes.

When managed strategically, energy intensity informs long-term investment decisions, including technology upgrades, electrification strategies, and the integration of alternative energy sources. Studies on sustainability-oriented performance management emphasize that such KPIs become strategically meaningful when they guide capital allocation and operational redesign rather than serving as static performance benchmarks (Schaltegger & Wagner, 2011). In mining, reducing energy intensity can simultaneously enhance cost competitiveness and mitigate regulatory and transition risks associated with decarbonization policies (IEA, 2021).

Water Balance

Water balance KPIs capture the relationship between water withdrawal, consumption, recycling, and discharge across mining operations. Given the site-specific nature of water availability and the high sensitivity of mining projects to hydrological conditions, water-related KPIs are among the most context-dependent indicators in the ESG landscape (Mudd, 2008). Universal water metrics often fail to reflect local scarcity, competing uses, and contamination risks, limiting their managerial usefulness.

Strategically managed water balance KPIs enable mining companies to align operational planning with local environmental constraints and stakeholder expectations. Research on mining sustainability highlights that water stewardship is increasingly linked to social license to operate, particularly in arid regions and water-stressed basins (Owen & Kemp, 2013). When embedded in strategic management systems, water KPIs support proactive risk management, long-term resource security, and investment prioritization in water-saving and recycling technologies.

Waste and Tailings Management

Waste and tailings KPIs occupy a central position in mining ESG management due to the sector’s exposure to high-consequence environmental and social risks. Tailings generation, storage, and long-term stability are intrinsically linked to processing technologies, ore characteristics, and facility design. The literature underscores that failures in tailings management represent not only environmental disasters but also profound governance and legitimacy failures (Prior et al., 2012; UNEP, 2020).

From a strategic perspective, waste and tailings KPIs should be designed to support lifecycle risk management rather than short-term output monitoring. Indicators related to tailings stability, facility integrity, and closure readiness enable boards and senior management to oversee risk exposure associated with long-lived assets. Empirical research suggests that mining firms with more robust tailings governance frameworks are better positioned to manage regulatory scrutiny and reputational risk, reinforcing the strategic value of such KPIs (Lodhia & Hess, 2014).

Strategic Management of Social KPIs

Social KPIs in the mining industry reflect the sector’s deep entanglement with labor-intensive operations and geographically embedded communities. Unlike environmental KPIs, social indicators often capture relational and process-oriented dimensions of performance, requiring careful integration into management systems to retain strategic relevance.

Health and Safety

Occupational health and safety (OHS) is a foundational social KPI in mining, given the sector’s historically high accident rates and exposure to hazardous working conditions. The literature consistently identifies OHS performance as both a moral imperative and a determinant of operational efficiency, workforce morale, and

productivity (Hilson, 2012). Safety KPIs—such as injury frequency rates or lost-time incidents—are widely reported, yet their strategic value depends on how they are interpreted and acted upon.

Strategic management of health and safety KPIs involves linking performance indicators to technological choices, training systems, and organizational culture. Research in performance management demonstrates that safety KPIs contribute to competitive advantage when they are integrated into continuous improvement processes and incentive structures, rather than treated as compliance indicators (Simons, 1995). In mining, improvements in safety performance are often associated with higher levels of mechanization and process control, underscoring the interplay between technology and social performance.

Local Communities

Community-related KPIs address the mining industry's dependence on social acceptance and stakeholder trust. Concepts such as social license to operate highlight that community relations are not peripheral but central to project continuity and risk management (Prno & Slocombe, 2012). However, translating community impacts into measurable KPIs remains challenging due to their qualitative and context-specific nature.

The strategic management literature suggests that community-related KPIs should focus on processes and outcomes that are within managerial influence, such as grievance resolution mechanisms, local employment, and community investment effectiveness (Owen & Kemp, 2013). When systematically monitored and reviewed at the strategic level, such KPIs enable mining companies to anticipate social risks, reduce conflict-related disruptions, and strengthen long-term stakeholder relationships. In this sense, social KPIs function as early-warning indicators rather than retrospective performance measures.

Strategic Management of Governance KPIs

Governance KPIs provide the structural backbone for effective ESG management in the mining industry by shaping how environmental and social risks are identified, assessed, and addressed within organizational decision-making processes.

Risk Management

Risk management KPIs capture the extent to which ESG-related risks are systematically integrated into corporate governance and strategic planning. In mining, risk exposure is strongly influenced by technological complexity, asset longevity, and regulatory uncertainty, making robust governance structures essential (Grant, 2016). Governance KPIs related to risk identification, escalation, and oversight enable boards and senior executives to monitor the alignment between operational realities and strategic objectives. The literature on strategic risk management emphasizes that performance indicators are most effective when they facilitate dialogue and learning rather than mechanistic control (Simons, 1995). In mining, governance KPIs that link ESG risks to investment decisions and project approvals enhance organizational resilience by ensuring that sustainability considerations are embedded in core management processes rather than treated as external constraints.

Transparency

Transparency-related KPIs reflect the quality, consistency, and credibility of ESG performance management and communication. While transparency is often discussed in the context of external reporting, its strategic importance lies in supporting internal accountability and stakeholder trust (Eccles et al., 2014). In the mining sector, transparency is particularly salient due to heightened scrutiny from regulators, investors, and civil society organizations.

Strategically managed transparency KPIs enable mining companies to demonstrate control over complex ESG risk domains and to reduce information asymmetries with key stakeholders. Research on sustainability governance suggests that transparency contributes to competitive advantage when it reinforces internal discipline and supports informed decision-making, rather than merely increasing disclosure volume (Schaltegger et al., 2017). In this respect, governance KPIs act as enabling mechanisms that connect environmental and social performance to strategic oversight.

Synthesis: ESG KPIs as Strategic Management Instruments

Across environmental, social, and governance dimensions, the literature converges on a central insight: ESG KPIs in the mining industry create strategic value only when they are actively managed within an integrated performance management system. Environmental KPIs translate technology-driven impacts into actionable efficiency and risk indicators; social KPIs capture workforce and community dynamics that shape operational continuity; and governance KPIs ensure that ESG considerations are embedded in strategic decision-making and oversight structures.

This integrative perspective reinforces the argument advanced in this study that sector-specific ESG KPIs, when strategically managed, function as instruments of sustainable competitive advantage rather than as passive reporting tools. By aligning ESG KPIs with mining technologies, operational realities, and governance processes, mining companies can enhance resilience, improve decision quality, and navigate the growing sustainability constraints that define the sector's competitive landscape.

Discussion

ESG KPIs as a Strategic Resource

The findings of this study support a growing body of literature suggesting that ESG KPIs should be interpreted not merely as measurement or disclosure tools, but as strategic resources embedded within organizational decision-making systems. From a strategic management perspective, resources become sources of advantage when they are valuable, context-specific, and difficult to substitute or imitate (Barney, 1991). In the mining industry, sector-specific ESG KPIs exhibit these characteristics precisely because they are closely aligned with proprietary technologies, site-specific conditions, and firm-specific governance arrangements.

Unlike generic ESG indicators, which primarily facilitate external comparability, sector-specific ESG KPIs translate technologically driven impacts and risks into managerially actionable signals. As demonstrated in the preceding sections, environmental KPIs such as energy intensity, water balance, and tailings management are directly shaped by extraction and processing technologies, while social and governance KPIs reflect organizational capabilities related to workforce management, community engagement, and risk oversight. When these KPIs are strategically managed, they enable firms to identify inefficiencies, anticipate constraints, and prioritize interventions that would otherwise remain obscured by aggregated or standardized metrics.

This resource-based interpretation of ESG KPIs aligns with strategic performance management theory, which emphasizes that performance indicators derive their strategic value not from their existence, but from their integration into planning, control, and learning processes (Kaplan & Norton, 1996; Simons, 1995). In mining, where technological lock-in and long asset lifecycles limit managerial flexibility, ESG KPIs function as boundary-spanning instruments that connect operational realities with strategic intent. They inform capital allocation decisions, shape technology adoption pathways, and support risk-informed governance at board and executive levels.

Importantly, the strategic value of ESG KPIs in mining is cumulative rather than static. Over time, firms that systematically manage sector-specific ESG KPIs develop organizational routines, data infrastructures, and governance practices that enhance their ability to respond to regulatory change, stakeholder scrutiny, and technological disruption. This path-dependent accumulation of ESG-related capabilities reinforces the argument that ESG KPIs constitute a strategic resource whose value increases as they become embedded in core management systems (Schaltegger & Wagner, 2011; Gond et al., 2012).

Competitive Advantage in the Mining Sector

The relationship between ESG performance and competitive advantage in mining has been widely debated, with empirical findings often yielding mixed results. However, much of this ambiguity can be attributed to the reliance on aggregated ESG scores or universal indicators that inadequately capture the sector's technological and risk characteristics (Fikru, 2021; Berg et al., 2022). The present study contributes to this debate by reframing competitive advantage not as a direct outcome of ESG "performance" per se, but as the result of strategically managing ESG KPIs in alignment with sector-specific technologies and governance structures.

In the mining sector, competitive advantage is increasingly shaped by a firm's ability to operate under tightening environmental and social constraints. Regulatory developments, investor expectations, and downstream supply chain requirements impose explicit and implicit costs on firms that fail to manage ESG risks effectively. Within this context, sector-specific ESG KPIs support competitive advantage through several interrelated mechanisms.

First, strategically managed ESG KPIs enhance operational resilience. Environmental indicators that reflect energy efficiency, water stewardship, and tailings stability enable firms to reduce exposure to resource scarcity, regulatory intervention, and catastrophic failures. Social KPIs related to health and safety and community relations reduce the likelihood of work stoppages, project delays, and reputational damage. Governance KPIs strengthen oversight and coordination across complex organizational structures, improving decision quality in high-risk environments (Grant, 2016; UNEP, 2020).

Second, ESG KPIs contribute to cost and risk differentiation rather than simple cost reduction. Mining firms that effectively manage technology-linked ESG risks are better positioned to internalize sustainability-related costs proactively, avoiding reactive expenditures associated with non-compliance, accidents, or social conflict. This differentiation is particularly relevant in capital-intensive projects with long payback periods, where unanticipated ESG disruptions can materially undermine project economics (Prior et al., 2012).

Third, sector-specific ESG KPIs support strategic legitimacy and access to critical resources, including capital, permits, and skilled labor. The literature on social license to operate underscores that sustained community acceptance and stakeholder trust are prerequisites for long-term competitiveness in mining (Prno & Slocumbe, 2012; Owen & Kemp, 2013). By embedding social and governance KPIs into strategic management processes, firms can demonstrate control over ESG risks in a manner that is credible to external stakeholders, thereby strengthening their competitive positioning.

Finally, ESG KPIs enable strategic alignment across organizational levels. When environmental, social, and governance indicators are integrated into performance management systems, they facilitate coherence between corporate strategy, operational execution, and governance oversight. This alignment is particularly important in multinational mining firms operating across diverse regulatory and socio-environmental contexts, where fragmented ESG management can erode both efficiency and legitimacy.

Importantly, competitive advantage in the mining industry should not be interpreted as short-term financial outperformance, but as enhanced resilience, risk-adjusted stability, and sustained operational viability under increasing ESG constraints. From this perspective, strategically managed ESG KPIs contribute to competitive advantage by enabling firms to anticipate constraints, internalize risks, and maintain legitimacy in environments characterized by high technological and regulatory uncertainty.

Implications for Management and Theory

The discussion yields several implications for both managerial practice and academic theory. From a management perspective, the findings suggest that mining companies should prioritize the strategic design and governance of ESG KPIs, rather than expanding the volume of reported indicators. Emphasis should be placed on selecting KPIs that reflect technological realities, material risks, and decision-making needs at different organizational levels.

From a theoretical standpoint, the study advances the literature on management of technology and sustainability by demonstrating that ESG KPIs function as mediating mechanisms between technological systems and competitive outcomes. This perspective extends existing ESG-performance debates by highlighting the role of strategic management processes in converting ESG measurement into competitive advantage. It also reinforces calls for sector-specific and context-sensitive approaches to sustainability performance measurement, particularly in technology-intensive industries.

Overall, the discussion supports the central proposition of this paper: in the mining industry, ESG KPIs create competitive advantage not by signaling compliance, but by enabling strategic control over technology-driven environmental and social risks. This insight provides a coherent explanation for why universal ESG metrics often fail to predict performance in mining and underscores the value of sector-specific, strategically managed ESG KPI frameworks.

While this study focuses empirically on the mining industry, the proposed conceptual framework is applicable to other technology-intensive industries characterized by capital-intensive assets, complex process technologies, and

elevated environmental and social risk profiles, such as energy production, metals processing, and chemical manufacturing. In these sectors, sector-specific ESG KPIs similarly mediate the relationship between core technologies, risk management structures, and strategic performance outcomes.

Conclusions and Future Research

Conclusions

This study set out to examine the strategic role of ESG KPIs in the mining industry through the lens of management of technology and strategic performance management. Responding to the growing recognition that generic ESG metrics are insufficient for technology-intensive sectors, the paper developed a sector-specific, management-oriented conceptual framework that positions ESG KPIs as strategic instruments rather than as compliance-driven reporting tools.

The analysis demonstrates that ESG KPIs in the mining industry derive their relevance and managerial value from their alignment with core extraction and processing technologies, site-specific operational conditions, and governance structures. Environmental KPIs such as energy intensity, water balance, and waste and tailings management were shown to be directly shaped by technological choices and therefore critical for strategic decision-making related to capital allocation, risk mitigation, and long-term operational resilience. Similarly, social KPIs related to occupational health and safety and local communities reflect the labor-intensive and geographically embedded nature of mining operations, while governance KPIs associated with risk management and transparency provide the institutional foundation for integrating ESG considerations into strategic oversight.

By conceptualizing ESG KPIs as strategic resources, the study advances existing debates on the relationship between ESG performance and competitive advantage in the mining sector. Rather than treating ESG outcomes as exogenous reputational signals or as aggregated scores detached from operational realities, the proposed framework emphasizes the role of strategic management practices in transforming ESG measurement into a source of sustainable competitive advantage. This perspective helps explain why empirical studies relying on universal ESG indicators often yield inconclusive results for mining firms: such indicators frequently fail to capture the sector's technological risk profile and managerial control mechanisms.

From a theoretical standpoint, the paper contributes to the literature on sustainability management and management of technology by integrating three previously fragmented streams of research: ESG performance measurement in mining, technology-intensive industries, and strategic performance management. The resulting framework offers a coherent explanation of how technology-driven impacts are translated into ESG KPIs and how these KPIs, when strategically managed, can support long-term competitiveness in a sector increasingly constrained by environmental, social, and governance considerations.

Managerial and Policy Implications

The findings carry several implications for managerial practice in the mining industry. First, managers should prioritize the strategic design and governance of ESG KPIs, focusing on indicators that are materially linked to mining technologies and operational risks rather than expanding the breadth of reported metrics. Second, ESG KPIs should be explicitly integrated into strategic planning, investment appraisal, and risk governance processes to ensure that sustainability considerations inform core managerial decisions. Third, boards and senior executives should treat ESG KPIs as dynamic tools for learning and adaptation, capable of supporting long-term resilience in the face of regulatory tightening, technological change, and stakeholder scrutiny.

At the policy and standard-setting level, the study reinforces the importance of sector-specific sustainability frameworks that recognize technological heterogeneity and impact pathways. While harmonization and comparability remain important objectives, excessive reliance on universal indicators may undermine the decision-usefulness of ESG information in high-impact sectors such as mining. Policymakers and standard setters may therefore benefit from further strengthening industry-based guidance that supports strategic ESG management rather than solely disclosure compliance.

Limitations and Directions for Future Research

As a conceptual and qualitative study, this research is subject to several limitations that also point to avenues for future inquiry. First, the proposed framework has not been empirically tested. Future research could examine its explanatory and predictive power through in-depth case studies of mining firms, comparative analyses across commodities, or survey-based studies of ESG KPI integration into strategic management systems. Such empirical work would allow for refinement of the framework and assessment of its applicability across different mining contexts and regulatory environments.

Second, while this study focused on the mining industry as a technology-intensive sector, future research could explore the transferability of the framework to other resource- and capital-intensive industries, such as energy, metals processing, or heavy manufacturing. Comparative studies could shed light on how differences in technological architectures and risk profiles influence ESG KPI design and strategic use.

Third, further research is needed to investigate the dynamic dimension of ESG KPI management. Longitudinal studies could examine how ESG KPIs evolve over project lifecycles, how firms adapt their KPI systems in response to technological innovation or regulatory change, and how such adaptations affect competitive outcomes over time.

In conclusion, this study underscores that the strategic value of ESG KPIs in the mining industry lies not in standardization, but in contextualization and technological alignment. By grounding ESG performance measurement in sector-specific technologies and embedding ESG KPIs within strategic management and governance processes, mining companies can move beyond compliance-oriented sustainability practices and position ESG performance measurement as a core instrument of strategic control in technology-intensive industrial systems, supporting long-term competitiveness and resilience.

Recommendations

Mining companies should design ESG KPI systems around the specific technological and operational characteristics of their activities rather than relying on uniform reporting templates. Different extraction methods, processing routes, tailings systems, and energy configurations create different sustainability risks and therefore require differentiated KPI architectures.

Managers should establish explicit links between ESG KPIs and key decision points across the mining project lifecycle, including feasibility studies, technology selection, mine planning, expansion projects, and closure strategies. This would allow ESG information to support forward-looking decisions rather than serving only retrospective reporting purposes.

The mining sector should also increase the use of leading indicators in addition to lagging indicators. For example, indicators related to tailings monitoring, workforce training, equipment modernization, grievance management, and water recycling capacity may provide earlier signals of emerging risks than traditional incident-based metrics. In addition, companies should strengthen cross-functional coordination in ESG KPI management. Environmental, social, operational, engineering, and financial teams should jointly participate in KPI selection and review processes to ensure that ESG indicators reflect both technical realities and strategic priorities.

From a governance perspective, boards and senior management should regularly review whether existing KPI systems remain aligned with changing regulatory expectations, stakeholder concerns, and technological developments. ESG KPIs should be periodically updated to reflect shifts in climate policy, resource availability, automation, digitalization, and new industry standards.

Finally, future sectoral guidance for the mining industry should place greater emphasis on the distinction between externally reported ESG indicators and internally managed strategic KPIs. Not all indicators that are useful for disclosure are equally useful for strategic control, and mining companies should avoid treating reporting metrics and management metrics as interchangeable.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Critical Success Factors for Building Information Modelling Implementation in the Jordanian Construction Industry

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Abstract: Building Information Modeling (BIM) is a powerful concept in the architecture, engineering and construction (AEC) industry that helps in project coordination, information sharing and collaboration among professionals involved in the building construction. Developed countries like the United Kingdom, Singapore and the United States have already developed their BIM frameworks and legislations and succeeded in raising their BIM maturity to the next levels. Unlike these developed economies, developing countries - like Jordan - still struggle to adopt BIM owing to their specific socio - technical challenges that often hinder the process of implementation. This study utilizes a meta - analytical method to synthesize the information published in 12 recent empirical studies or surveys conducted on the Jordanian AEC industry within the period from 2015 to 2025. Approximately 520 responses from AEC stakeholders including architects, civil engineers, quantity surveyors and project managers were aggregated in this study. Twenty - eight CSFs were extracted from the synthesized studies and were grouped into five main components by performing exploratory factor analysis based on their collected mean values after ranking them using the relative importance index (RII). The five components were: (1) Institutional and Government Readiness (C1), (2) Organizational Leadership and Strategic Vision (C2), (3) Human Capital and Technical Capacity (C3), (4) Socio - Cultural Orientation (C4) and (5) Legal and Standardization Frameworks (C5). The RII value for each of the five identified components were 0.94, 0.91, 0.89, 0.87 and 0.85, respectively. The top five ranking CSFs from the synthesized literature included government support and national mandate (RII = 0.94), top management support and commitment (RII = 0.91), availability of specialized education and training programs (RII = 0.89), availability of efficient and robust information technology (IT) infrastructure (RII = 0.87) and standardization of BIM processes and standards (RII = 0.85). This study consolidates and context - specific CSF framework for the adoption of BIM in Jordan, which can also benefit other developing countries facing similar socio - technical challenges.

Keywords: Building information modelling, Critical success factors, AEC industry, Digital transformation.

Introduction

The international construction industry faces substantial pressures related to escalating costs, schedule slippage and poor collaboration among diverse project parties, prompting a widespread digital revolution. Central to this transformation is Building Information Modelling (BIM), a system based on a digital representation of the physical and functional qualities of a built asset, facilitating collaboration throughout its entire life cycle (Eastman et al., 2011). Unlike traditional Computer - Aided Design (CAD), BIM creates a coordinated 3D digital model than disconnected 2D drawings, promoting teamwork among consultants and owners to help information sharing and reduce design errors. Globally, a range of governments and industry bodies have spurred BIM adoption, especially in developed nations, like the United Kingdom mandating BIM Level 2 for public projects since 2016, Singapore and the United States. This trend reflects a proven ability to transform industry sectors and boost international competitiveness and ROI (Kassem & Amor, 2021). In contrast, the adoption rate for BIM is limited and inconsistent in developing countries, Jordan being an example. This stems from sociotechnical issues, such as poor digital infrastructure, a lack of skilled professionals, reluctance to embrace cooperative approaches and a lack of formal guidelines and legislation. Jordanian construction accounts for approximately 4-5% of the gross

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domestic product (GDP) and is an important employer. Theoretical awareness of BIM benefits (design coordination, automated clash detection, 4D/5D modeling capabilities) in Jordan is increasing, but it has been implemented slowly and is only used by a small group of consultants in Amman (Hiyassat et al., 2022).

Some of the barriers are high costs for software, hardware, lack of national mandates, a lack of BIM training and the prevalence of confrontational contractual agreements. While existing literature on Critical Success Factors (CSFs) for BIM has become abundant in a global context, none of the studies carried out so far have proposed a consolidated quantitative CSF framework for the Jordanian AEC industry. Studies like Matarneh et al., (2017), Sweis et al. (2019) and Bani - Hani et al., (2020) examine individual barriers and enablers of BIM implementation in Jordan, but no study attempts to synthesize CSFs from various empirical Jordanian studies meta - analytically to create a prioritized CSF framework. This research addresses this gap by conducting a meta - analytical synthesis of CSFs for BIM implementation in the Jordanian AEC industry.

The study aims to: (1) identify BIM CSFs reported in Jordan - focused empirical studies published between 2015 and 2025, (2) rank these CSFs based on the aggregated survey data using the Relative Importance Index (RII) and (3) group them into higher - level components using exploratory factor analysis to generate an integrated CSF framework that'll support policy and industry practice. The remainder of this paper is organized as follows: Section 2 discusses literature review and theoretical background, Section 3 presents the methodology, Section 4 discusses the results, Section 5 presents findings and discussion, Section 6 draws conclusions and Section 7 presents specific recommendations.

Literature Review and Theoretical Framework

Critical Success Factors: Concepts and Typologies

Strategic management literature describes Critical Success Factors (CSFs) as "the limited number of areas in which results, if they're satisfactory, will determine the success of an enterprise." (Rockart, 1979, p. 25). Pinto and Slevin (1989) expanded this concept to project implementation and suggested that the project context, type of project and work environment will influence the set of critical factors for project success. For BIM adoption, Succar (2009) further delineated factors affecting successful implementation into "Drivers - which are defined as stimuli, proactive causes and positive forces that start and sustain the development and adoption of BIM" and "Enablers - which are defined as factors that help reduce barriers and increase the likelihood of successful implementation of BIM within a firm or industry.

A multi - dimensional list of categories for factors that lead to success in BIM adoption has been highlighted by previous literature. These categories are technological (related to hardware, software, interoperability (often with IFC) and infrastructure), organizational (related to management support, the presence of a BIM champion, alignment with business goals), human (related to skills and training, capacity for change management), institutional (related to government regulations, procurement, national standards) and cultural (related to teamwork willingness, trust and comfort with digital transformation) (Ghaffarianhoseini et al. , 2017; Morlhon et al., 2014; Abdirad & Dossick, 2016; Arayici et al., 2012). In Amuda - Yusuf (2018), these categories were organized into a hierarchy CSF model, which showed that institutional and governmental factors laid the foundation for the organizational and individual - level factors to operate.

BIM Adoption in Developing Countries: Comparative Context

The experiences of developing economies in the adoption of BIM technologies often exhibit common traits relevant to Jordan. Eadie et al.'s research on the Malaysian context concluded that government support, client demand and education were major factors motivating BIM adoption, while costs, technical skills and industry standards were the most significant hindrances (Abubakar et al., 2014). Similar patterns of motivation from government policies and client push, with significant barriers stemming from inadequate training resources and a lack of a supporting legislative or regulatory framework, were observed in Nigeria (Ugwu & Kumaraswamy, 2007). In the Kingdom of Saudi Arabia, it was highlighted that although senior management engagement served as a facilitator, resistance towards collaborative workflows, a characteristic shared with the Jordanian situation, represented one of the most substantial impediments to widespread adoption. The general consensus across studies from these developing nations is that overcoming the limitations of traditional 2D CAD software and integrating a BIM - based workflow poses a considerable cultural and organizational hurdle as much as it does a technological one (Succar, 2009). According to the BIM maturity framework, developing nations generally fall between Level

0 and Level 2 on the continuum. Most Jordanian companies operate at Level 1 (using 2D/3D CAD managed in different ways) or Level 2 (using BIM for collaboration with several separate discipline models), while developed nations such as the United Kingdom and Singapore are aiming to achieve Level 3 (full integration and interoperability using BIM) as a required standard for public construction and infrastructure. This level of maturity difference necessitates that developing economies like Jordan adopt a proactive and cohesive strategy involving all stakeholders and guided by data - driven prioritization of critical success factors (CSFs).

BIM in Jordan: Current State and Challenges

Matarneh and Hamed (2017) examined barriers to the AEC industry's digital transformation, such as inadequate government assistance, expensive software and low professional awareness. Sweis et al. (2019) surveyed 143 Jordanian construction practitioners and their findings showed that the most critical success factors were government enforcement of BIM, education and IT infrastructure, cultural resistance and unclear legal legislation were the top inhibitors. Bani - Hani and Al - Ghzawi (2020) agreed with Sweis et al. And additionally added that, since the construction supply chain is fragmented in Jordan and owned by many family - run SMEs, the long - term perspective required for BIM adoption and investment in new technologies has been shortened, putting them on the lowest priority compared with other issues.

Hiyassat et al. (2022) added to the list contractual framework and client demand as inhibiting BIM adoption, due to a general lack of client requests in both the public and private sectors. These papers suggest a negative trend where low BIM adoption is likely to remain stable because top - down policies (e. g. , through government mandate) are missing and the industry lacks sufficient motivation to transition to a new phase. The current paper builds on the existing body of work and combines it with other studies to build one empirical CSF framework using meta - analytical techniques, to increase statistical validity and to reduce potential individual biases in specific studies.

Methodology

Research Design and Approach

The present paper applies a systematic meta - analytic method, This type of quantitative research is applicable for the combination and accumulation of outcomes that have been produced across several independent studies that target the same phenomenon (Borenstein et al., 2009). In construction management studies, meta - analysis has been increasingly adopted, aiming to summarize varying empirical evidence found by different studies to eliminate idiosyncratic errors and sampling bias introduced from any single study, thereby generating a more reliable result than any of the selected studies could possibly reach on its own (Hwang et al. , 2019). The methodological study followed the Preferred Reporting Items for Systematic Reviews and Meta - Analyses PRISMA statement (Moher et al., 2009).

Data Collection and Source Selection

An extensive literature review was carried out in prominent databases: Scopus, Web of Science, ASCE Library and Google Scholar. The literature search was performed using the query: ("BIM" OR "Building Information Model*") AND ("Jordan" OR "Jordanian") AND ("critical success factors" OR "barriers" OR "adoption" OR "implementation"). The search time frame was confined to January 2015-December 2025 to include only recent research. The systematic literature search yielded a total of 47 potentially relevant research papers. These papers were initially filtered according to four inclusion criteria: (a) Must be an empirical study involving the collection of primary data from the construction industry (e. g. , questionnaires, interviews or mixed - methods studies). (b) Must've the implementation of BIM in the Jordanian construction industry as its main focus. (c) Must include quantitative importance levels of critical success factors (CSFs) or BIM barriers that can be measured and compared among the studies. (d) Must be published as a peer - reviewed article in journals or in conference proceedings covered in major citation databases. After applying five exclusion criteria - theoretical papers, qualitative papers not reporting quantified critical success factors/barriers, irrelevant studies, irrelevant data (data can be quantified) or irrelevant industries - the search resulted in 12 studies. Overall, the 12 chosen studies involved 520 respondents from the Jordanian AEC industry. Among these, architects accounted for 32% of respondents, civil engineers for 41%, quantity surveyors for 15% and project managers for 12%.

Data Quantification: Relative Importance Index (RII)

Each research conducted was given a questionnaire employing a 5-point Likert scale (1=Not Important, 5=Important) concerning every CSF identified. The RII for each of the identified CSFs can be expressed by the following:

$$RII = \Sigma(w) / (A \times N)$$

In this case, w signifies the relative weight attributed by the responders to each survey item in the interval [1, 5], A stands for the maximum weight (i. e. , 5) available on the scale, N represents the number of responders in each study. RII varies between 0 and 1, with greater values meaning the factor holds greater significance. For the studies that reported responses in frequency counts than pre - computed RIIs, the respective RIIs were estimated based on the frequencies provided using the described calculation methodology. In instances where the RIIs of some factors appeared in several research efforts, the overall RII for each specific factor was calculated using weighted average techniques based on the size of the sample in each relevant study to establish a consolidated value for each critical factor. Reliability tests were performed on the summed Likert - type scaled information, which resulted in Cronbach's alpha of $\alpha = 0.87$, thereby confirming strong internal reliability across the collected sample.

Factor Analysis and Component Grouping

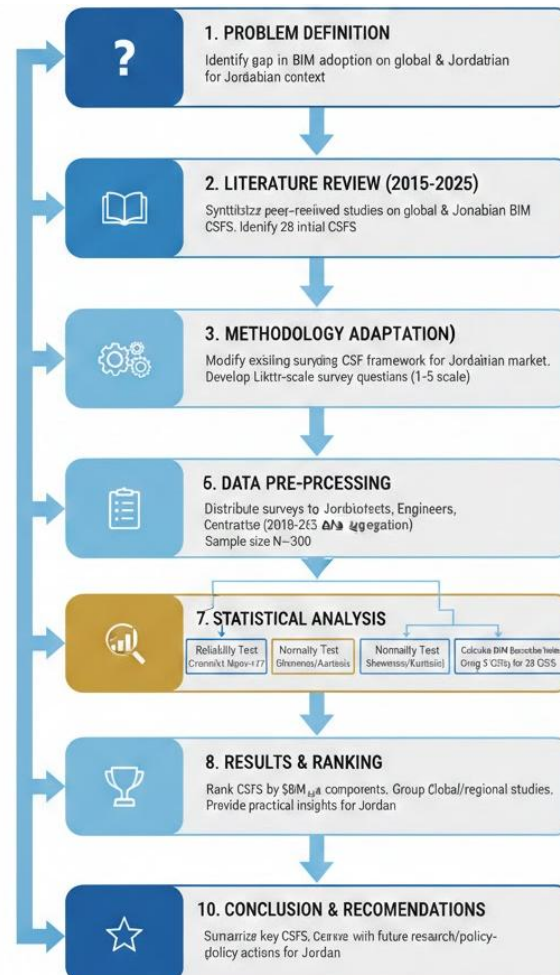


Figure 1. Conceptual framework of CSFs grouping — five-component hierarchical structure

To reduce the 28 CSFs to a core set of main elements, a principal component analysis (PCA) followed by varimax rotation was implemented using the aggregated RII data. Based on the Kaiser - Meyer - Olkin (KMO) value of 0.79 (which exceeded 0.60) and the statistical significance of Bartlett's Test of Sphericity ($p < 0.001$), factor analysis was appropriate for this sample. The Kaiser criterion (factors with eigenvalues > 1.0) was employed. This

approach resulted in five components that explained a cumulative 73.4% of the total variance. Item loading above 0.50 was considered a significant factor loading, defining the component in which the item was placed. The resulting five components provided the foundation of the CSF framework used in this research. See Figure 1 for the proposed conceptual framework illustrating how the 28 CSFs were mapped onto the five components.

Table 1. Ranked CSFs for BIM implementation in Jordan (N = 28 factors; aggregated from 12 studies)

Rank	Critical Success Factor	RII	Category	Component
1	Government Support & National BIM Mandates	0.94	Institutional	Comp. 1
2	Top Management Commitment	0.91	Organizational	Comp. 2
3	Education, Training & Professional Development	0.89	Human Capital	Comp. 3
4	IT Infrastructure & High-Speed Internet Access	0.87	Technological	Comp. 1
5	Standardization of BIM Protocols (ISO 19650)	0.85	Process/Regulatory	Comp. 5
6	Availability of Software Funding/Subsidies	0.84	Financial	Comp. 1
7	Client Demand & BIM Awareness Campaigns	0.82	Stakeholder	Comp. 2
8	Legal Frameworks for Data Ownership & Liability	0.80	Regulatory	Comp. 5
9	Change Management Strategies & Programs	0.78	Cultural	Comp. 4
10	Software Interoperability (IFC Open Standards)	0.76	Technological	Comp. 1
11	BIM Champion Presence within Organization	0.75	Organizational	Comp. 2
12	University Curriculum Integration of BIM	0.74	Human Capital	Comp. 3
13	Industry–Academia Collaboration	0.73	Human Capital	Comp. 3
14	Integrated Project Delivery (IPD) Frameworks	0.72	Process	Comp. 5
15	Clear Return on Investment (ROI) Demonstration	0.71	Financial/Strategic	Comp. 2
16	Collaborative Contractual Relationships	0.70	Cultural/Regulatory	Comp. 5
17	Cloud-Based BIM Platform Adoption	0.68	Technological	Comp. 1
18	Knowledge Management & Lessons Learned	0.67	Organizational	Comp. 2
19	Supplier & Subcontractor BIM Capability	0.65	Stakeholder	Comp. 4
20	Resistance to Change Mitigation	0.64	Cultural	Comp. 4
21	BIM Execution Plan (BEP) Development	0.63	Process	Comp. 5
22	Cross-Disciplinary Collaboration Culture	0.62	Cultural	Comp. 4
23	Hardware Upgrade & Maintenance Programs	0.60	Technological	Comp. 1
24	Pilot Project Implementation & Demonstration	0.59	Organizational	Comp. 2
25	Professional Body Accreditation for BIM	0.57	Institutional	Comp. 1
26	Procurement Reform in Public Sector	0.56	Institutional	Comp. 1
27	Language Barriers in BIM Documentation	0.52	Cultural	Comp. 4
28	Facility Management Integration (BIM–FM)	0.48	Technological/Process	Comp. 5

Results: Ranking and Grouping CSFs in Jordan

Ranked CSFs by Relative Importance Index

Table 1 presents all 28 identified CSFs ranked by their aggregated Relative Importance Index (RII) value, along with the component grouping derived from factor analysis. The rankings reflect the synthesized perspective of approximately 520 Jordanian AEC professionals across 12 empirical studies

Factor Analysis: Five-Component Structure

The exploratory factor analysis yielded five distinct components with eigenvalues greater than 1.0, collectively accounting for 73.4% of the total variance. Table 2 summarizes the components, their constituent CSFs, eigenvalues, and percentage of variance explained.

Table 2. Factor analysis results: five-component structure

Component	Label	Eigenvalue	% Variance Explained
1	Institutional and Government Readiness	5.82	20.8%
2	Organizational Leadership and Strategic Vision	4.41	15.7%
3	Human Capital and Technical Capacity	3.76	13.4%
4	Socio-Cultural Orientation	3.12	11.1%
5	Legal and Standardization Frameworks	3.42	12.4%

Discussion of Key Components

Institutional and Government Readiness (Component 1)

Government support was identified as the most crucial success factor (RII = 0.94). This outcome is widely supported by international studies of BIM maturity. The UK government's 2011 BIM Strategy Paper led to mandatory BIM Level 2 for centrally procured public projects starting in 2016. This regulatory requirement generated irreversible market incentives for firms to comply, resulting in significant increases in BIM maturity throughout the industry (Kassem & Amor, 2021). Singapore also established a national BIM roadmap that the Building and Construction Authority mandated in 2010. As a result, BIM adoption has reached almost 100% among private companies over a decade. In contrast, Jordan, which has no national BIM policy mandate, remains a low BIM adoption country due to a lack of policy - driven innovation. Additionally, Jordan ranked sixth in available government subsidies for BIM software (RII = 0.84), which disadvantages SMEs unable to bear the costs associated with proprietary BIM software.

The availability of IT infrastructure (RII = 0.87) and cloud - based platforms (RII = 0.68) also played a role. Both were identified within this category and reflect the extent to which the environment in a country is ready to support BIM technology through its infrastructure requirements, policy and digital availability. High - speed internet access, which is essential for collaborative cloud - based BIM software (e. g. , Autodesk BIM 360, Trimble Connect), remains problematic in parts of Jordan and is challenging for companies that focus on regional infrastructure projects that occur outside of Jordan's major urban areas.

Organizational Leadership and Strategic Vision (Component 2)

Top management commitment received the second highest RII score (0.91), highlighting leadership opinion as crucial for deciding the organization's readiness to adopt the Building Information Modeling technology. A considerable number of studies in developing regions found that once management considers BIM a cost than an advantage, companies may either give up after the pilot phase or confine BIM to selected projects instead of firmwide implementation. In Jordan, this obstacle becomes more significant due to the abundance of private, family - managed companies, where investment decisions are made by individual owners who may not be exposed to the data and advantages BIM can provide in the long term. Creating an internal BIM champion within the organization was identified as an important supportive element (RII = 0.75) and a manager championing the technology helps to bridge the strategic intent and the operational application of BIM. Pilot projects were recommended by participants as a step towards creating the business case for BIM. Most organizations agreed that the clear ROI to be gained from adopting BIM is another significant motivating factor (RII = 0.71).

Participants acknowledged the use of pilot projects (RII = 0.59) as a means of gaining initial experience with the technology, establishing the business case for further implementation. This offers organizations in Jordan a route for getting started with BIM without imposing firmwide standards initially, they could use pilot projects to produce undeniable cost savings and improvements.

Human Capital and Technical Capacity (Component 3)

The skill gap is a significant structural obstacle for the Jordanian AEC industry (RII=0.89). A small proportion of Jordanian universities (namely, University of Jordan, Jordan University of Science & Technology and Jerash University) have incorporated BIM modules into civil engineering and architectural bachelor degree programs, but the speed of formal BIM training has been slow compared to the current needs of the AEC sector. Jordanian industry professionals acquire BIM skills mainly by self - study through online courses (like those that lead to Autodesk Certification) or by incurring high expenses to participate in international BIM consulting services, hence creating access inequality where only large companies are benefiting and can afford the necessary knowledge and skills, unlike small and medium - sized ones. In addition, the importance of industry - academia collaboration (RII=0.73) indicates that universities, professional organizations (such as the Jordan Engineers Association) and companies could join hands to set up partnerships that design collaborative frameworks and training pathways or further enhance continuing professional development courses that are fit for purpose, suit Jordan's real market needs and enhance BIM literacy across all industry segments.

Socio-Cultural Orientation (Component 4)

Another reason is because the construction firms have high cultural resistance (RII = 0.64, ranked 20th), which forces them to work in silos and as rivals to one another, whereas BIM encourages people to trust one another and work collectively. The traditional contracts here are designed to make engineers and architects work alone, keep their information secret to enhance their professional use in contractual discussions and share information only with the owners of the projects and when asked by them, because of this, none of the consultants trust one another in Jordan. Nothing formal has been added to the contracts in Jordan to motivate sharing and collaboration yet. BIM awareness sessions carried out at the level of trade association (Jordan Engineers Association, Jordan Construction Contractors Association) may promote collaboration. More incentives, such as implementing collaborative contracts in Jordan, like the NEC4 or IPD contracts, can push cultural change over time. English is a common challenge to learning BIM for non - English speakers (RII = 0.52, ranked 27th), The majority of BIM software, standards documents (ISO 19650, PAS 1192) and training documentation are in English, which creates a problem for many Arabic - speaking professionals who can't speak fluent English.

Legal and Standardization Frameworks (Component 5)

The absence of legal clarity around the digital model as a deliverable, the IP rights therein, the associated liabilities and so on constitutes a contractually and commercially risky environment. In many instances, this prevents uptake within firms. However, this problem is compounded by the lack of any specific Jordanian standard related to BIM, which can substitute the UK's PAS 1192 system (which has now been effectively superseded by ISO 19650, although the UK officially adopted it and issued the first in a series of national annexes to complement the international standard). This creates a lack of standardization which leads to interoperability and contract disputes and confusion over the liability attached to errors within a jointly created model. Instead, there's a strong need for the introduction of a protocol based on ISO 19650 standards but custom - built for the Jordanian context with reference to its existing legal/contractual background, addressing: BIM standards related to information modelling/sharing, clarity around author liability for the BIM model, data security and ownership and licensing/legal standards for sharing information through the Common Data Environment. Furthermore, the addition of explicit BIM - related clauses in the standard Jordanian procurement contract provisions under the FIDIC Red Book contract, would begin to institutionalize these protections and address the fear of legal risk which currently prevents many firms from embracing full BIM.

Conclusion

The first step toward systematizing the body of research and to investigate the critical factors (CSFs) behind BIM success adoption in Jordanian construction firms, was carried out using a systematic meta - analytic review based

on 12 published empirical studies and data gathered from approximately 520 relevant participants. After conducting the analyses, the researchers recognized 28 individual CSFs and arranged them according to the aggregated Relative Importance Index. Then, using exploratory factor analysis (EFA), five dimensions related to the adoption and implementation process were generated. The study, as a result, concluded that BIM success can't solely focus on technical- and human - oriented issues, instead, a systemic perspective emphasizing the technical, organizational, cultural and regulatory components is the correct way for BIM implementation in Jordan. From top - management commitment and government support and mandate, to having human capital development and a standard and legal regulatory environment. The importance of government and national mandates (RI = 0.94) needs emphasis as private sector - driven adoption has proven not to be enough for a market composed of supply chain segmentation, low capital to carry out BIM and a resistance attitude due to cultural resistance, to name some problems. Jordan can't have the BIM progression that Singapore or the UK have experienced without a similar mandate to enforce the market. At the organizational level, managers have more control over top - management commitment (RI = 0.91) and human capital development (RI = 0.89). Finally, legal clarity, with regards to data ownership or standardization (component 5), sets the tone for the trust between supply chain companies.

Overall, BIM adoption in Jordan doesn't require an individual action from technology, instead, it requires the full alignment of government agencies, industry leaders and other relevant bodies. This research presents a framework of five dimensions based on CSFs, providing clear actions and a guide to prioritize investments for various government stakeholders, companies, professional bodies and academic organizations working to enable BIM readiness in Jordan. Given Jordan's role as a hub in the MENA region, pushing towards BIM implementation should be seen as an immediate necessity since it has become a mandatory requirement in many of the new infrastructure projects funded by global institutions.

Limitations and Future Research

The current meta - analysis is characterized by several inherent limitations that need to be considered when interpreting the findings and guiding future research endeavors. Firstly, the quality and integrity of the underlying studies selected for inclusion are fundamental to the reliability of the meta - analysis. While attempts were made to mitigate heterogeneity through techniques such as the weighted RII, variability existed across the 12 primary studies concerning sample profiles, the survey instruments employed and the scale used for responses, inevitably leading to some degree of aggregation error. Secondly, the time frame covered (2015-2025) mirrors the transitional phase of growing BIM awareness in Jordan, however, the swiftly accelerating pace of digital innovation, the introduction of cloud - based BIM, digital twin technology and artificial intelligence applications in architectural design, means that the significance of certain critical success factors (CSFs), those about the technological aspect, is likely to evolve in the coming years. Lastly, the study's restricted geographical focus to Jordan means that the results can't be generalized without qualification to other contexts. Nevertheless, the methodological framework developed herein remains adaptable and applicable to other emerging economies within the Middle East and North Africa region that share comparable characteristics of the built environment sector.

In future research, an essential next step would involve the collection of primary empirical data through a comprehensive, large - scale survey administered to AEC professionals in Jordan. This would serve to validate the 28 CSFs identified in the present study and would further help the application of structural equation modelling (SEM) to examine the causal relationships between distinct components of the CSF model and BIM adoption outcomes. Furthermore, conducting longitudinal research designed to track the progressive advancement of BIM maturity in Jordanian firms over extended periods would offer invaluable insights into how the relative weight of various CSFs fluctuates as firms move through different stages of BIM adoption. A comparative, cross - national study that positions Jordan within the wider MENA region, encompassing nations such as the UAE, Saudi Arabia and Egypt, would provide further substantial contributions to the literature on BIM adoption in developing economies.

Recommendations

Given the study's findings, tailored and targeted recommendations are presented to the key stakeholders identified as crucial for propelling the advancement of Building Information Modelling (BIM) adoption within Jordan:

Government and Regulatory Bodies

- Formulate and enact a National BIM Strategy with a mandated, phased approach to implementation. This strategy should begin with a mandatory requirement for BIM on public sector projects exceeding a specific capital value threshold. The objective should be to achieve BIM Level 2 adoption across the entire public sector within a five - year timeframe.
- Establish a dedicated National BIM Institute or task force within the Ministry of Public Works and Housing. This body will be responsible for developing a BIM standard localized to Jordan's legal, contractual and linguistic nuances, while remaining aligned with international standards such as ISO 19650.
- Incorporate BIM - specific clauses into Jordanian public procurement rules and standard contract templates. These provisions should clearly define responsibilities concerning data ownership, model liability and information management procedures.
- Carry out financial incentive schemes to reduce the cost - related barriers to BIM adoption. Such incentives might include subsidized software licences, tax relief on expenditures related to BIM training and the provision of low - interest loans to support small and medium - sized enterprises in their adoption of new technologies.

Industry Leaders and Firms

- Institute a framework for BIM leadership within organizations by assigning designated BIM Managers or BIM Champions and integrating BIM performance criteria into project management systems and quality assurance protocols.
- Begin the process of BIM adoption by selecting several pilot projects that offer high potential for demonstrable success and clear returns on investment. Rigorous documentation of project outcomes and ROI will serve to build internal evidence, thereby supporting wider adoption initiatives throughout the firm.
- Make significant investments in ongoing professional development. Collaboration with universities and international BIM certification bodies should be pursued to offer employees recognized BIM qualifications that attest to their skills and competencies.
- Actively engage with supply chain partners - including subcontractors, specialist consultants and suppliers - by introducing them to BIM capability development programmes. This will ensure a unified approach to model quality across all levels of the project's supply chain.

Educational Institutions and Professional Bodies

- Make BIM a compulsory element within the curricula of civil engineering, architecture and quantity surveying undergraduate and postgraduate programmes offered by universities throughout Jordan. The BIM learning outcomes should be standardized and aligned with the current demands of the industry.
- Develop and provide BIM training materials, technical guides and standard documentation in Arabic. This is essential to address the language barrier that restricts access to valuable international BIM resources for many Arabic - speaking professionals.
- Establish dedicated Industry - Academia BIM Research Centers. These centers should focus on co - developing applied research projects, offering industry placement opportunities with BIM - active firms and acting as hubs for the delivery of continuous professional development courses.

Scientific Ethics Declaration

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Conflict of Interest

* The author declares that there is no conflict of interest

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Early Prediction of Tactical Transitions in Cyber Attack Processes Through Network Flows

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Abstract: Cyber attacks are becoming increasingly complex, comprehensive, and dynamic. This makes it crucial not only to detect malicious activity but also to predict how an attack may progress in its early stages. This study predicts MITRE ATT&CK tactical transitions using Zeek-derived network flows from the UWF-ZeekData24 dataset (Elam et al., 2025). The core objective is to examine whether the next tactic can be inferred from time-ordered network behavior by treating attack activity as a temporal process. The analysis uses 1,916,757 raw flow records, removes duplicate records from the main analytical pipeline, aggregates flows into fixed-duration windows, and constructs a leakage-controlled next_tactic target. Static machine learning models, temporal deep learning architectures, and a first-order Markov baseline are evaluated under chronological train-validation-test partitioning. The best static models, Random Forest and XGBoost, reached test Macro-F1 = 0.4996, Balanced Accuracy = 0.6667, and Top-2 Accuracy = 0.9973 in the 10-minute window configuration. The best temporal model, LSTM with sequence length 3, matched but did not exceed this performance, while the Markov baseline achieved the same Top-1 and Top-2 accuracy. A reviewer-motivated ablation further compared raw-flow-only, tactical-context-only, and full feature settings to clarify what signal drives the prediction. Early prediction analysis showed that useful next-tactic ranking remained possible when only 10% of the attack process was observed. The findings indicate that ATT&CK-based tactical forecasting from Zeek flow summaries, optionally assisted by current tactical context, can support proactive early warning for cyber attack progression modeling, although minority tactic recovery remains constrained by severe class imbalance.

Keywords: Cyber attack prediction, MITRE ATT&CK, Tactical transition prediction, Zeek network flows, Early warning systems

Introduction

Traditional intrusion detection systems usually frame the analytical task as a binary distinction between benign and malicious traffic. This framing remains useful, but it is limited for operational security centers because it describes the current state of an incident rather than the likely direction of adversarial behavior. As attacks become more complex and dynamic, security teams need early indicators of what an adversary may do next so that defensive playbooks can be prioritized before the full attack process unfolds.

The MITRE ATT&CK framework provides a structured vocabulary for representing adversarial tactics and techniques. In this study, ATT&CK is used not only as a labeling scheme but also as a temporal structure for modeling tactical movement across an attack process. This perspective shifts the analytical question from whether traffic is malicious to which tactical stage is likely to follow the currently observed behavior.

Zeek network telemetry is well suited to this objective because it summarizes connection behavior, service and protocol patterns, duration, packet counts, byte counts, and destination diversity without requiring payload inspection. When such flow records are aggregated into time windows, they can represent behavioral states that are compatible with tactical transition analysis. At the local-network level, Tas (2025) showed that protocol-specific weaknesses such as ARP spoofing can be examined through simulated attack architectures and anomaly

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analysis, underscoring the value of behavioral network evidence for identifying malicious activity. At the modeling level, Tas (2025) emphasized that target leakage, training-test contamination, preprocessing leakage, and disregard of temporal order can inflate predictive performance. Together, these observations support the present study's use of Zeek-derived behavioral summaries, chronological partitioning, and explicit leakage control when forecasting ATT&CK tactical transitions.

This study aims to predict early-stage MITRE ATT&CK tactical transitions using network flows obtained from the UWF-ZeekData24 dataset. The contribution is a leakage-controlled and chronologically evaluated next-tactic prediction framework for cyber attack progression modeling. Unlike classical intrusion detection studies, the proposed approach offers a proactive early warning view of attack evolution rather than a reactive malicious/benign decision. The framework is positioned as a ranked decision-support layer rather than a fully autonomous replacement for analyst judgment.

The study addresses three research questions: Can Zeek-derived window features predict the next MITRE ATT&CK tactic with operationally meaningful performance? Do temporal deep learning models improve over static models and a Markov baseline? How early can tactical transition prediction remain informative when only a partial attack process is observed?

Literature Review

Recent cybersecurity analytics increasingly emphasize behavioral context rather than isolated malicious/benign labels. The MITRE ATT&CK framework is central to this shift because it organizes adversary behavior into tactics, techniques, and procedures that can be used to reason about attack progression (MITRE, 2026). ATT&CK-oriented analytics also support threat-informed defense by connecting observed events to adversarial intent, campaign stage, and response planning. Recent systematization studies further show that ATT&CK is now used across detection engineering, threat intelligence, risk analysis, and incident response, while also identifying the need for stronger operational evaluation of ATT&CK-based methods (Al-Sada et al., 2023; Roy et al., 2023).

Prior work on ATT&CK-based cyber threat intelligence has shown that unstructured threat reports and security observations can be mapped to tactics and techniques, creating a bridge between low-level telemetry and higher-level adversary behavior (Husari et al., 2017). More recent work has extended this mapping problem to NIDS rules and analyst-facing alert explanations, indicating that ATT&CK labels can support SOC triage when combined with machine learning or language-model-assisted enrichment (Daniel et al., 2024). This literature motivates the present study's focus on tactical transitions. Instead of treating ATT&CK labels as static categories, the study models them as ordered states whose next step may be predicted from current network behavior and tactical context.

Network-flow intrusion detection research provides the second foundation of the study. Public IDS datasets and Zeek-like telemetry have been widely used to evaluate machine learning models, but dataset realism, temporal dependence, and class imbalance remain recurring concerns (Sharafaldin et al., 2018; Ring et al., 2019). Recent work using MITRE ATT&CK-labeled data has also examined RandomForestNN-style classification under adversarial AI black-box conditions, showing that ATT&CK-labeled network traffic continues to be an active testbed for robust machine learning research (Mink et al., 2026). For this reason, the present design uses chronological splitting, leakage control, class-level reporting, and Top-k metrics rather than relying on raw accuracy alone.

The methodological literature further supports the use of balanced metrics and temporal baselines. In imbalanced domains, dominant classes can inflate accuracy while rare classes remain poorly recovered (Branco et al., 2016; He & Garcia, 2009). For future-state prediction, chronological validation is preferable to random splitting because random partitions can leak temporal structure into evaluation (Bergmeir & Benitez, 2012). Markov models remain useful as interpretable transition baselines, while LSTM-type architectures provide a comparison point for longer-range sequence dependence (Hochreiter & Schmidhuber, 1997; Rabiner, 1989).

A large portion of machine-learning-based intrusion detection research still evaluates models as if the operational objective were a single final label. Surveys and comparative studies of machine learning and deep learning in cybersecurity show that classification accuracy has often been reported as the primary success indicator, even when the target distribution is highly skewed and when the temporal structure of attacks is not represented explicitly (Apruzzese et al., 2018; Buczak & Guven, 2016; Xin et al., 2018). This convention is useful for

benchmarking, but it is less aligned with security operations, where analysts usually need to know what is unfolding, what may happen next, and which response path should be prioritized.

The cyber kill-chain perspective provides one conceptual basis for this shift from detection to progression analysis. Kill-chain models describe attacks as staged processes, and ATT&CK provides a more granular and operationally maintained vocabulary for representing adversarial behavior within those processes (Hutchins et al., 2011; MITRE, 2026). For network telemetry, this means that the analytical unit should not be only a connection or a flow record. It can also be a temporal window that summarizes the behavior of an attack stage and supports inference about the subsequent stage.

Recent deep learning studies have shown that sequence models can be effective for cyber intrusion tasks when meaningful temporal order is preserved (Ferrag et al., 2020). Recurrent models such as LSTM and GRU are designed to model temporal dependencies, while temporal convolutional networks and Transformer architectures provide alternative ways of representing ordered observations (Bai et al., 2018; Cho et al., 2014; Vaswani et al., 2017). However, these architectures do not automatically guarantee better operational value. If transitions are low-entropy or strongly dependent on the current state, simpler baselines may match complex models. This is why the present study compares temporal deep learning with both static machine learning and a Markov transition baseline.

Evaluation design is especially important in this setting. Time-dependent security data violate the assumptions behind ordinary random train-test partitioning, because nearby observations may share campaign-specific structure, infrastructure, and tactical state. Temporal validation is therefore a methodological requirement rather than a cosmetic choice (Bergmeir & Benitez, 2012). Dataset shift is another concern: if the distribution of tactics changes between training and testing periods, aggregate accuracy can overstate operational reliability (Moreno-Torres et al., 2012). Model selection bias is also possible when many algorithms are compared on a narrow evaluation design (Cawley & Talbot, 2010). The present study explicitly reports class distribution shift and treats model comparison as descriptive rather than as a statistically definitive ranking.

The study also draws from the literature on imbalanced learning and diagnostic metrics. When a dominant class accounts for most examples, conventional accuracy can remain high even if minority classes are ignored. Precision-recall based reasoning, macro-averaged metrics, balanced accuracy, and class-level reports are more appropriate in such conditions (Branco et al., 2016; Saito & Rehmsmeier, 2015). The Matthews correlation coefficient can also provide a more informative summary than accuracy in skewed binary settings (Chicco & Jurman, 2020), although the present paper emphasizes multiclass Macro-F1 and Top-k accuracy because the primary task is next-tactic ranking.

This study is positioned at the intersection of these strands. It extends Zeek-based intrusion analytics from binary detection toward ATT&CK-based next-tactic forecasting. Its contribution is not only model comparison, but also an evaluation design that asks whether early, ranked tactical suggestions can be produced under leakage-controlled and chronologically realistic conditions. In this sense, the study contributes an ATT&CK-based next-tactic prediction framework that transforms Zeek network flows into early warning signals for cyber attack progression modeling. The study therefore treats tactical transition prediction as a bridge between low-level network-flow features and higher-level security operations decision support.

Method

Dataset and Preprocessing

The empirical analysis uses the UWF-ZeekData24 dataset, an enterprise MITRE ATT&CK-labeled network attack traffic dataset released by the University of West Florida Cyber Analytics Research Group (Elam et al., 2025; University of West Florida, 2026). In this project, the data were stored as seven parquet partitions. The loading report shows 1,916,757 network flow records and 27 columns loaded successfully with the Polars engine. No file-level loading failure or schema mismatch was detected. Duplicate control identified 18,144 duplicate records, which were excluded from the main modeling pipeline, leaving 1,898,613 records for analytical processing.

The tactical distribution is highly imbalanced. Credential Access dominates the attack records, followed by Reconnaissance, Defense Evasion, Initial Access, and Exfiltration. At the next_tactic target level, Reconnaissance constitutes the largest window-level target class. Because of this imbalance, the analysis does not rely on accuracy alone and emphasizes Macro-F1, Balanced Accuracy, Top-k Accuracy, and per-class results.

Table 1. Dataset and modeling summary

Dataset characteristic	Value
Raw flow records	1,916,757
Loaded parquet files	7
Duplicate records removed	18,144
Records retained	1,898,613
Valid 10-minute transition windows	2,432
Final predictors	23
Temporal split	70% / 15% / 15%

Table 2. Literature positioning

Theme	Relevance to this study	Representative sources
ATT&CK framework	Adversary behavior is represented as tactics and techniques; this supports behavioral, phase-aware security analytics.	MITRE, 2026
ATT&CK analytics and CTI extraction	Recent ATT&CK-oriented work motivates mapping alerts and reports to tactics, techniques, and TTP sequences rather than using isolated labels.	Husari et al., 2017; MITRE, 2026
Network-flow intrusion datasets	Flow-level IDS research emphasizes dataset realism, temporal split discipline, and careful interpretation of high accuracy under skewed labels.	Sharafaldin et al., 2018; Ring et al., 2019
Imbalanced classification	Macro-F1, balanced accuracy, and class-level reports are necessary when dominant classes can inflate accuracy.	Branco et al., 2016; He & Garcia, 2009
Temporal and transition modeling	Chronological validation and Markov/sequence baselines are appropriate when the prediction target is a future tactical state.	Bergmeir & Benitez, 2012; Rabiner, 1989

Research Design

The study follows a quantitative predictive research design. Its purpose is not to explain the complete causal mechanism of adversarial behavior, but to test whether time-ordered Zeek flow summaries and tactical context can provide an early ranked estimate of the next MITRE ATT&CK tactic. The design is empirical because all modeling decisions are evaluated against observed windows derived from the UWF-ZeekData24 dataset. It is also temporal because observations are ordered by `window_start` and evaluated forward in time. The unit of analysis is the fixed-duration attack-behavior window rather than the individual raw flow. This choice is central to the research design. Individual flows are often too narrow to represent tactical behavior, whereas windows can summarize traffic volume, service diversity, byte and packet asymmetry, and tactical context. A window-level design also makes it possible to define `next_tactic` as a future tactical state and to evaluate early prediction before the whole attack process has been observed.

The dependent variable is `next_tactic`. For each active attack window, the next different tactic in the subsequent ordered windows is assigned as the prediction target. Windows without a later tactical transition are removed from the main next-tactic modeling dataset. This target construction operationalizes attack progression as a transition problem. It differs from conventional intrusion detection because the model does not simply ask whether traffic is malicious. It asks which tactical stage is likely to follow the current state. The research design includes three model families to separate three possible sources of predictive signal. Static machine learning models test whether a single window summary contains enough information for next-tactic prediction. Temporal deep learning models test whether short sequences of windows add useful information beyond the current summary. The Markov baseline tests whether the transition process is mostly explained by the current tactical state. This three-way comparison is important because a complex model is not automatically preferable when a simple transition model captures the same structure.

Window Construction and Leakage Control

Raw flows were aggregated into fixed-duration time windows. The principal configuration used 10-minute windows because preliminary sensitivity analysis indicated that this window length best balanced behavioral stabilization and alert latency. The resulting feature set contains 23 predictors: 18 numerical and 5 categorical variables. These variables summarize flow volume, duration statistics, packet and byte asymmetries, service and protocol structure, destination diversity, and current tactical context.

Table 3. Research design matrix

Design element	Configuration	Rationale
Research type	Quantitative, empirical, predictive modeling study	The study tests whether time-ordered Zeek windows can forecast the next ATT&CK tactic.
Unit of analysis	10-minute attack-behavior window	Raw flows are converted into comparable temporal observations.
Primary target	next_tactic	The target represents the next different MITRE ATT&CK tactic after the current tactical state.
Main predictors	Zeek behavioral summaries and tactical context	Network-flow statistics are combined with current and previous tactical state variables.
Validation logic	Chronological 70/15/15 split	Evaluation follows a forward-in-time design and avoids random temporal leakage.
Model families	Static ML, temporal DL, Markov baseline	The design compares feature-based learning, sequence learning, and transition probability modeling.
Primary metrics	Macro-F1, balanced accuracy, Top-k accuracy	Metrics were selected to avoid over-interpreting raw accuracy under severe class imbalance.
Operational question	Early ranked next-tactic warning	The output is intended to support SOC triage through a short list of likely next tactics.

Table 4. Validity controls

Validity concern	Control or interpretation
Label leakage	Ground-truth labels, next_tactic, identifiers, raw timestamps, and raw IPs were excluded from the feature matrix.
Temporal leakage	Train, validation, and test periods are ordered chronologically, with no random shuffling.
Class imbalance	Macro-F1, balanced accuracy, Top-k accuracy, and per-class F1 are reported instead of accuracy alone.
Tactical-context dependency	The paper frames results as tactical-context-assisted prediction and states the need for an upstream ATT&CK mapping component.
Model comparison	Findings are interpreted descriptively because the project uses one chronological split rather than repeated folds.
Binary auxiliary task	Binary detection is not treated as the main contribution because the test period is single-class.

A strict leakage-control strategy was applied because label leakage can artificially inflate predictive performance in data mining experiments (Kaufman et al., 2012). Ground-truth label fields, the dependent variable, raw timestamps, unique identifiers, raw IP addresses, and future-derived fields were excluded from predictors. The target next_tactic was constructed from the subsequent tactical state, and no_transition windows were removed. Thus, only features observable at scoring time were retained.

The tactical-context variables require a careful operational interpretation. In the offline experiment, tactic_current, tactic_previous, and tactic_changed_flag represent the currently inferred tactical state at the window level. In a deployed system, these variables would need to be supplied by an upstream ATT&CK mapping component, analyst-confirmed alert stream, or a current-tactic classifier. Therefore, the full-feature results are interpreted as tactical-context-assisted next-tactic prediction, while the ablation experiment separately tests whether Zeek-derived flow summaries alone can preserve the same ranking behavior.

The intended SOC workflow is as follows: Zeek logs are aggregated into behavioral windows; an upstream ATT&CK mapping or current-tactic classifier assigns the current tactical state when available; the forecasting layer ranks likely next tactics; and analysts use the Top-k output to prioritize playbooks, log sources, and defensive controls. This architecture keeps the model in a decision-support role and avoids treating next-tactic prediction as an automatic operational verdict.

Table 5. Next-tactic target distribution

Next tactic	Windows	Percent	Rank
Reconnaissance	2089	85.8964	1
Credential Access	248	10.1974	2
Defense Evasion	51	2.097	3
Initial Access	44	1.8092	4

Overall Research Workflow

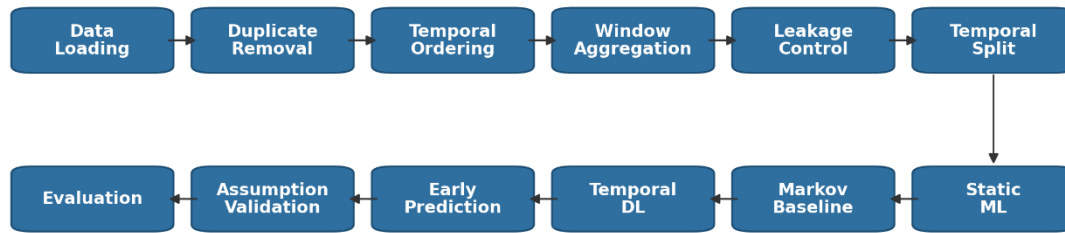


Figure 1. Research workflow

Data Processing Pipeline



Figure 2. Processing pipeline

Experimental Design

The modeling data were divided chronologically rather than randomly, following the principle that temporal prediction should be evaluated forward in time rather than by random mixing of past and future observations (Bergmeir & Benitez, 2012). The training period spans 2024-02-28 04:00:00 to 2024-03-20 20:30:00, the validation period spans 2024-03-20 20:40:00 to 2024-03-23 09:10:00, and the test period spans 2024-03-23

09:20:00 to 2024-03-27 22:10:00. The corresponding split sizes are 1,702 training windows, 364 validation windows, and 366 test windows.

Three model families were compared. Static models included Logistic Regression, Random Forest (Breiman, 2001), LightGBM, XGBoost (Chen & Guestrin, 2016), and MLP. Temporal deep learning models included LSTM, GRU, TCN, and Transformer architectures with sequence lengths of 3, 5, and 10. A first-order Markov chain with Laplace smoothing was used as an interpretable transition baseline. After the initial reviewer-style audit, an additional ablation experiment was added. This experiment compared three feature settings under the same chronological split: raw-flow-only features, tactical-context-only features, and the full feature set. The purpose was to distinguish whether prediction was driven by Zeek behavioral summaries, current tactical state, or their combination.

Results and Discussion

Next-Tactic Prediction

Table 6 reports test performance for static machine learning models. Random Forest and XGBoost achieved the strongest results, each reaching Accuracy = 0.9973, Macro-F1 = 0.4996, Balanced Accuracy = 0.6667, and Top-2 Accuracy = 0.9973. LightGBM and MLP were close, whereas Logistic Regression lagged behind, especially in Macro-F1 and Top-2 Accuracy.

The high accuracy should be interpreted cautiously. The test set is dominated by Reconnaissance and contains very few minority-class examples. Therefore, Macro-F1 and per-class F1 provide a more honest assessment of balanced multiclass recovery. Operationally, the results support ranked next-tactic recommendation, but they do not show uniform success across all ATT&CK tactics.

Table 6. Static model test results

Model	Accuracy	Macro-F1	Balanced Acc.	Top-2	Top-3
Logistic Regression	0.4973	0.4003	0.4766	0.9426	1
Random Forest	0.9973	0.4996	0.6667	0.9973	1
Lightgbm	0.9918	0.4988	0.6646	0.9973	1
Xgboost	0.9973	0.4996	0.6667	0.9973	1
Mlp	0.9945	0.4964	0.6591	0.9973	1

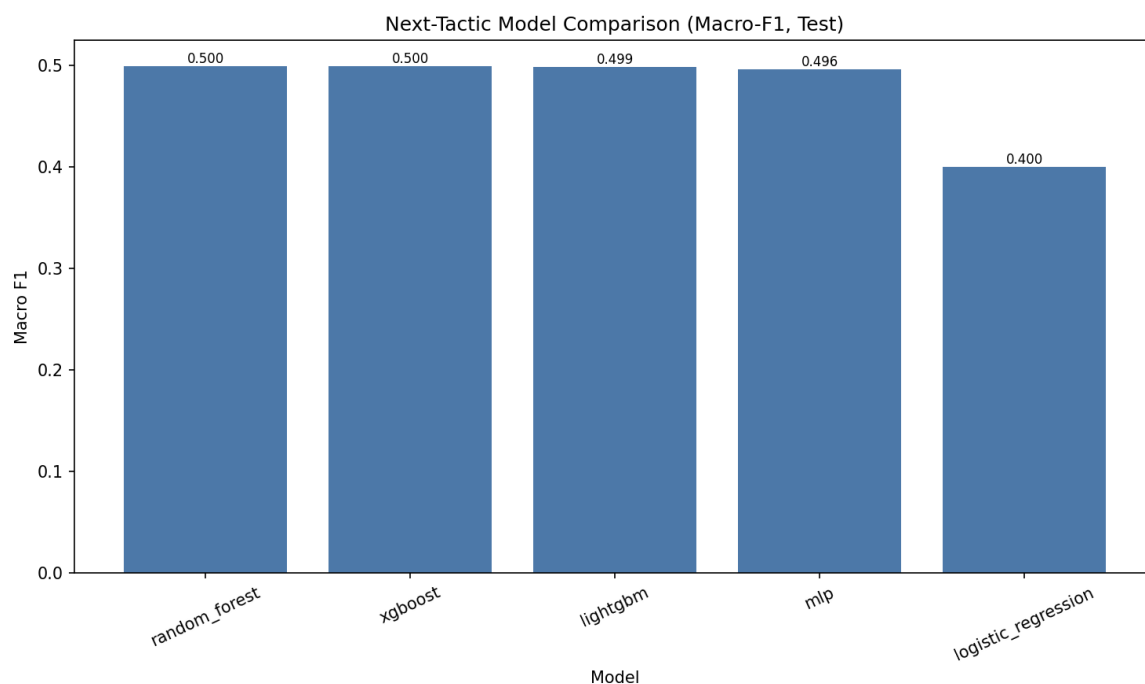


Figure 3. Static model comparison

The contrast between Accuracy and Macro-F1 is one of the most important findings of the study. Accuracy suggests that the task is almost solved, but Macro-F1 shows that the solution is uneven across tactics. This difference is expected in a transition dataset where one or two tactical paths dominate the chronology. For an operational SOC, the implication is that the model may be valuable as a candidate-ranking tool, but it should not be used as an autonomous rare-tactic detector without additional balancing or confirmation mechanisms.

The static model results also show that nonlinear models are more appropriate than a linear baseline for this feature space. Logistic Regression performed substantially worse than tree-based models on Macro-F1 and Top-2 Accuracy. This does not mean that Logistic Regression is unusable; rather, it indicates that the interaction between flow-volume features, diversity features, service categories, and tactical context is not well captured by a simple linear boundary. The strong performance of Random Forest and XGBoost is consistent with their ability to handle heterogeneous feature types and nonlinear splits.

Feature Contribution Analysis: Flow Features and Tactical Context

The reviewer-motivated ablation analysis clarifies the source of predictive signal. The raw-flow-only Random Forest model matched the full-feature Random Forest on the test split, reaching Accuracy = 0.9973, Macro-F1 = 0.4996, Balanced Accuracy = 0.6667, and Top-2 Accuracy = 0.9973. This result shows that the study's title is not merely supported by tactical-context variables; Zeek-derived behavioral summaries alone can reproduce the dominant transition pattern in this dataset.

At the same time, the context-only condition should be interpreted cautiously. XGBoost with only tactical-context variables matched the full model, whereas Random Forest with the same variables performed poorly in Accuracy and Macro-F1 while still retaining high Top-k ranking. This model-family sensitivity indicates that the transition structure is low-entropy and state-dependent, but also that direct class prediction remains unstable under severe imbalance.

Overall, the ablation strengthens the paper's framing. The framework should not be presented as uniformly accurate multiclass prediction for all tactics. It is better described as an early next-tactic ranking approach in which Zeek window summaries and tactical context can each encode dominant transition regularities, while rare tactic recovery remains unresolved.

Table 7. Feature contribution analysis of flow and tactical-context features

Feature set	Model	Features	Accuracy	Macro-F1	Balanced Acc.	Top-2
Raw-flow-only	Random Forest	20	0.9973	0.4996	0.6667	0.9973
Raw-flow-only	XGBoost	20	0.9945	0.4992	0.6656	0.9973
Context-only	Random Forest	3	0.123	0.2516	0.3344	0.9973
Context-only	XGBoost	3	0.9973	0.4996	0.6667	0.9973
Full model	Random Forest	23	0.9973	0.4996	0.6667	0.9973
Full model	XGBoost	23	0.9973	0.4996	0.6667	0.9973

Temporal and Markov Models

Temporal deep learning did not produce a meaningful improvement over the best static models. The best temporal configuration was LSTM with sequence length 3, which matched the best static Macro-F1 and Top-2 Accuracy. This suggests that, at 10-minute resolution, much of the useful temporal information is already captured by the current window summary and tactical context variables.

The Markov baseline reinforces this interpretation. The first-order Markov chain achieved test Top-1 Accuracy = 0.9973 and Top-2 Accuracy = 0.9973, matching the strongest machine learning models on ranking-oriented metrics. Thus, the transition structure in this dataset appears strongly state-dependent. The practical implication is that interpretable transition baselines should be retained in operational systems rather than treated as weak reference models.

This result is valuable because it prevents an overstatement of deep learning. In many cybersecurity studies, the inclusion of LSTM, GRU, TCN, or Transformer architectures can create the impression that sequence complexity is necessary. The present results show a more cautious picture. At the selected temporal resolution, the next tactic is largely determined by the current tactical state and the dominant transition pattern in the dataset. Complex

temporal architectures may become more useful in higher-entropy campaigns, multi-actor environments, or datasets where tactical transitions are less repetitive.

The Markov result also improves interpretability. A transition matrix can be inspected by analysts, compared with threat intelligence expectations, and monitored for drift over time. If a deployed system observes that real transition probabilities deviate from the learned matrix, this could indicate a new campaign pattern or a change in adversary behavior. In this sense, the Markov baseline is not only a benchmark. It is also a diagnostic artifact for operational monitoring.

Table 8. Temporal model test results

Model	Seq.	Accuracy	Macro-F1	Balanced Acc.	Top-2
LSTM	3	0.9973	0.4996	0.6667	0.9973
GRU	5	0.9863	0.498	0.6625	0.9973
LSTM	10	0.9808	0.4972	0.6604	0.9973
TRANSFORMER	3	0.9616	0.4948	0.6531	0.9973
TRANSFORMER	10	0.956	0.4936	0.651	0.9973

Table 9. Markov baseline performance

Model	Split	N	Top-1	Top-2	Top-3
Markov chain	Test	366	0.9973	0.9973	1.0000

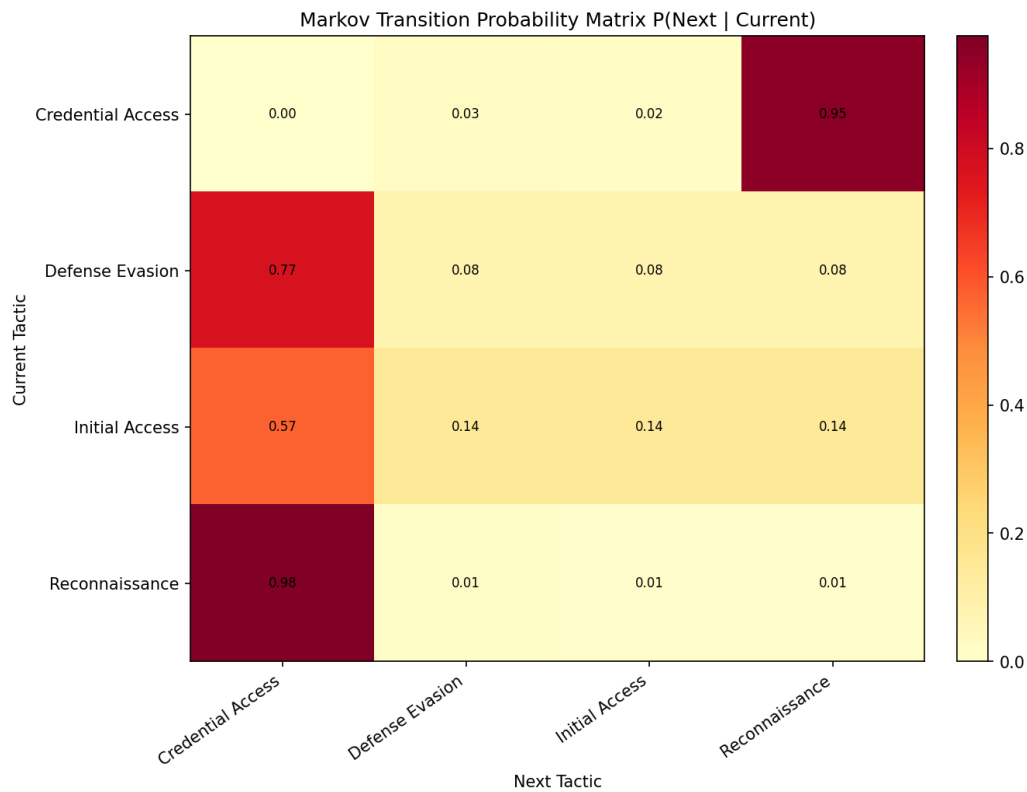


Figure 4. Transition probability heatmap

Early Prediction

A central goal of the study was to determine whether tactical transition prediction remains informative before the whole attack process is observed. Table 10 shows that at only 10% observation, the Random Forest model achieved Accuracy = 0.9178, Macro-F1 = 0.4879, Balanced Accuracy = 0.6667, and Top-2 Accuracy = 0.9178. Macro-F1 remained stable as observation increased, while accuracy and Top-2 performance generally improved. This result supports the proactive early warning premise of the study. The model can generate useful ranked next-tactic suggestions early in the attack process. However, the stability of Macro-F1 also indicates that observing more of the attack does not solve the minority-class bottleneck by itself.

The early prediction experiment should be interpreted as a partial-observability simulation. It does not prove that every SOC can obtain the same performance at the first minutes of a live attack. It shows that, under the present feature construction and tactical-context assumption, meaningful next-tactic ranking can be retained even when only a small portion of the post-training attack horizon is used for evaluation. This distinction is important because early warning systems must operate under uncertainty, delayed labels, and incomplete context.

The practical value of early ranking lies in decision support. A Top-2 tactical candidate list can help analysts prioritize playbooks, decide which logs to inspect next, and prepare controls associated with likely follow-on tactics. This is different from issuing a single deterministic prediction. Under imbalance and uncertainty, a ranked output is more realistic because it communicates the model's short list of likely tactical states rather than pretending that the next stage is known with full certainty.

Table 10. Early prediction results

Observed %	N	Accuracy	Macro-F1	Balanced Acc.	Top-2
10	73	0.9178	0.4879	0.6667	0.9178
25	182	0.9066	0.4866	0.5	0.9396
50	365	0.9534	0.4935	0.5	0.9781
75	547	0.9689	0.4956	0.5	0.9872
100	730	0.9753	0.4965	0.5	0.9849

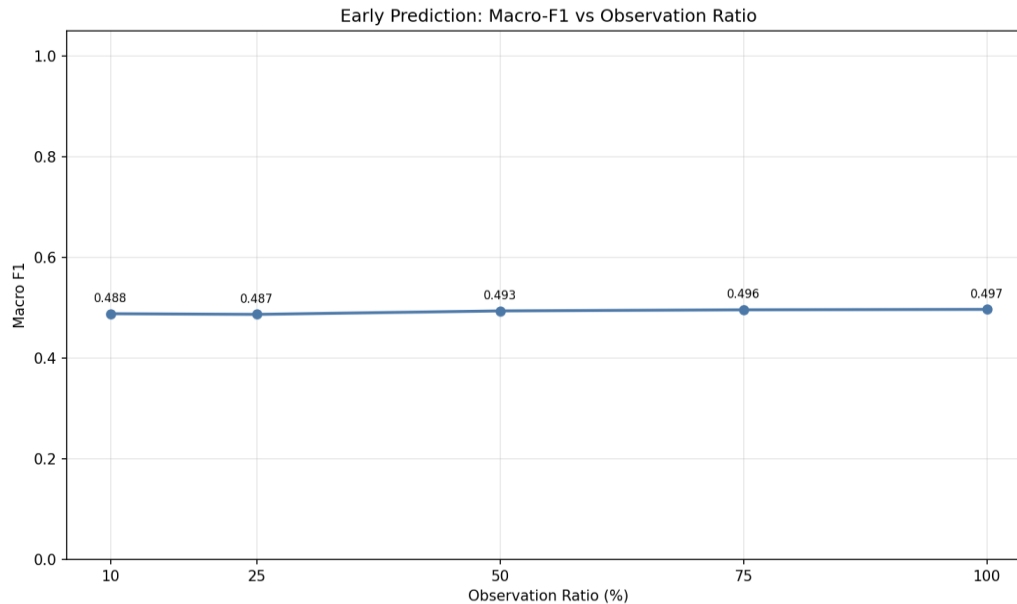


Figure 5. Early prediction curve

Window Size and Class-Level Behavior

Window-size sensitivity analysis showed that the 10-minute configuration provided the best overall balance. One-minute windows were too noisy, five-minute windows improved but remained weaker, and 30-minute windows reduced the number of test examples substantially. The 10-minute setting achieved the highest Macro-F1 while maintaining near-perfect Top-2 Accuracy. Class-level evaluation reveals the main limitation of the framework. Credential Access and Reconnaissance were recovered almost perfectly in the test split, whereas Initial Access had only one test example and was not recovered. Defense Evasion had no test support. Therefore, the proposed approach is strongest as an operational ranked-warning mechanism for dominant transitions, while rare tactic recovery requires additional data and imbalance-aware modeling.

The window-size result also provides an operational design recommendation. Very short windows can support low-latency alerting, but they may not accumulate enough behavioral evidence to represent a tactical state. Very long windows can stabilize behavior, but they reduce sample count and delay response. The 10-minute setting appears to balance these competing requirements for this dataset. This should not be generalized blindly to every network; rather, it provides an empirical starting point for SOC deployments that use Zeek-like telemetry.

The per-class results clarify why minority-aware design remains necessary. If an organization is most concerned with rare but high-impact stages such as Exfiltration or Defense Evasion, the current model would require additional data, synthetic augmentation, cost-sensitive learning, or hierarchical modeling. A future version could first predict a broader tactical family and then refine the prediction into a tactic or technique. Such a hierarchy may reduce the damage caused by extremely sparse leaf classes.

Table 11. Window-size comparison

Window	N	Accuracy	Macro-F1	Balanced Acc.	Top-2
1	2210	0.3937	0.2841	0.2935	0.7231
5	726	0.7755	0.3481	0.3837	0.8967
10	366	0.9973	0.4996	0.6667	0.9973
30	36	0.9444	0.4857	0.5	0.0556

Table 12. Per-class next-tactic results

Class	Precision	Recall	F1	Support
Credential Access	1	1	1	44
Defense Evasion	0	0	0	0
Initial Access	0	0	0	1
Reconnaissance	0.9969	1	0.9984	321

Interpretability and Assumption Checks

Permutation importance analysis identified `tactic_current` as the most important predictor in the full-feature model. Its disruption produced the only meaningful reduction in Macro-F1, whereas traffic-volume, byte-ratio, packet-ratio, and service-diversity features provided secondary support. The ablation analysis qualifies this result: although `tactic_current` dominates the full model's internal importance ranking, raw Zeek-flow summaries can still reproduce the dominant test-set transition pattern when tactical-context variables are removed. Assumption checks confirmed chronological split ordering and leakage-control integrity, but they also showed class-distribution shift and severe imbalance. These checks are important because they prevent overly optimistic interpretation of accuracy and clarify why Macro-F1, Balanced Accuracy, Top-k Accuracy, and per-class reporting are emphasized throughout the study.

The interpretability findings change how the contribution should be stated. The paper should not claim that all tactics are accurately predicted under balanced conditions. Instead, the evidence supports a combined view: Zeek-derived behavioral summaries and tactical-context variables both capture dominant transition regularities, but rare-tactic recovery remains limited. The model can be understood as a forecasting layer that operates after, or alongside, ATT&CK-oriented enrichment.

The assumption checks also strengthen the paper by making weaknesses explicit. The failed or partially satisfied assumptions are not hidden; they are incorporated into the interpretation. This is a better scientific position than reporting only the strongest metrics. In particular, the lack of a valid binary test regime and the absence of some minority tactics in the test set are treated as constraints on inference rather than as minor technical details.

Conclusion

This study examined whether Zeek-derived network flow behavior can be used to predict the next MITRE ATT&CK tactic before a cyberattack process fully unfolds. Using the UWF-ZeekData24 dataset, a leakage-controlled and chronological next_tactic prediction pipeline was developed. The strongest static models reached Macro-F1 = 0.4996, Balanced Accuracy = 0.6667, and Top-2 Accuracy = 0.9973 on the 10-minute window configuration. A new ablation analysis showed that raw-flow-only Random Forest performance matched the full-feature setting, while tactical-context-only performance was model-sensitive.

The results show that next-tactic prediction is feasible as a ranked early warning task. Temporal deep learning models did not outperform the best static models, and a first-order Markov baseline matched the strongest Top-k performance. This indicates that the tactical transition process in this dataset is largely state-driven at the chosen aggregation level.

The main contribution is therefore not simply higher classification accuracy, but a reframing of network intrusion analytics from reactive detection to proactive ATT&CK-based tactical forecasting and attack progression modeling. For security operations centers, the framework can support earlier prioritization of defensive actions by offering a short list of likely next tactics.

Recommendations

Future studies should validate the framework on multiple Zeek corpora, mixed attack-normal test periods, and higher-entropy attack campaigns. Rare tactics such as Defense Evasion and Initial Access require cost-sensitive learning, targeted resampling, hierarchical tactic-technique modeling, or additional attack scenarios. Operational deployments should retain a Markov baseline for interpretability and calibration, while using machine learning models to exploit richer behavioral features when transition entropy is higher.

Limitations

The study is limited by its dependence on a single dataset and a campaign-specific transition structure. The chronological test split contains few or no examples of some minority tactics, which restricts conclusions about rare transitions. The auxiliary binary detection experiment is not treated as a main contribution because the test period contains only normal traffic. Finally, feature importance results explain model behavior but should not be interpreted as causal evidence.

A further limitation concerns the tactical-context variables. Because `tactic_current` and `tactic_previous` are strong predictors, the full-feature framework assumes that current tactical state can be obtained before next-tactic scoring. This is plausible in a SOC pipeline that already maps alerts to ATT&CK tactics, but it is a dependency rather than a raw Zeek-flow property. The added raw-flow-only ablation reduces this concern for the present dataset, yet an end-to-end deployment should still include a validated current-tactic mapping component.

Model comparison is also limited by the single chronological split. This design is operationally realistic and avoids random temporal leakage, but it does not support strong statistical claims about algorithm superiority of the kind normally expected in multi-dataset classifier comparisons (Demsar, 2006). Repeated rolling-origin validation or cross-campaign testing would be needed before claiming that one model family is generally superior.

Data Availability Statement

The study uses the UWF-ZeekData24 dataset obtained from the University of West Florida Network Traffic Flow Datasets portal. The dataset provider states that the articles and datasets are distributed under the Creative Commons Attribution (CC BY) license. Derived analytical outputs are stored in the project workspace and include preprocessing scripts, modeling scripts, tabular summaries, and visual outputs used to prepare this manuscript. Dataset redistribution should follow the original dataset provider's access and licensing conditions.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

* No human participants, personal intervention, or human-subject experimental procedure were involved in this study.

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Conflict of Interest

* The author declares that there is no conflict of interest

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* The study is based on analytical outputs generated from the UWF-ZeekData24 dataset and the author's experimental pipeline.

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Multi-Criteria Decision-Making Application in Human Resource Management: The Case of a Cyber Security Specialist

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Abstract: Information security is of vital importance for individuals, organizations, and societies to sustain their existence in the digital age. However, information security management processes constitute a complex structure that requires the simultaneous coordination of the fundamental objectives of confidentiality, integrity, and availability. In addition, information security policies differ at the individual, organizational, and societal levels. While individuals implement their own policies to ensure their personal information security, organizations rely on cybersecurity specialists. This is because the protection of organizational assets is of great importance in terms of sustainability. As a matter of fact, an organization that fails to ensure information security may experience not only financial losses but also reputational damage. This situation poses a significant risk to the sustainability of the organization. In order to minimize these risks, organizations need to select the most suitable cybersecurity specialist. To address this problem faced by organizations, a two-stage solution is proposed in the literature. First, the criteria affecting the selection and their relative importance levels must be determined. The second stage involves the evaluation of alternatives. In this study, the first stage is addressed. The criteria affecting the recruitment process of cybersecurity specialists are identified and their importance levels are calculated. In total, 5 main criteria and 24 sub-criteria are considered in the study. The inclusion of the “inclination toward artificial intelligence” criterion reflects the innovative aspect of the study. Due to the hierarchical structure of the problem, one of the multi-criteria decision-making methods, the Analytic Hierarchy Process (AHP), is employed for evaluation. As a result of the evaluation, experience and certifications emerge as the most prominent main criteria. In addition, the inclination toward artificial intelligence also holds a significant place in the selection of cybersecurity specialists.

Keywords: Information security, Selecting a cybersecurity expert, Multi-criteria decision making, Analytic hierarchy process

Introduction

With the rapid advancement of technology, although significant improvements have been achieved in cybersecurity and its supporting infrastructure, cyberspace is still far from being completely secure (Shiva et al., 2010). This situation compels cybersecurity service providers to continuously monitor emerging technological developments and adapt their personnel accordingly. In today's rapidly evolving technological environment, cybersecurity companies must place particular emphasis on human resource management processes to deliver their products effectively and ensure their sustainable use. This is because all cybersecurity products and services are ultimately created through the integration of employees' knowledge and skills with technology.

Furthermore, it is difficult to recruit qualified cybersecurity professionals. Therefore, for organizations, it is crucial to effectively manage every stage of the human resource process, beginning with personnel selection and extending to employee training, performance evaluation, and promotion (Furnell et al., 2017). The first stage of human resource management is personnel selection, and all subsequent human resource activities depend on this initial step. This highlights the critical importance of the personnel selection process. Selecting an unsuitable candidate may negatively affect subsequent processes, including employee training, organizational commitment,

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and overall job performance. Moreover, considering that cybersecurity is a mission-critical function responsible for protecting organizational information assets, the importance of selecting the right personnel becomes even more significant.

Personnel management, one of the core business processes of organizations, encompasses numerous decision-making activities. Following the identification of staffing needs, personnel selection represents one of the most critical decision-making stages within the human resource management process because organizations make substantial investments in newly hired employees. An inappropriate hiring decision may result not only in financial losses but also in wasted time, reduced organizational efficiency, and even reputational damage. Consequently, the personnel selection process is of strategic importance (Danişan et al., 2022).

Motivated by the importance of this problem, the present study addresses the selection of a cybersecurity specialist for employment in a financial institution. The personnel selection problem has been extensively investigated in the literature across various sectors, including the food industry (Chuang et al., 2020), textile industry (Danişan et al., 2022), logistics (Nong & Ha, 2021), security services (Kose et al., 2013), tourism (Urosevic et al., 2017), service systems (Uslu et al., 2021), and information technology, which is closely related to the application domain of the present study (Raj Mishra et al., 2020). Multi-Criteria Decision-Making (MCDM) methods are widely employed to solve personnel selection problems in these sectors. Pandey et al. (2026) provided a comprehensive literature review summarizing these studies.

A review of personnel selection studies in the field of information technology reveals the application of several MCDM techniques, including the Analytic Hierarchy Process (AHP) (Erdem, 2016), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Samanlioglu et al., 2018), Additive Ratio Assessment (ARAS) (Raj Mishra et al., 2020), Evaluation Based on Distance from Average Solution (EDAS) (Karabasevic et al., 2018), and Step-wise Weight Assessment Ratio Analysis (SWARA) (Heidary Dahooie et al., 2018).

A review of the literature specifically addressing cybersecurity specialist selection indicates that only one related study exists. Yumusak and Eren (2022) calculated the weights of the criteria affecting cybersecurity specialist selection using the AHP method and subsequently ranked candidate alternatives using the PROMETHEE method. Although personnel selection has been extensively investigated within the information technology domain, research focusing specifically on cybersecurity specialist selection remains very limited. In the present study, the criteria affecting the selection of a cybersecurity specialist for a financial institution are evaluated using the AHP method. Furthermore, the set of 24 evaluation criteria employed in this study has, to the best of the authors' knowledge, not previously been considered together in the existing literature.

The remainder of this paper is organized as follows. Section 2 introduces the Analytic Hierarchy Process (AHP). Section 3 presents the proposed solution model for the cybersecurity specialist selection problem and describes the application steps in detail. Finally, Section 4 discusses the findings and presents the conclusions of the study.

Method

In this study, the Analytic Hierarchy Process (AHP) was employed because the decision problem exhibits a hierarchical structure.

Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making (MCDM) method first developed by Thomas L. Saaty in 1980 to solve complex decision problems involving multiple criteria (Saaty, 1980). The method enables decision-makers to incorporate both objective and subjective judgments into the decision-making process. Owing to its flexibility and ease of application, AHP has been widely utilized in various decision-making problems across different disciplines. One of the primary reasons for its widespread adoption is that its methodology is intuitive and easily understood by decision-makers. The application steps of the AHP method are presented below.

Step 1: Construction of the Hierarchical Structure

In the first step, a hierarchical decision structure is established for the problem under consideration. This hierarchy generally consists of the overall goal at the top level, the evaluation criteria and sub-criteria at the intermediate levels, and the decision alternatives at the lowest level.

Step 2: Pairwise Comparison of the Criteria

Based on the hierarchical structure established in Step 1, pairwise comparison matrices are constructed. At this stage, the criteria are compared with one another, and the alternatives are evaluated with respect to each criterion through pairwise comparisons. These comparison matrices are developed using the fundamental importance scale proposed by Saaty (1980). The Saaty importance scale is presented in Table 1.

Table 1. Saaty importance scale	
Important Values	Value Definitions
1	Equally important
3	Somewhat important
5	Very important
7	Extremely important
9	Absolutely important
2, 4, 6, 8	Intermediate values

Step 3: Obtaining the Normalized Matrices and Relative Importance Weights.

For each criterion, the normalization process is performed using Equation (1), and the importance weights are calculated using Equation (2).

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}} \quad (1)$$

$$w_i = \frac{\sum_{i=1}^n b_{ij}}{n} \quad (2)$$

Step 4: Calculating and Verifying Consistency Ratios for Comparison Matrices.

The consistency index (CI) and the consistency ratio (CR) are calculated to determine the consistency of the comparisons. The formulas used to calculate the CI and CR are given in Equation (3) and Equation (4).

$$CI = \frac{\lambda_{maks} - n}{n - 1} \quad (3)$$

$$CR = \frac{CI}{RI} \quad (4)$$

CR values less than 0.1 are considered consistent. The RI values are given in Table 2.

Table 2. RI values (Saaty, 1980)														
n	1 ve 2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0,58	0,9	1,12	1,2	1,32	1,41	1,45	1,49	1,51	1,48	1,56	1,57	1,59

Step 5: Identifying and Selecting the Best Alternative.

Based on the results of the AHP method, the alternative with the highest importance weight is selected as the best alternative.

Case Study

With the advent of Industry 4.0, ensuring information security for rapidly digitizing companies has become of great importance. As the importance of information security grows day by day and demand for solutions to these problems increases, the need for a qualified workforce has also risen. In this context, this study examines the recruitment process at a financial company providing services in the field of cybersecurity. The company in question identified a need for cybersecurity specialists, and this study aimed to optimize this recruitment process. The study was conducted in three main phases: first, problem definition; second, the identification of criteria influencing the selection process; and finally, the evaluation of these criteria using the AHP method.

Problem Definition

Cybersecurity is of critical importance for banks, insurance companies, investment firms, and fintech companies to conduct their operations securely. This sector is one of the primary targets of cyberattacks due to the high volume of financial transactions it handles and the sensitive customer data it processes. Therefore, selecting the right cybersecurity specialist plays a decisive role in protecting the organization's information assets. For this reason, this study addresses the problem of selecting a cybersecurity expert to work in the financial sector. The criteria influencing personnel selection were identified and prioritized. The study examined five main criteria and 24 sub-criteria.

Determining the Criteria

In determining the criteria to be considered during the selection process for a cybersecurity specialist to be employed in the financial sector, we drew upon current studies in the literature and expert opinions. There is one study in the literature that addresses the selection of cybersecurity specialists. However, there are no studies specifically focused on the selection of cybersecurity specialists for the financial sector. By combining the studies in literature and expert opinions, the criteria presented in Table 3 were established.

Table 3. Criteria influencing the selection of cyber security specialists

Main criteria	Sub-criteria
1. Education Level (C1)	1. Associate's degree (C1.1)
	2. Bachelor's degree (C1.2)
	3. Master's degree (C1.3)
	4. Doctorate (C1.4)
2. Professional Certifications (C2)	1. CISSP (C2.1)
	2. CEH (C2.2)
	3. CompTIA Security+ (C2.3)
	4. OSCP (C2.4)
	5. CISM (C2.5)
3. Analytical and Cognitive Competencies (C3)	1. Analytical thinking (C3.1)
	2. Crisis management (C3.2)
	3. Research skills (C3.3)
	4. Ability to learn quickly (C3.4)
4. Communication and Social Skills (C4)	1. Ability to work in a team (C4.1)
	2. Written and oral communication (C4.2)
	3. Leadership (C4.3)
	4. Time management (C4.4)
	5. Ability to work under pressure (C4.5)
5. Technical Knowledge and Competencies (C5)	1. Knowledge of network security (C5.1)
	2. Knowledge of operating systems (C5.2)
	3. Software security (C5.3)
	4. Malware analysis (C5.4)
	5. Penetration testing experience (C5.5)
	6. Proficiency in artificial intelligence (C5.6)

Level of Education

The level of education is a key criterion in selecting a cybersecurity specialist, as it reflects the candidate's theoretical foundation, analytical thinking skills, research abilities, and aptitude for professional development. Cybersecurity is a complex field comprising a combination of many disciplines, such as computer networks, operating systems, cryptography, software development, risk management, and information security. Therefore, the quality and level of a candidate's education can directly impact their ability to understand and solve security problems.

Professional Certifications

Professional certifications are nationally or internationally recognized documents that demonstrate that cybersecurity specialists possess specific knowledge, skills, and practical competencies. Due to the constantly evolving nature of technologies and threats in the field of cybersecurity, certifications are considered an important indicator that an individual possesses up-to-date knowledge and meets specific professional standards. For this reason, they are one of the key criteria evaluated alongside technical knowledge and experience in personnel selection processes.

Analytical and Cognitive Competencies

These competencies are of fundamental importance for cybersecurity experts to analyze complex security problems, accurately assess threats, and develop effective solutions. Attacks encountered in the field of cybersecurity are often multi-stage, dynamic, and involve a degree of uncertainty. Therefore, it is not enough for experts to possess only technical knowledge; they must also have strong analytical thinking, problem-solving, critical thinking, and decision-making skills.

Communication and Social Skills

Communication and social skills are of great importance not only for cybersecurity experts to solve technical problems but also to establish effective collaboration with various stakeholders, raise security awareness, and ensure proper coordination during crises. Today, cybersecurity has evolved beyond a purely technical activity; it has become a strategic discipline requiring collaboration among information technology, senior management, legal, human resources, and other business units. Therefore, strong communication skills are just as essential as technical knowledge among the core characteristics of a successful cybersecurity specialist.

Technical Knowledge and Competencies

Technical knowledge and competencies are among the most important criteria in selecting a cybersecurity specialist. This is because cybersecurity specialists are responsible for protecting an organization's information assets, detecting attacks, addressing security vulnerabilities, and responding quickly to potential threats. Effectively carrying out these tasks requires strong technical knowledge and practical skills.

Prioritization of Criteria Using the AHP Method

In the first step of the application, a hierarchical structure was established. The objective is to select a cybersecurity specialist. In line with this objective, five main criteria and 24 sub-criteria are presented in Figure 1. After the hierarchical structure was established, the pairwise comparison matrix for the main criteria was created using Table 1. Table 4 presents the pairwise comparison matrix for the main criteria. The normalized decision matrix was constructed by applying Equation 1 to the matrix shown in Table 4. The normalized decision matrix for the main criteria is presented in Table 5.

The weights of the main criteria were calculated by applying Equation 2 to the data in Table 5. The weights of the main criteria are shown in Figure 2. The most important main criterion was "Technical Knowledge and Competencies." When Equations 3 and 4 were applied, the consistency ratio was found to be 0.004. Since this value is less than 0.10, the result is consistent.

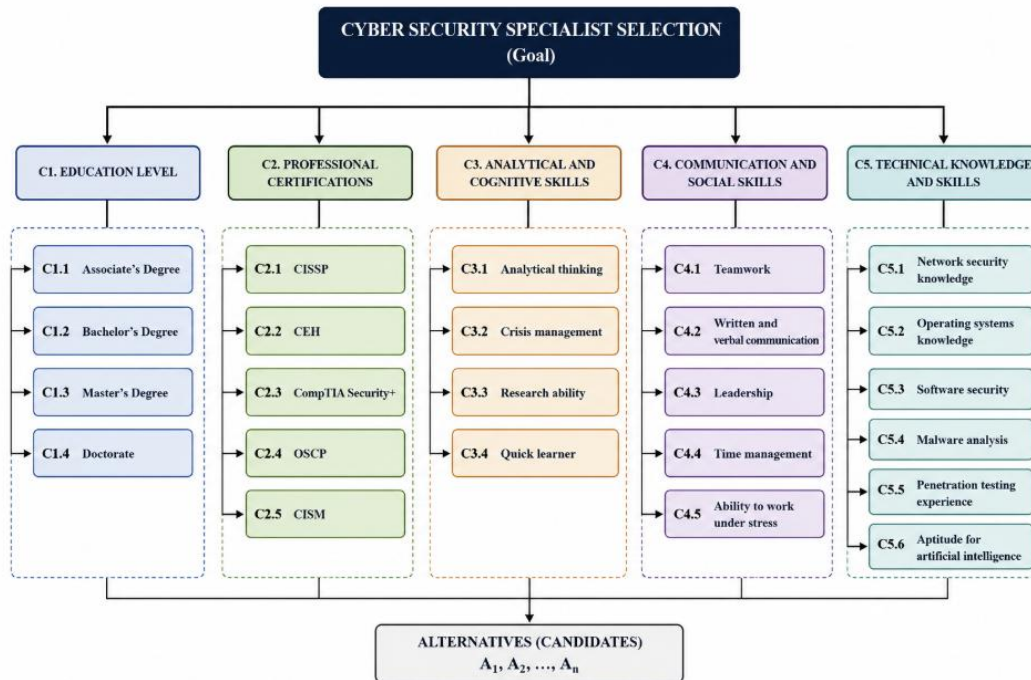


Figure 1. Hierarchical structure

Table 4. Pairwise comparison matrix of the main criteria

	C1	C2	C3	C4	C5
C1	1	0,500	0,200	0,250	0,143
C2	2	1	0,333	0,2	0,200
C3	5	3	1	2	0,500
C4	4	3	0,5	1	0,333
C5	7	5	2	3	1

Table 5. Normalized decision matrix for the main criteria

	C1	C2	C3	C4	C5
C1	0,053	0,040	0,050	0,039	0,066
C2	0,105	0,080	0,083	0,031	0,092
C3	0,263	0,240	0,248	0,310	0,230
C4	0,211	0,240	0,124	0,155	0,153
C5	0,368	0,400	0,496	0,465	0,460

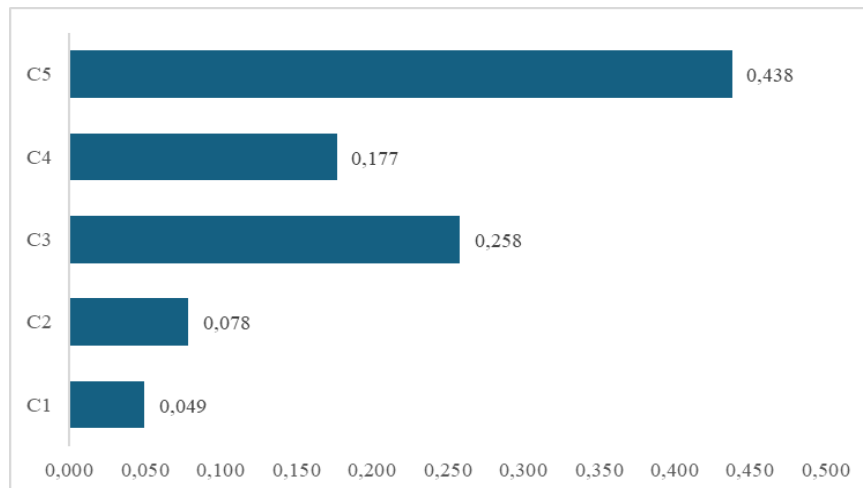


Figure 2. Main criterion weights

After the weights of the main criteria were calculated, the subcriteria for each main criterion were evaluated. The data related to the evaluation are presented in Table 6.

Table 6. AHP data for subcriteria

	C1.1	C1.2	C1.3	C1.4	local criteria weights		
C1.1	1	0,500	0,200	0,167		0,068	
C1.2	2	1	0,333	0,2		0,113	
C1.3	5	3	1	0,333		0,282	
C1.4	6	4	3	1		0,537	
	C2.1	C2.2	C2.3	C2.4	C2.5		
C2.1	1	5,000	3,000	0,500	6,000	0,304	
C2.2	0,2	1	0,250	0,2	3,000	0,079	
C2.3	0,333	4	1	0,333	3,000	0,157	
C2.4	2	5	3	1	7,000	0,414	
C2.5	0,167	0,333	0,333	0,143	1	0,045	
	C3.1	C3.2	C3.3	C3.4			
C3.1	1	4	7	9		0,597	
C3.2	0,250	1	5	7		0,270	
C3.3	0,143	0,2	1	3		0,089	
C3.4	0,111	0,143	0,333	1		0,044	
	C4.1	C4.2	C4.3	C4.4	C4.5		
C4.1	1	0,500	5,000	0,167	0,200	0,104	
C4.2	2	1	3,000	0,5	0,250	0,133	
C4.3	0,2	0,333	1	0,25	0,143	0,048	
C4.4	6	2	4	1	0,500	0,274	
C4.5	5	4	7	2	1	0,440	
	C5.1	C5.2	C5.3	C5.4	C5.5	C5.6	
C5.1	1	0,500	3	5	2	6	0,254
C5.2	2	1	4	6	3	8	0,390
C5.3	0,333	0,250	1	2	0,500	4	0,102
C5.4	0,2	0,167	0,5	1	0,333	3	0,063
C5.5	0,5	0,333	2	3	1	5	0,158
C5.6	0,167	0,125	0,25	0,333	0,2	1	0,033

Table 7. Sub-criterion weights

Main criteria	Sub-criteria	Weights
1. Level of Education (C1)	Associate's Degree	0.003
	Bachelor's Degree	0.006
	Master's Degree	0.014
	Doctorate	0.027
	CISSP	0.024
2. Professional Certifications (C2)	CEH	0.006
	CompTIA Security+	0.012
	OSCP	0.032
	CISM	0.004
	Analytical thinking	0.154
3. Analytical and Cognitive Competencies (C3)	Crisis management	0.070
	Research ability	0.023
	Quick learner	0.011
	Teamwork	0.018
	Written and verbal communication	0.024
4. Communication and Social Skills (C4)	Leadership	0.008
	Time management	0.048
	Ability to work under stress	0.078
	Network security knowledge	0.111
	Operating systems knowledge	0.171
5. Technical Knowledge and Competencies (C5)	Software security	0.045
	Malware analysis	0.028
	Penetration testing experience	0.069
	Aptitude for artificial intelligence	0.015

Finally, the global subcriterion weights were calculated by multiplying the local subcriterion weights by the main criterion weights. The subcriterion weights are presented in Table 7.

Results and Discussion

The problem of selecting a cyber security specialist at a financial company was addressed using the AHP method. The criteria in the problem were prioritized, and the results are presented in Figure 3. According to the analysis results, the sub-criterion with the highest weight is Operating System Knowledge (C5.2), with a weight of 0.171. This result indicates that it is considered a critical requirement for a cybersecurity specialist working in the financial sector to possess advanced knowledge of the security, configuration, and management of Windows, Linux, and Unix-based systems. Analytical Thinking (C3.1) ranks second, with a weight of 0.154. It is clear that analytical thinking skills play a major role in analyzing cyberattacks, incident response, threat hunting, and solving complex security problems. Network Security Knowledge (C5.1) (0.111) ranks third. Given the financial sector's high exposure to network-based attacks, proficiency in secure network architecture, firewalls, IDS/IPS systems, and network protocols emerge as a critical competency.

When the resulting global weights are evaluated together, it becomes evident that technical knowledge and experience are the most decisive factors in selecting cybersecurity specialists in the financial sector. In particular, knowledge of operating systems, analytical thinking, and network security emerged as the three most critical sub-criteria in the decision-making process. In contrast, educational level and certain professional certifications carry lower weights and are not decisive factors on their own in selecting a candidate. This situation demonstrates that the financial sector places greater emphasis on practical technical competencies, problem-solving skills, and qualities that can ensure operational success, rather than theoretical knowledge. These findings reflect the sector's need for experts with strong practical skills, analytical thinking, and the ability to make effective decisions in critical situations, given the rapidly evolving cyber threat landscape.

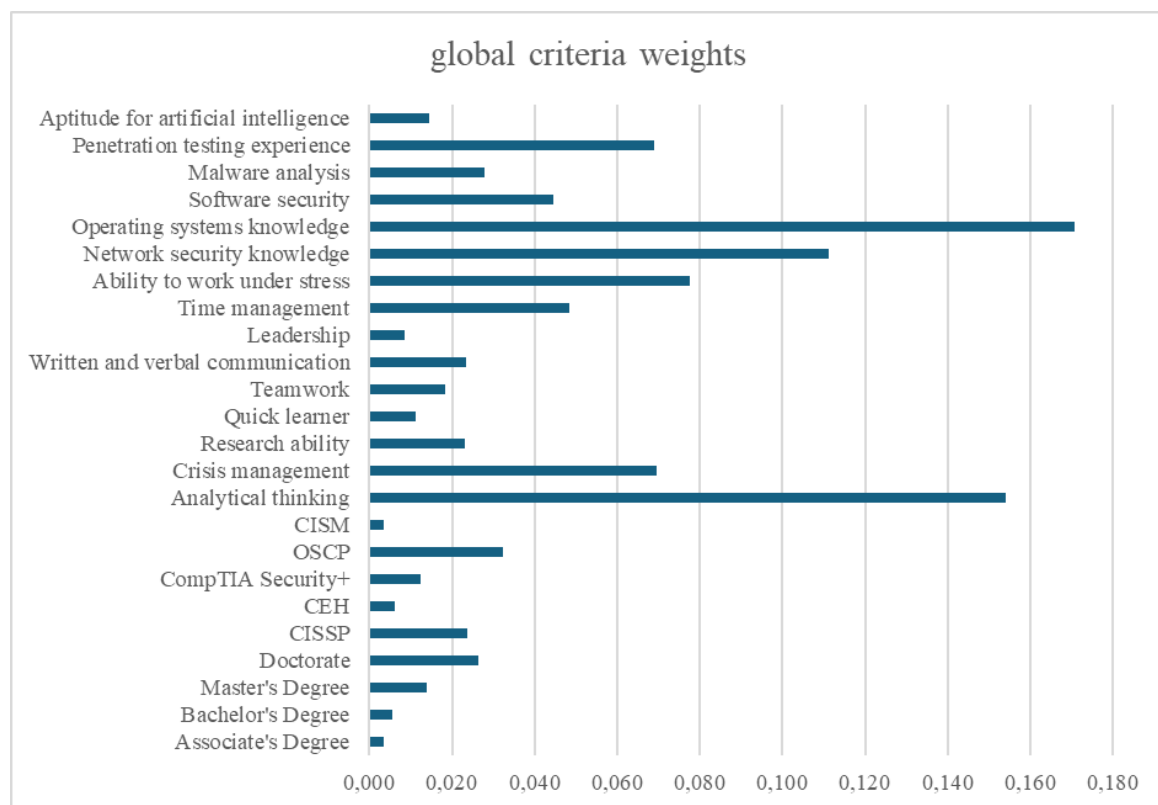


Figure 3. AHP results

Conclusion

In this study, which addresses personnel selection, the Analytic Hierarchy Process (AHP)—one of the multi-criteria decision-making methods—was used. The consistency indices obtained upon verification of the results

are presented in Table 8. Upon evaluation of the consistency indices, it was concluded that the results are consistent, as all values were less than 0.10.

Table 8. Consistency rates

Evaluation Criteria	Consistency Rate
Main Criteria	0,040
Education Level (C1)	0,017
Professional Certifications (C2)	0,060
Analytical and Cognitive Competencies (C3)	0,089
Communication and Social Competencies (C4)	0,088
Technical Knowledge and Competencies (C5)	0,024

This study, which addresses the problem of selecting cybersecurity specialists in financial companies, contributes to the literature in terms of its scope of application and the criteria used. While there is one study in the literature on the selection of cybersecurity specialists, there are no studies specifically addressing the financial sector. When evaluating the criteria, a maximum of 18 criteria were considered, including criteria such as certifications and aptitude for artificial intelligence, which are addressed for the first time in the literature. In this study, 24 sub-criteria were evaluated. From this perspective, it is a comprehensive study.

Recommendations

This study addresses the problem of selecting a cybersecurity specialist at a financial company. The problem consists of two stages. The first stage involves determining and weighting the criteria. In the second stage, the alternatives are evaluated based on these criteria. This study does not include the second stage. This stage, in which the alternatives are evaluated, could be added to the study. The study could be examined using fuzzy multi-criteria decision-making methods. Finally, a more comprehensive study could be conducted by identifying artificial intelligence tools for the “suitability for artificial intelligence” criterion.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Conflict of Interest

* The author declares that there is no conflict of interest.

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Enhancing Industrial Logistics Efficiency Through Lean and Simulation

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Abstract: This study presents an applied engineering approach to the reorganization and optimization of logistics operations in an industrial manufacturing environment. The research addresses inefficiencies identified in warehouse layout, internal transportation, production planning, and expedition processes within a construction materials facility. The primary objective was to enhance operational performance by reducing material handling waste, improving customer service levels, increasing safety conditions, and optimizing space utilization. A structured methodology was adopted, combining lean principles, inventory parameter revision, ABC classification, Kanban-based production control, layout redesign, and discrete-event simulation modeling. Time studies and value stream mapping were conducted to diagnose the current state and identify critical bottlenecks. Based on the findings, a new storage configuration organized by product rotation and production flow was implemented, along with standardized loading procedures and improved traffic circulation zones. A digital Kanban tool was developed to stabilize production planning and reduce variability in stock levels. To validate the proposed improvements, a simulation model was developed representing the current and redesigned systems. The results demonstrate a reduction of over 10 kilometers in daily forklift travel distance, nearly two hours of labor time saved per day, and a 28-second decrease in loading time per pallet. The findings confirm that integrating lean engineering practices with simulation technology enables measurable performance gains and supports data-driven decision-making in industrial logistics systems.

Keywords: Industrial engineering, Operations management, Arena simulation software, Lean logistics, Supply chain optimization.

Introduction

Industrial logistics plays a fundamental role in manufacturing competitiveness by ensuring that materials, products, and information flow efficiently throughout the production system. In many industrial facilities, however, warehouse layouts, storage policies, production planning, and internal transportation evolve incrementally in response to operational needs rather than through systematic engineering design. As a result, companies often experience excessive forklift travel, inefficient material handling, congestion in loading areas, unstable inventory levels, and underutilization of warehouse space. Although these inefficiencies may appear minor when analysed individually, their cumulative effect can significantly reduce productivity, increase operating costs, compromise safety, and negatively affect customer service.

Lean Manufacturing provides a structured framework for identifying and eliminating activities that do not add value to the customer. Within logistics operations, Lean principles have been widely applied to improve warehouse organization, material flow, inventory management, visual control, and process standardization. Tools such as Value Stream Mapping (VSM), ABC classification, Kanban systems, and standardized work contribute to reducing transportation, waiting times, excess inventory, and unnecessary movements. Nevertheless, implementing Lean improvements in complex logistics environments often involves substantial operational changes, making it difficult to predict their impact before implementation. Discrete-event simulation (DES) complements Lean methodologies by enabling engineers to analyse dynamic logistics systems, evaluate alternative operating scenarios, and quantify the expected benefits of proposed improvements without disrupting

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real operations. By modelling material flows, resource utilization, operational constraints, and process variability, simulation supports evidence-based decision-making and reduces the risks associated with layout modifications and process redesign. Consequently, the integration of Lean methodologies with simulation has emerged as an effective approach for improving manufacturing and warehouse performance.

Although previous studies have investigated Lean logistics, warehouse layout optimization, inventory control, Kanban systems, and discrete-event simulation independently, relatively few applied studies present an integrated engineering approach that combines these techniques within a real industrial environment and validates the proposed improvements through quantitative simulation. In particular, there remains a need for case studies demonstrating how layout redesign, inventory parameter revision, production planning, and standardized logistics procedures can be jointly implemented and evaluated using measurable operational indicators.

This paper addresses this gap through a case study conducted in a Portuguese construction materials manufacturing company. The research focuses on improving warehouse operations by integrating Lean engineering principles with discrete-event simulation. The proposed improvement programme combines warehouse layout redesign, ABC-based storage allocation, inventory parameter revision, digital Kanban implementation, standardized loading procedures, and traffic flow reorganization. To assess the effectiveness of these interventions, a simulation model was developed in Arena® Simulation Software, representing both the current and redesigned logistics systems under identical operating conditions. The study seeks to answer the following research questions:

- How can Lean tools be applied to identify and reduce waste in industrial logistics operations?
- How can warehouse layout redesign and ABC-based storage allocation improve material handling efficiency?
- To what extent can digital Kanban and revised inventory parameters contribute to more stable production planning?
- How can discrete-event simulation support the evaluation of logistics improvement initiatives before implementation?

The proposed improvements are assessed using key logistics performance indicators, including forklift travel distance, labour time, and pallet loading time. The results demonstrate substantial reductions in unnecessary internal transportation, improvements in warehouse organization and loading efficiency, and enhanced production planning stability. These findings illustrate the practical value of integrating Lean methodologies with simulation-based analysis to support data-driven logistics decision-making.

The main contribution of this research is the presentation of a comprehensive industrial engineering framework that combines Lean logistics practices and discrete-event simulation to redesign warehouse operations and quantitatively validate the expected operational improvements. Beyond its contribution to the academic literature, the study provides practitioners with a structured methodology that can be adapted to similar manufacturing environments seeking to improve logistics performance while minimizing implementation risk.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature on Lean logistics, warehouse optimization, inventory management, and discrete-event simulation. Section 3 describes the research methodology and case study. Section 4 presents the simulation model and discusses the experimental results. Finally, Section 5 summarizes the main conclusions, practical implications, limitations, and directions for future research.

Literature Review

Lean Logistics and Warehouse Optimization

Lean thinking seeks to maximize customer value by systematically eliminating activities that do not add value while promoting continuous improvement and flow efficiency (Womack & Jones, 1997). Within industrial logistics, Lean principles have been successfully applied to reduce transportation, waiting time, excessive inventory, unnecessary motion, and process variability through techniques such as Value Stream Mapping (VSM), standardized work, visual management, pull systems, and continuous improvement (Alejandro-Chable et al., 2024; Hines et al., 2004; Rother & Shook, 2003; Wronka, 2017).

Warehouse performance depends heavily on layout design, storage allocation, and material flow. Poorly designed warehouses increase travel distance, congestion, handling effort, and safety risks, whereas layouts based on

product flow and operational priorities improve accessibility, throughput, and resource utilization (Bartholdi & Hackman, 2014; Boysen et al., 2019; de Koster et al., 2007; Gu et al., 2010). Although these contributions remain foundational, recent research emphasizes that modern warehouses must also accommodate increasing product variety, shorter lead times, and greater operational flexibility (Boysen et al., 2019; van Gils et al., 2019).

ABC classification remains one of the most widely adopted approaches for warehouse optimization because it aligns storage locations with product movement frequency. High-rotation items are positioned closer to picking or shipping areas, reducing travel distances and material handling effort (Bartholdi & Hackman, 2014; Frazelle, 2016). Recent studies continue to demonstrate that ABC-based storage assignment contributes to improved warehouse productivity and more efficient resource utilization, particularly when combined with data-driven warehouse management systems (Kusrini et al., 2018; Zhen & Li, 2022).

Warehouse design must also consider safety and traffic management. Clearly defined circulation routes, appropriate segregation between pedestrians and forklifts, and efficient loading areas reduce congestion and improve operational reliability (Richards, 2014; Tompkins et al., 2010). Consequently, warehouse layout should be regarded as an integrated logistics system rather than merely a physical arrangement of storage locations.

Inventory Control and Digital Kanban

Effective inventory management balances product availability with inventory holding costs while supporting production stability and customer service (Chopra & Meindl, 2019; Silver et al., 2017). Inventory policies based on appropriate reorder points, safety stocks, lot sizes, and replenishment rules reduce stockouts, unnecessary inventory accumulation, and operational variability (Axsäter, 2015; Chopra, 2020). Since inventory decisions directly influence warehouse occupancy, production planning, and internal transportation, they should be integrated with logistics and warehouse management rather than treated as isolated planning activities (Jacobs & Chase, 2018; Martin Christopher, 2016).

Kanban systems complement inventory management by synchronizing production with actual consumption through pull-based replenishment mechanisms (Monden, 2012; Ohno, 1988). Unlike forecast-driven push systems, Kanban limits work-in-process inventory while improving production flow and coordination between manufacturing and logistics (Slack & Lewis, 2019). The effectiveness of Kanban depends on well-defined operating parameters and stable production processes (Lage & Filho, 2008; Thürer et al., 2016).

Recent advances in Industry 4.0 have extended traditional Kanban into digital environments. Digital Kanban systems improve information visibility, communication speed, and decision consistency by integrating enterprise information systems and real-time operational data (Buer et al., 2018; Rahardjo et al., 2023). This evolution reflects the broader concept of Lean 4.0, where digital technologies strengthen Lean implementation without replacing its fundamental principles (Kolberg & Zühlke, 2015; Mayr et al., 2018; Tortorella & Fettermann, 2018). Nevertheless, several authors emphasize that digitalization should support clearly identified operational problems rather than being implemented as an objective (Abi Saad et al., 2024; Ciano et al., 2021).

Discrete-Event Simulation for Logistics Improvement

Discrete-event simulation (DES) has become one of the most widely used techniques for analysing complex manufacturing and logistics systems because it allows alternative scenarios to be evaluated before physical implementation (Banks et al., 2010; Law, 2015; Robinson, 2014). By representing entities, resources, queues, operational constraints, and process variability, DES enables engineers to estimate system performance under realistic operating conditions while avoiding costly trial-and-error interventions.

Arena® Simulation Software is particularly suited to modelling warehouse and manufacturing operations due to its process-oriented architecture, which supports the representation of material flows, resource allocation, storage operations, loading activities, and internal transportation. Simulation outputs typically include waiting times, throughput, queue lengths, travel distances, and resource utilization, providing quantitative evidence for evaluating operational improvements (Law, 2015). Simulation has been extensively applied to warehouse management, material handling, production planning, and supply chain optimization (Detty & Yingling, 2000; Mourtzis, 2020; Negahban & Smith, 2014; Tako & Robinson, 2012). More recently, simulation has increasingly been integrated with digital manufacturing technologies, digital twins, machine learning, and reinforcement

learning to support data-driven logistics decision-making (Agalianos et al., 2020; De Vito et al., 2024; Kogler & Maxera, 2025; Leon et al., 2023; Skapinyecz, 2025; Wooley et al., 2025).

The complementary nature of Lean methodologies and simulation has been widely recognised. Lean identifies sources of operational waste and proposes process improvements, whereas simulation provides a quantitative framework for validating these improvements before implementation. Integrating both approaches enables organizations to reduce decision uncertainty, evaluate multiple alternatives, and support evidence-based logistics redesign.

Although previous studies have examined Lean logistics, warehouse optimization, inventory management, Kanban systems, and discrete-event simulation separately, fewer contributions have integrated these techniques within a single industrial case study while quantitatively validating the proposed improvements through simulation. This research addresses that gap by combining Lean logistics tools, inventory parameter optimization, warehouse layout redesign, digital Kanban, and discrete-event simulation into a unified framework for improving industrial logistics performance.

Methodology

Research Design

This research adopted a quantitative case study methodology integrating Lean engineering principles with discrete-event simulation (DES) to improve warehouse logistics in a Portuguese construction materials manufacturing company. The objective was to identify operational inefficiencies, redesign logistics processes, and quantitatively evaluate the proposed improvements before implementation.

The methodological framework consisted of six sequential phases (Figure 1): (i) diagnosis of the current logistics system; (ii) identification of operational waste; (iii) design of Lean improvement actions; (iv) development and validation of a discrete-event simulation model; (v) comparison of the current and proposed scenarios; and (vi) evaluation of operational performance using quantitative key performance indicators (KPIs).

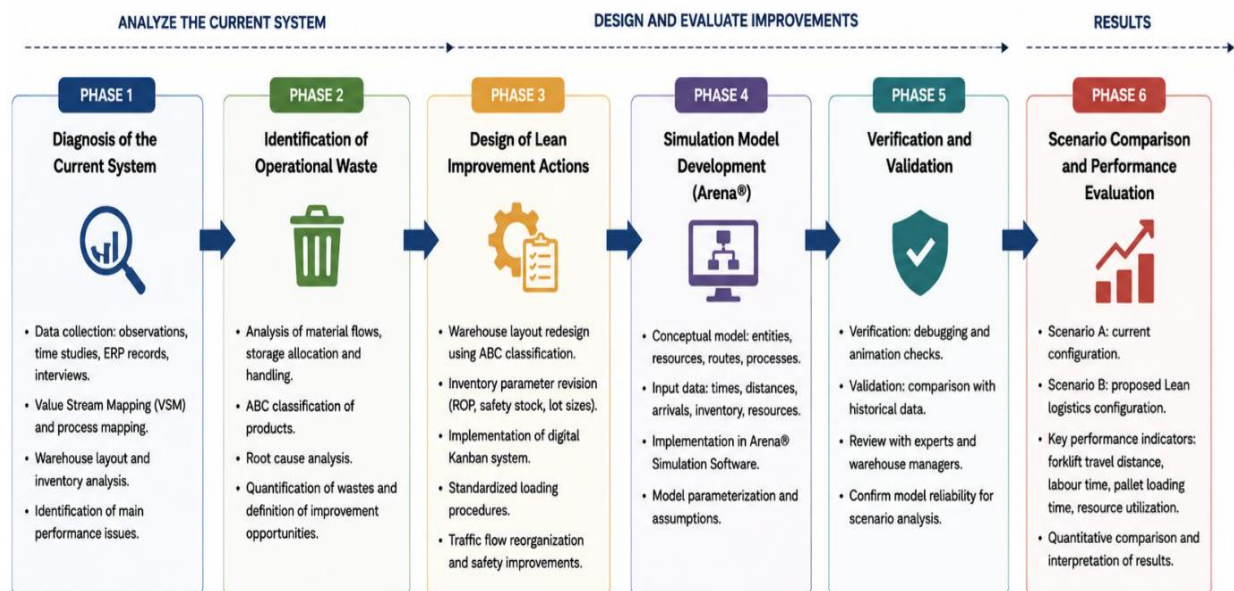


Figure 1. Summarizes the overall research framework adopted in this study

The methodology follows a structured engineering workflow that integrates Lean improvement techniques with discrete-event simulation to support evidence-based warehouse redesign. Each phase produces specific outputs that serve as inputs for the subsequent stage. Table 1 summarizes the objectives, techniques, and expected outcomes of each methodological phase. This structured approach combines process improvement techniques with simulation-based decision support, allowing engineering solutions to be assessed under realistic operating conditions while avoiding disruption to the actual production system.

Table 1. Research methodology

Phase	Objective	Main Techniques	Outputs
1. System Diagnosis	Understand the current logistics system	Direct observation, time studies, interviews, ERP data, Value Stream Mapping (VSM), process mapping	Current-state analysis and identification of operational issues
2. Waste Identification	Detect non-value-added activities	ABC classification, warehouse layout analysis, process analysis	Improvement opportunities and root causes of inefficiencies
3. Lean Improvement Design	Develop engineering solutions	Layout redesign, inventory parameter revision, Digital Kanban, standardized procedures, traffic flow redesign	Proposed Lean logistics configuration
4. Simulation Model Development	Build the DES model	Arena® Simulation Software, conceptual modelling, model parameterization	Validated simulation model of the logistics system
5. Verification and Validation	Ensure model reliability	Debugging, animation analysis, comparison with historical data, expert validation	Verified and validated simulation model
6. Performance Evaluation	Assess the proposed improvements	Scenario comparison, KPI analysis	Quantitative evaluation of operational performance improvements

Data Collection and System Diagnosis

Data collection was conducted over four consecutive weeks within the company's logistics department. Information was obtained through direct observation, time studies, interviews with warehouse supervisors and forklift operators, ERP production records, warehouse inventory reports, and customer dispatch records. The collected data included pallet production rates, forklift travel distances, loading times, truck arrivals, warehouse occupancy, inventory levels, production schedules, and product rotation frequencies. These data served both to diagnose the current logistics system and to parameterize the simulation model. The diagnosis combined Value Stream Mapping (VSM), process mapping, warehouse layout analysis, and ABC inventory classification. Five major sources of operational waste were identified:

- excessive forklift transportation;
- inefficient storage allocation;
- unnecessary material handling;
- congestion in loading areas;
- unstable production planning caused by outdated inventory parameters.

Among these issues, excessive forklift travel represented the largest proportion of non-value-added activities, largely because high-demand products were stored far from expedition areas. The analysis also revealed considerable variability in loading operations due to inconsistent working procedures and inefficient traffic circulation.

Lean Improvement Design

Based on the diagnosis, a set of complementary Lean improvement actions was developed to optimize material flow and warehouse performance. The warehouse layout was redesigned using ABC classification, relocating high-rotation products closer to loading docks while allocating low-demand products to more distant storage locations. Inventory policies were revised through adjustments to reorder points, safety stock levels, and production lot sizes in order to stabilize production planning and reduce inventory variability.

A digital Kanban system was introduced to synchronize production with warehouse consumption, replacing manual planning procedures with a pull-based replenishment mechanism. In addition, standardized loading procedures and dedicated forklift circulation routes were established to reduce process variability, eliminate unnecessary movements, and improve operational safety. Rather than implementing isolated improvements, the proposed solution integrates layout redesign, inventory optimization, visual production control, and process standardization into a unified logistics improvement framework.

Simulation Model Development

Following the design of the Lean improvement strategy, a discrete-event simulation (DES) model was developed using Arena® Simulation Software to evaluate the proposed logistics improvements before implementation. The conceptual model represents the complete warehouse logistics process, beginning with pallet production and ending with truck dispatch. Pallets and customer orders were modelled as entities, while forklifts, loading operators, and loading docks were defined as system resources. The model incorporates routing logic based on warehouse layout, product classification, loading priorities, and resource availability, thereby reproducing the operational behaviour of the real logistics system. Model input parameters were obtained from the operational data collected during the diagnosis phase. These included pallet production rates, forklift travel distances, loading times, truck arrivals, warehouse occupancy, inventory levels, and production schedules. Whenever appropriate, stochastic variables were represented using probability distributions fitted to the observed data, enabling the model to capture the variability inherent in warehouse operations. The Arena implementation followed the conceptual model without altering the observed logistics logic. The model was designed to support scenario analysis by allowing warehouse layouts, inventory policies, traffic routes, and loading procedures to be modified while maintaining identical operating conditions across experiments. Figure 2 presents the conceptual framework of the simulation model, while Figure 3 illustrates its implementation in Arena® Simulation Software.

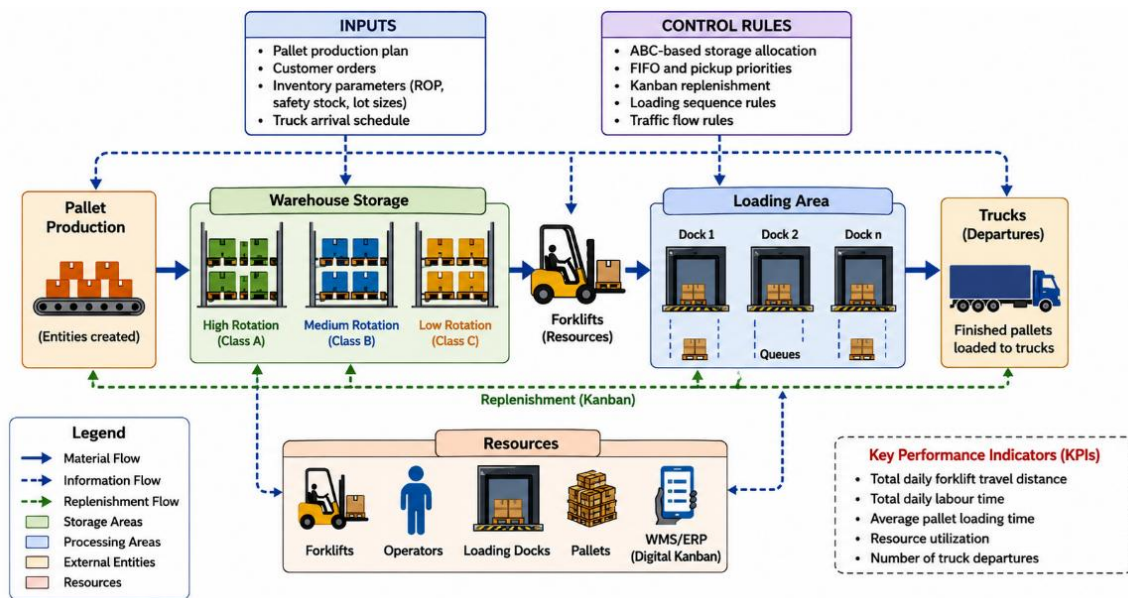


Figure 2. Conceptual model of the warehouse logistics system

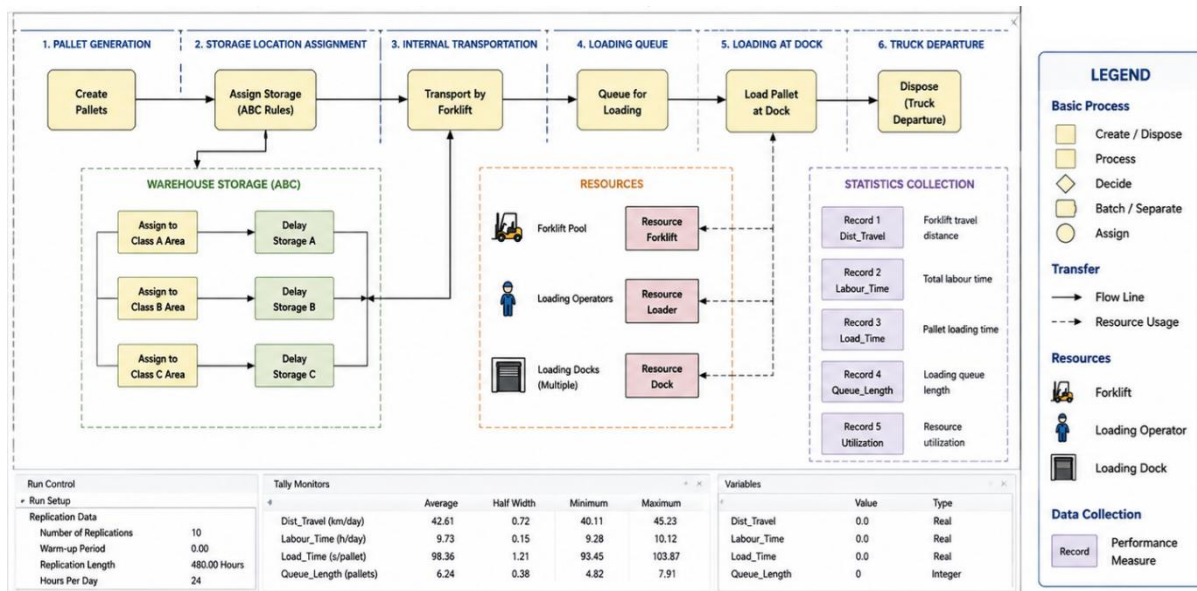


Figure 3. Arena simulation model implementation of the warehouse logistics system

Model Verification and Validation

Model credibility was established through both verification and validation procedures following recommended practices for discrete-event simulation studies. Verification was conducted throughout model development to ensure that the Arena implementation accurately reflected the conceptual model. This process included step-by-step debugging, animation analysis, logical consistency checks, and verification of entity routing, resource allocation, queue behaviour, and event sequencing. Multiple trial simulations were performed to confirm that the model operated without logical or computational errors.

Validation focused on assessing whether the simulation adequately represented the behaviour of the real logistics system. Simulation outputs for the current warehouse configuration were compared with historical operational data, including forklift travel distances, pallet loading times, and daily operational performance. In addition, the conceptual model, assumptions, and preliminary simulation results were reviewed with warehouse managers and logistics specialists to confirm that the model realistically represented actual operating conditions. The combined verification and validation procedures increased confidence that the simulation model was suitable for evaluating alternative warehouse configurations and supporting engineering decision-making.

Experimental Design

Two simulation scenarios were analysed:

- **Scenario A** - Current warehouse configuration.
- **Scenario B** - Proposed Lean logistics configuration incorporating layout redesign, revised inventory policies, digital Kanban, standardized loading procedures, and optimized forklift circulation.

Both scenarios used identical demand patterns, production schedules, and resource availability to ensure that any observed performance differences resulted exclusively from the proposed engineering improvements. The simulation experiments focused on three primary key performance indicators (KPIs):

- total daily forklift travel distance;
- total labour time required for warehouse operations;
- average pallet loading time.

Additional indicators, including warehouse flow efficiency and resource utilization, were analysed to support the interpretation of the simulation results.

Performance Evaluation

Simulation outputs obtained from the current and proposed scenarios were compared to quantify the operational impact of the proposed Lean interventions. The evaluation focused on reductions in non-value-added transportation, improvements in loading efficiency, labour savings, and overall warehouse performance. Percentage improvements were calculated for each KPI, allowing the effectiveness of the proposed logistics redesign to be objectively assessed.

The resulting performance indicators provide quantitative evidence supporting the implementation of the proposed warehouse configuration and demonstrate the value of integrating Lean methodologies with discrete-event simulation for industrial logistics optimization.

Results and Discussion

The simulation experiments compared the current warehouse configuration (Scenario A) with the proposed Lean logistics system (Scenario B) under identical operating conditions. Thirty independent simulation replications were performed for each scenario, and 95% confidence intervals were calculated for all key performance indicators (Table 2). This experimental design ensured that the observed differences resulted exclusively from the proposed engineering improvements rather than variations in demand or operational conditions.

Table 2. Comparison of logistics performance indicators obtained from the simulation of the current (Scenario A) and proposed (Scenario B) warehouse configurations

Performance Indicator	Unit	Current System (Scenario A)	Proposed System (Scenario B)	Improvement	Improvement (%)
Forklift travel distance	km/day	34.82	24.31	-10.51	-30.2%
Labour time	h/day	15.84	13.87	-1.97	-12.4%
Average loading time	sec/pallet	101.6	73.5	-28.1	-27.7%
Forklift utilization	%	86.4	74.1	-12.3 pp	-14.2%
Loading dock utilization	%	78.9	69.6	-9.3 pp	-11.8%
Throughput	pallets/day	214	219	+5	+2.3%
Average queue length	pallets	7.8	4.6	-3.2	-41.0%
Order completion time	min/order	46.2	37.4	-8.8	-19.0%

Table 2 summarizes the quantitative results obtained from the simulation experiments, while Figure 4 illustrates the relative percentage improvement achieved by the proposed Lean logistics configuration compared with the current warehouse system. The comparison demonstrates that the redesigned warehouse consistently outperformed the existing configuration across all evaluated key performance indicators (KPIs). Significant reductions were observed in internal transportation, labour requirements, loading time, queue length, and order completion time, while warehouse throughput was maintained and slightly increased. These results indicate that the proposed engineering interventions successfully eliminated non-value-added activities without compromising operational capacity.

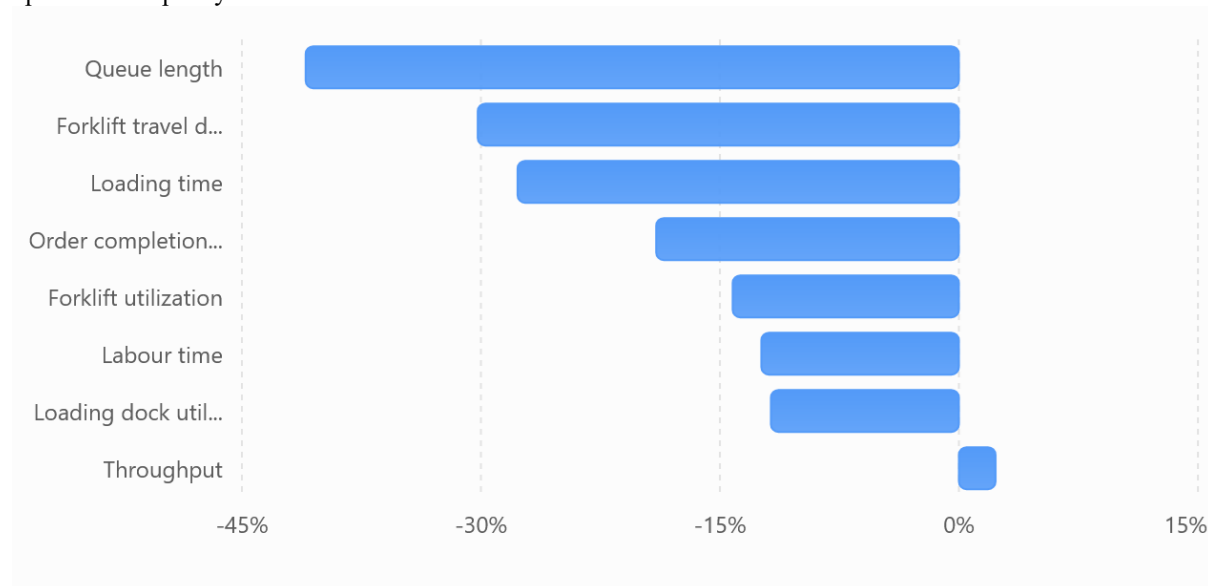


Figure 4. Percentage improvement of key logistics performance indicators

The observed improvements are not attributable to a single modification but rather to the combined implementation of complementary Lean initiatives, including warehouse layout redesign, ABC-based storage allocation, revised inventory parameters, digital Kanban implementation, standardized loading procedures, and optimized forklift circulation. The integration of these measures produced a more balanced logistics system, demonstrating the benefits of adopting a holistic engineering approach instead of isolated process improvements. The following subsections analyse each performance indicator individually and discuss the engineering implications of the observed improvements, relating the simulation results to Lean logistics principles and previous research.

Reduction of Internal Transportation

The most significant improvement was observed in daily forklift travel distance, which decreased from 34.82 km/day to 24.31 km/day, corresponding to a reduction of 10.51 km/day (approximately 30%). This reduction was primarily achieved through the relocation of high-rotation products closer to the expedition area using ABC-based storage allocation, together with the redesign of internal circulation routes.

From a Lean perspective, transportation represents one of the seven classical forms of operational waste (Ohno, 1988). The proposed warehouse layout directly addresses this source of waste by minimizing unnecessary movements while improving the proximity between storage locations and loading docks. Similar improvements have been reported by Bartholdi and Hackman (2014), who demonstrated that optimized storage allocation substantially reduces travel distances and material handling effort. Likewise, Zhen and Li (2022) observed significant productivity gains following warehouse layout optimization based on product rotation. Beyond reducing travelled distance, the redesigned layout is expected to decrease forklift operating time, equipment wear, energy consumption, and operator fatigue while simultaneously improving workplace safety through more organized traffic circulation.

Improvement of Labour Productivity

Total labour time decreased from 15.84 h/day to 13.87 h/day, representing a saving of 1.97 h/day (approximately 12%). This improvement was not associated with workforce reduction but rather with increased operational efficiency. Shorter travel routes, improved storage accessibility, standardized loading procedures, and reduced searching time collectively eliminated several non-value-added activities previously performed during warehouse operations.

These findings reinforce the central Lean principle that productivity improvements should be achieved by eliminating waste rather than increasing employee workload. Similar conclusions were reported by Alejandro-Chable et al. (2024), who demonstrated that integrating Lean logistics practices improves operational performance primarily through process redesign rather than additional resource investment. From a managerial perspective, labour savings of nearly two hours per operational day may be reallocated to value-adding logistics activities or provide additional operational flexibility during periods of higher demand.

Loading Performance

Average pallet loading time decreased from 101.6 s/pallet to 73.5 s/pallet, corresponding to an improvement of 28.1 seconds per pallet. Although the reduction for a single pallet appears relatively small, its cumulative impact becomes substantial when hundreds of pallets are dispatched each day. Faster loading operations reduce truck waiting times, improve dock availability, and increase warehouse responsiveness without requiring additional loading resources.

The observed improvement resulted from three complementary interventions: improved product positioning, reduced congestion near loading docks, and standardized loading procedures. This demonstrates that relatively simple organizational changes can generate measurable operational gains when implemented as part of an integrated Lean logistics strategy.

Resource Utilization and System Balance

The proposed warehouse configuration also produced a more balanced utilization of logistics resources. Forklift utilization decreased from 86.4% to 74.1%, while loading dock utilization decreased from 78.9% to 69.6%. Although lower utilization might initially appear undesirable, these results indicate a reduction in operational bottlenecks and provide additional capacity to accommodate demand variability without creating excessive queues or delays. Highly utilized logistics resources frequently become system bottlenecks, reducing operational flexibility and increasing the likelihood of congestion.

Consistent with this interpretation, the average queue length decreased from 7.8 to 4.6 pallets, while average order completion time was reduced from 46.2 to 37.4 minutes. These improvements demonstrate that the redesigned warehouse achieved smoother material flow and more balanced resource allocation throughout the logistics process.

Throughput Performance

An important observation is that warehouse throughput remained stable despite the substantial reduction in resource utilization. Daily throughput increased slightly from 214 to 219 pallets, indicating that the proposed

improvements enhanced operational efficiency without reducing production capacity. This finding confirms that the observed performance gains resulted from eliminating operational waste rather than reducing system workload. Similar conclusions have been reported in previous studies combining Lean principles with simulation-based analysis, where productivity improvements were achieved primarily through better process organization rather than increased resource availability (Detty & Yingling, 2000; Robinson, 2014). Maintaining throughput while reducing transportation effort and labour requirements represents one of the strongest indicators that the proposed engineering solution effectively improves warehouse performance.

Engineering Implications

The results demonstrate that significant logistics improvements can be achieved without major capital investment. Most of the observed gains resulted from redesigning warehouse layout, revising inventory parameters, implementing digital Kanban, and standardizing operating procedures rather than acquiring additional equipment or increasing staffing levels.

The study also confirms the complementary relationship between Lean methodologies and discrete-event simulation. Lean tools provided a systematic framework for identifying operational waste and designing improvement actions, whereas simulation enabled these alternatives to be quantitatively evaluated before implementation. This reduced implementation risk while providing objective evidence to support engineering decision-making.

Overall, the findings demonstrate that integrating Lean engineering practices with discrete-event simulation constitutes an effective and replicable methodology for improving warehouse logistics performance in manufacturing environments. The proposed framework may therefore serve as a practical decision-support approach for organizations seeking to optimize warehouse operations while minimizing operational disruption.

Conclusion

This study presented an integrated engineering approach to improving warehouse logistics in a construction materials manufacturing company through the combination of Lean methodologies and discrete-event simulation. The research addressed operational inefficiencies associated with warehouse layout, internal transportation, inventory management, production planning, and loading operations. By integrating Value Stream Mapping (VSM), ABC-based storage allocation, inventory parameter revision, digital Kanban implementation, standardized loading procedures, and warehouse layout redesign, a comprehensive logistics improvement strategy was developed and evaluated using Arena® Simulation Software.

The simulation results demonstrated that the proposed warehouse configuration generated measurable improvements across all analysed logistics performance indicators. Daily forklift travel distance was reduced by more than 10 km, labour requirements decreased by nearly two hours per day, and average pallet loading time was reduced by approximately 28 seconds. Additional improvements were observed in queue length, order completion time, and resource utilization, while warehouse throughput was maintained and slightly increased. These findings indicate that significant operational gains can be achieved through process redesign and improved material flow without requiring major capital investment or additional logistics resources.

Beyond the quantitative improvements, the study highlights the complementary roles of Lean engineering and discrete-event simulation. Lean methodologies provided a systematic framework for identifying operational waste and designing process improvements, whereas simulation enabled these improvements to be evaluated under realistic operating conditions before physical implementation. This integration reduced implementation uncertainty supported objective comparison between alternative logistics configurations, and provided quantitative evidence to support engineering decision-making. Consequently, the proposed framework extends previous research by demonstrating how multiple Lean practices can be combined within a single industrial improvement project and validated through simulation in a real manufacturing environment.

From a practical perspective, the proposed methodology offers manufacturing companies a structured and replicable approach for improving warehouse performance. The study demonstrates that optimizing warehouse layout, aligning storage locations with product rotation, revising inventory parameters, implementing digital Kanban systems, and standardizing logistics procedures can substantially improve operational efficiency while maintaining service levels. Because these improvements rely primarily on process redesign rather than additional

equipment, the proposed framework represents a cost-effective strategy that may be adapted to other industrial sectors with similar logistics characteristics.

This research is subject to several limitations. The study was conducted within a single manufacturing facility operating in the construction materials sector; therefore, the numerical results should not be generalized directly to other industrial contexts without considering differences in production processes, warehouse configurations, product characteristics, and demand patterns. Furthermore, the simulation model focused primarily on operational performance indicators and did not explicitly evaluate economic measures such as investment costs, maintenance requirements, energy consumption, or environmental impacts. Incorporating these dimensions could provide a more comprehensive assessment of logistics improvement projects.

Future research may extend the proposed framework by integrating digital twins, real-time warehouse monitoring systems, Internet of Things (IoT) technologies, autonomous guided vehicles (AGVs), machine learning algorithms, and reinforcement learning techniques to support adaptive warehouse optimization. Additional case studies involving different manufacturing sectors would also contribute to validating the broader applicability of the methodology and further strengthen the evidence supporting the integration of Lean engineering principles with simulation-based decision support.

Overall, the results confirm that combining Lean logistics practices with discrete-event simulation provides a robust engineering methodology for warehouse redesign and logistics optimization. The proposed approach enables organizations to evaluate improvement alternatives before implementation, reduce operational risk, and support data-driven decision-making, thereby contributing to more efficient, flexible, and sustainable industrial logistics systems.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Conflict of Interest

* The author declares that there is no conflict of interest.

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Synthesis and Characterization of S-Triazine-Schiff Bases and Transition Metal Complexes

Ziya Erdem Koc
Selcuk University

Abstract: In this study, a new synthetic route for preparing multidirectional ligands was developed by using as starting material 2-chloro-4,6-diamino-1,3,5-triazine (CDAT) core. In the synthesis of new triazine centered dipodal Schiff bases have been synthesized via condensation reactions between 1 equiv. (CDAT) and 2 equiv. aldehyde molecules according to the methods mentioned in published literature. (CDAT) has been reacted with 2-hydroxybenzaldehyde (SA) molecule in the presence of acetic acid and acetone to get 2-chloro-4,6-N,N'-bis(2-hydroxybenzylidene)-1,3,5-triazine (CDATSA). On the other hand, pentadentate (ONNNO) Schiff bases, mononuclear [Fe(CDATSA)Cl] have been gained via the reaction with nonaqueous FeCl₃. The complexes were characterized as high spin d⁵ (S = 5/2) distorted trigonal bipyramidal. As a result, ligand has been characterized by FT-IR and ¹H-NMR. Structures of isolated monomers have been clarified with the analysis of FT-IR and elemental analysis and data of magnetic susceptibility.

Keywords: Schiff base, Dipodal, 2-Chloro-4,6-diamino-1,3,5-triazine, Metal complexes.

Introduction

Schiff bases, also referred to as imines, constitute an important class of compounds formed through the condensation of primary amines with aldehydes or ketones, making them valuable intermediates in synthetic organic chemistry (Koç, 2011). The characteristic imine (C=N) linkage is generated via a reversible dehydration reaction between amino and carbonyl groups, imparting dynamic covalent behavior to these molecules. Owing to their excellent coordination ability, Schiff bases readily chelate a wide variety of transition metal ions, and their corresponding metal complexes have become indispensable in coordination chemistry and bioinorganic research. Extensive investigations over recent decades have demonstrated that Schiff bases and their metal complexes possess broad practical importance (Jayabalakrishnan et al., 2002). They have found applications in analytical chemistry, radioactive material separation, medicinal chemistry, polymer and dye industries, and plastic manufacturing. In addition, their diverse biological and pharmacological properties have attracted considerable scientific interest (Arslaner et al., 2017; Ugras et al., 2006). Iron(III) coordination compounds have remained an active research area over the past two decades, particularly because high-spin Fe(III) complexes exhibit interesting magnetic and structural properties (Gembicky et al., 2000). Our previous studies have focused on the synthesis and characterization of several s-triazine-based coordination compounds (Koç & Uysal, 2010; Uysal & Koç, 2010). Building upon these investigations, the present work describes the preparation of novel Fe(III) complexes incorporating Schiff base ligands derived from CDAT. The Schiff base ligand (CDATSA) was synthesized through the condensation reaction between CDAT and the corresponding salicylaldehyde (SA), as illustrated in Scheme 1. Subsequent coordination of CDATSA with FeCl₃ afforded the mononuclear high-spin Fe(III) complex, [Fe(CDATSA)Cl] (Scheme 2). The synthesized ligands and their corresponding complexes were comprehensively characterized using elemental analysis, FT-IR spectroscopy, ¹H NMR spectroscopy, and magnetic susceptibility measurements, confirming the proposed molecular structures.

Experimental

Materials and Methods

The chemicals were purchased from Aldrich and Merck was used as received. Melting points were measured using an Optimelt Automated Melting Point System (Digital Image Processing Technology) SRS apparatus (Nyköping-Sweden). Elemental analyses (C, H, N) were performed using a Leco, CHNS-932 model analyzer (Massachusetts, USA). ^1H NMR spectra were recorded by the Varian, 400 M spectrometer at room temperature. (California, USA). FT-IR spectra were recorded using a Perkin-Elmer Spectrum 100 with Universal ATR Polarization Accessory (Shelton, USA). Magnetic susceptibilities of the metal samples were measured at 296 K using a Sherwood Scientific MX Gouy magnetic susceptibility apparatus (Gouy method) with $\text{Hg}[\text{Co}(\text{SCN})_4]$ as a calibration by the constant magnetic field. The effective magnetic moments, μ_{eff} , per metal atom were calculated from the expression, $B.M.$, where χ_M is the molar susceptibility (Cambridge, UK). TGA analyses of the compounds were performed on the Mettler Toled *Third Level Headings*

Synthesis of 2-Chloro-4,6-*N,N'*-bis(2-hydroxybenzylidene)-1,3,5-triazine (DACTSA)

2-Hydroxybenzaldehyde (2 mmol, 0.27 g) is dissolved in 30 mL of acetone. 2 drops of acetic acid are added and mixed. Then, 2-chloro-4,6-diamino-1,3,5-triazine (1 mmol, 0.14 g) is dissolved in 15 mL of acetone and added to the solution. The mixture is stirred at 90°C for 8 hours. When the reaction is complete, the light green precipitate is separated with filter paper, leaving behind a blue band. The obtained filtrate is left to crystallize. After filtration, light green powder is obtained and dried in an oven. M.P.: 130°C ; 87%, FT-IR (cm^{-1}) 3492 (OH), 1655 ($\text{CH}=\text{N}$), 1578 ($\text{C}=\text{N}_{\text{triazin}}$). ^1H NMR ($\text{DMSO}-d_6$) δ 10.88 (s, 2H), 10.61 (s, 2H), 9.82 (s, 2H), 7.51-6.30 (m, 6H).

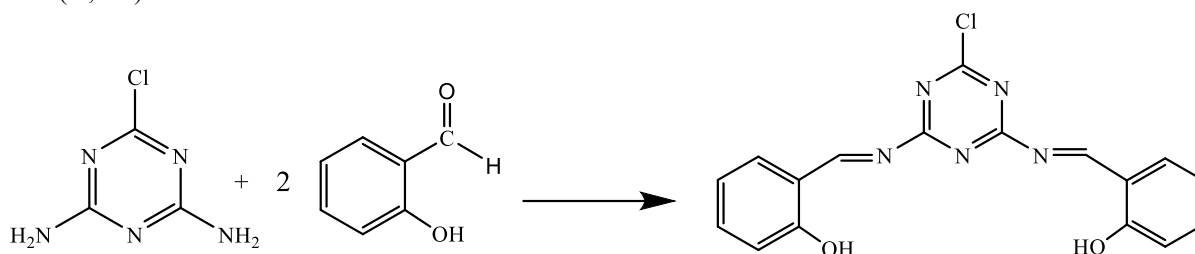


Figure 1. Synthesis of (CDAT) ligand

The Fe(III) complex of 2-chloro-4,6-*N,N'*-bis(2-hydroxybenzylidene)-1,3,5-triazine [$\text{Fe}(\text{CDATSA})\text{Cl}$]

(CDATSA) (1 mmol, 0.38 g) is dissolved in 20 mL of acetone. Then, FeCl_3 (1 mmol, 0.16 g) solution dissolved in 20 mL ethanol is added. It is mixed under reflux at 100°C for 4 h. The resulting black precipitate is filtered and dried in a vacuum desiccator. E.n.: $>350^\circ\text{C}$; %70, FT-IR (cm^{-1}) 1650 ($\text{CH}=\text{N}$), 1570 ($\text{C}=\text{N}_{\text{triazin}}$).

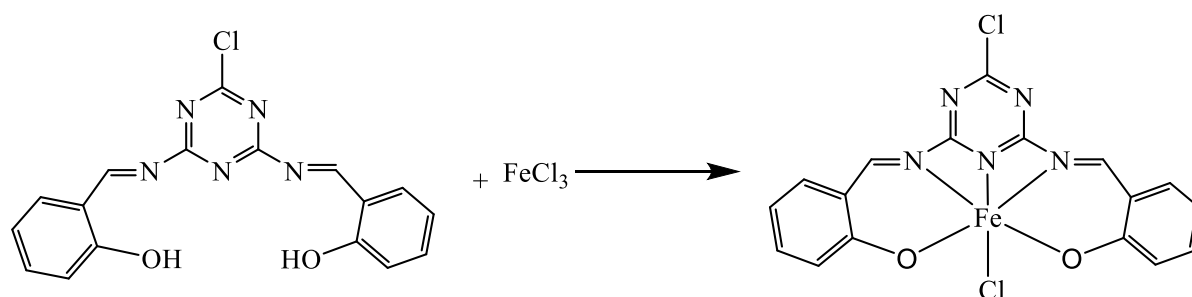
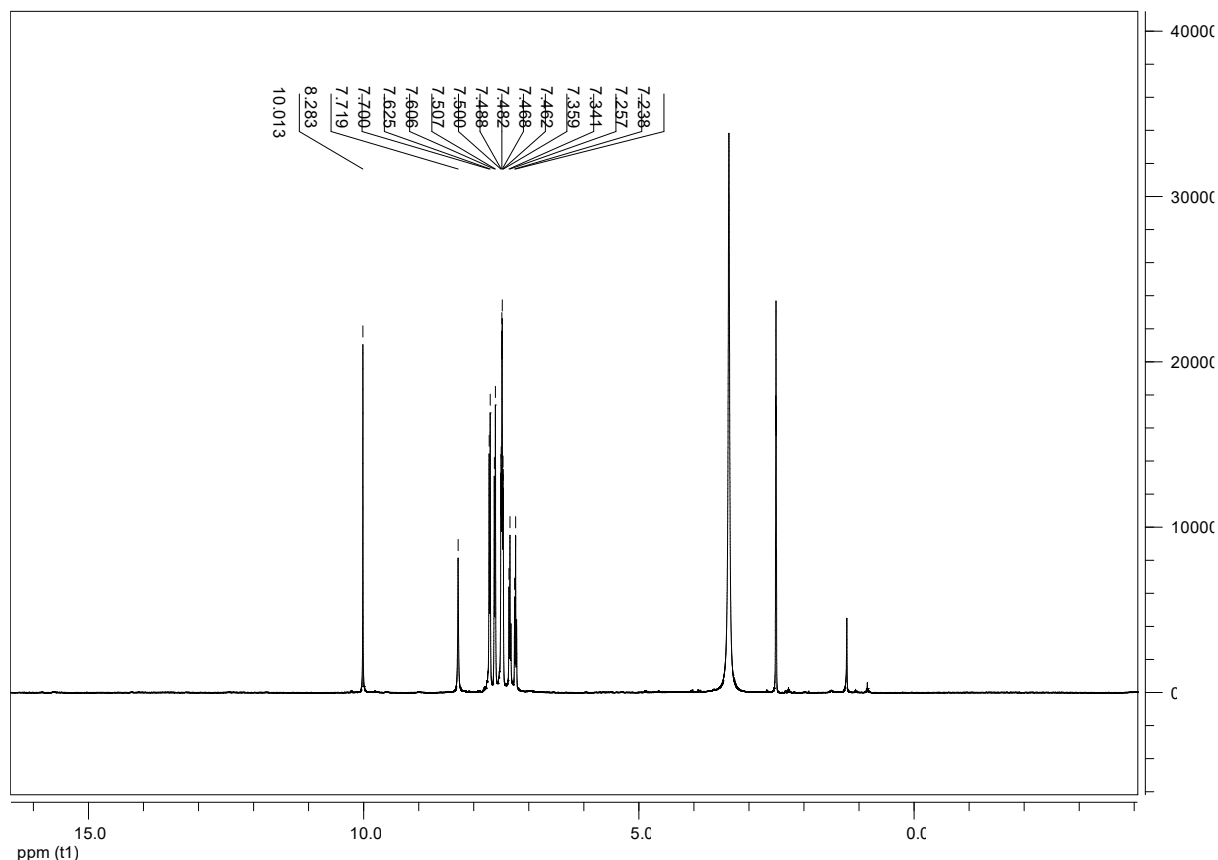


Figure 2. [$\text{Fe}(\text{CDATSA})\text{Cl}$] complex

Results and Discussion

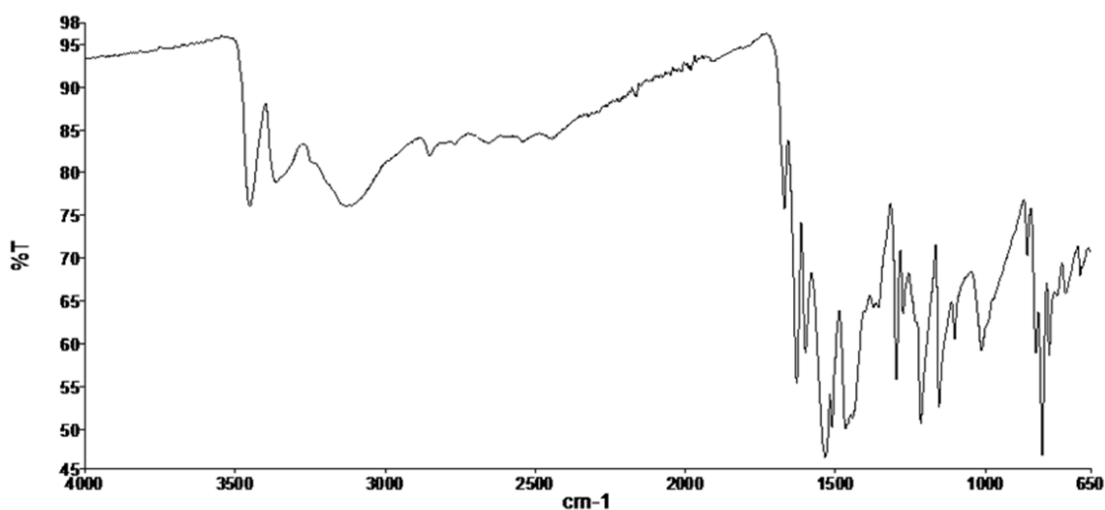
In this study, heterocyclic Schiff base monomer 2-chloro-4,6-*N,N'*-bis(2-hydroxybenzylidene)-1,3,5-triazine (CDATSA) was synthesized by the reaction of 2-chloro-4,6-diamino-1,3,5-triazine (CDAT) and 2-hydroxybenzaldehyde [SA], which was used as the output material. A single oxygen-coordinated monomer

complex obtained with the synthesized $[\text{Fe}(\text{CDATSA})\text{Cl}]$ complex was obtained. ^1H NMR spectrum of the monomer ligand OH protons (DACTSA) observed a corresponding singlet chemical shift value of 10.01 ppm. In addition, aromatic CH was observed to be 7.24-7.72 ppm and 8.28 ppm respectively at $\text{CH}=\text{N}$ singlet chemical shift. (Tahmassebi & Sasaki, 1998).



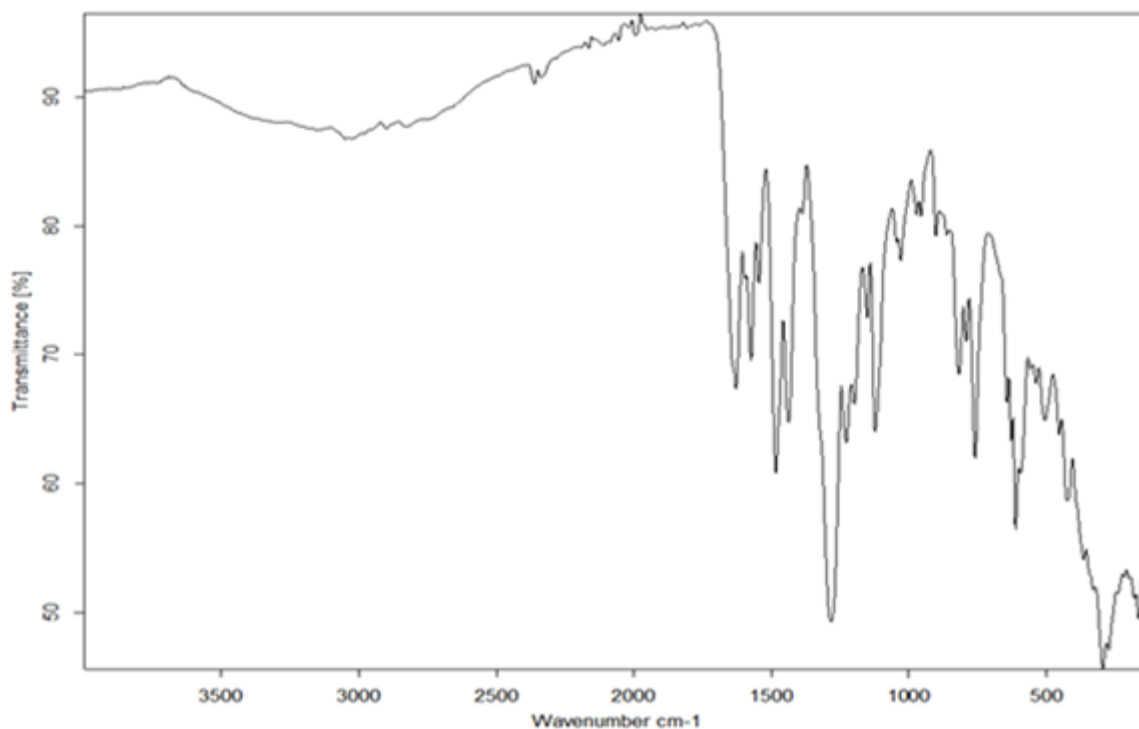
Scheme 1 ^1H NMR spectrum of the monomer ligand (CDAT)

FT-IR spectra of the compounds were obtained. The obtained monomer ligand and their FT-IR spectral data of the Fe(III) complex are given in the experimental section. When we examine these values; OH peaks, which were not found in the input materials of the monomer ligand, were observed as $\text{OH } 3492 \text{ cm}^{-1}$ because of the condensation reaction with 2-hydroxybenzaldehyde in the $\text{C}=\text{N}$ group 1655 cm^{-1} . In addition, it was observed that the OH peaks of the compounds coordinated with a single oxygen were lost. In Salen complexes, M-O and M-N bonds were also observed at $750\text{-}840 \text{ cm}^{-1}$ and $755\text{-}680 \text{ cm}^{-1}$, respectively (Koc ve Ucan, 2007).



Scheme 2. FTIR spectrum of the monomer ligand (DTMP)

All the magnetic moments of the complexes were measured at room temperature. Based on spectral evidence, the magnetic moment values metal atom of monomer $[\text{Fe}(\text{CDATSA})\text{Cl}]$ complex show paramagnetic behavior with a magnetic susceptibility value atom: 5.25, respectively. B.M. in which the Fe(III) cations have an approximately octahedral environment. The magnetic behavior of Fe(III) complexes is in good harmony with the proposed mononuclear structures.(Koc & Ucan, 2008).



Scheme 3. FTIR spectrum of the $[\text{Fe}(\text{CDATSA})\text{Cl}]$

Conclusion

In this study, 2-chloro-4,6-diamino-1,3,5-triazine (**CDAT**) was used as the starting material. (**CDAT**) reacted with the addition of 2-hydroxybenzaldehyde in the presence of acetone to obtain 2-Chloro-4,6-N,N'-bis(2-hydroxybenzylidene)-1,3,5-triazine (**CDATSA**). Complexation was carried out with the obtained (**CDATSA**). anhydrous FeCl_3 . In addition, Schiff base compounds with different donor groups were synthesized by the condensation of these aldehyde and amine group molecules. Its monodirectional Fe(III) mono homonuclear complexes.

Recommendations

The introductory substances used in this study are ligands and complexes that are newly studied and not encountered in literature. We think that the obtained ligands and complexes will gain importance especially in terms of environmental chemistry. In addition, in our studies that progress as molecular magnetic materials due to their magnetic properties, new and more usable properties will be examined by focusing more on this issue.

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Magnetically Recoverable Fe–Co–N Functionalized Pomegranate Peel–Derived Pyrolyzed Hydrochar for High-Efficiency Malachite Green Remediation: Integrated Kinetic, Isotherm, and Mechanistic Insights

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Abstract: In this study, waste biomass was strategically valorized to fabricate a magnetically recoverable Fe–Co–N functionalized pyrolyzed hydrochar (Fe–Co–N/HCpp) composite derived from pomegranate peel via a two-stage thermal treatment (300/700 °C), and its performance for Malachite Green (MG) removal from aqueous media was systematically investigated. FT-IR, XRD, SEM and EDX analyses comprehensively elucidated the structural, chemical, and morphological characteristics, confirming effective surface functionalization and successful heteroatom incorporation. The synthesized composite exhibited pronounced magnetic responsiveness, enabling rapid and straightforward adsorption without secondary contamination. Batch adsorption experiments were conducted to assess MG removal efficiency as a function of contact time, adsorbent dosage, initial dye concentration, and solution pH. Equilibrium and kinetic data were rigorously analyzed using established isotherm and rate models to clarify the governing adsorption mechanism. The results revealed that MG removal efficiency significantly increased with increasing pH, attaining a maximum at pH 8, while adsorption capacity increased proportionally with higher initial dye concentrations due to the enhanced mass-transfer driving force. Equilibrium data were best described by the Langmuir isotherm, yielding a maximum monolayer adsorption capacity of 333.40 mg g⁻¹, whereas kinetic analysis demonstrated superior conformity to the pseudo-second-order model. The adsorption system reached equilibrium within 45 min, during which most accessible active sites became saturated, as evidenced by the negligible additional uptake beyond this contact duration. The outstanding adsorption performance of the composite is attributed to synergistic contributions from electrostatic interactions, π – π electron donor–acceptor interactions between aromatic dye molecules and the carbonaceous matrix, surface complexation mechanisms, and coordination interactions involving Fe–Co catalytic centers. Overall, the findings indicate that fruit peel biomass can be effectively transformed into an environmentally sustainable, cost-efficient, and high-performance magnetic adsorbent, offering a promising alternative to commercial adsorbents for advanced wastewater treatment applications.

Keywords: Pomegranate peel, Hydrochar, Fe-Co, Malachite green, Urea

Introduction

Dye-contaminated effluents remain an important environmental concern because they reduce light penetration, suppress photosynthesis, alter oxygen demand and other water-quality parameters, and exert acute or chronic toxicity across aquatic biota. In addition, some dyes and dye-derived products continue to raise mutagenic, carcinogenic, and teratogenic concerns, with potential human exposure occurring through contaminated water,

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irrigated soils, and food webs (Islam et al., 2025). One of the most widely used industrial dyes and organic contaminants that can be discovered in water is malachite green (MG) dye. MG is employed as a food colorant and dyeing agent in the food and textile sectors (Oladoye et al., 2023). MG remains a high-priority model contaminant because it is a cationic dye with persistent use histories in textile and related industrial streams, and because recent researches still describe it as environmentally hazardous, toxic, and genotoxic/mutagenic, with continued concern over contaminated wastewaters (Oladoye et al., 2023; Wang et al., 2022).

Pomegranate peel is a logical precursor since it is an plentiful agro-industrial waste that has already been confirmed in numerous nearby carbon-material studies. Sassi et al. (2023) demonstrated that pomegranate-peel biochar can exhibit a high surface area, mesoporous structure, and effective dye uptake capacity. Similarly, Mussa et al. (2025) reported that pomegranate-peel biochar showed strong MG-specific adsorption, achieving 99.85% removal under optimized batch conditions. Pomegranate peel is a promising precursor for MG-relevant adsorbents.

Typical hydrothermal carbonization (HTC) operates at about 180–250 °C under autogenous pressure sufficient to keep water liquid, commonly reported as roughly 10–50 bar, with residence times from about 2 to 12 hours (Khan et al., 2022). Pomegranate peel may be transformed into hydrochar through microwave-assisted hydrothermal carbonization at 200°C for 1 hour, yielding a porous, amorphous material with quantifiable surface charge characteristics and abundant oxygenated functionality, according to Hessien (2022). Accordingly, converting raw pomegranate peel into hydrochar and subsequently into pyrolyzed hydrochar offers a rational strategy for balancing the oxygen-containing surface functionalities generated during hydrothermal processing with the enhanced aromaticity and pore development typically associated with high-temperature carbonization (Mussa et al., 2025).

Recent studies indicate that magnetic hydrochars and magnetized plant-based adsorbents can enhance contaminant uptake by introducing additional active sites and distinctive interfacial chemistry, while also improving adsorbent handling and reducing downstream separation challenges. Although iron oxides remain the most widely used magnetic components because of their stability and relatively low toxicity, more advanced metal configurations may offer additional benefits. In particular, Fe-containing phases provide magnetic responsiveness and metal-related complexation sites, while Co can act synergistically with Fe in bimetallic carbon systems and promote structural ordering of the carbon matrix. Nitrogen doping provides an additional level of functionality by generating defect-rich, electronically modulated surfaces, influencing pore development, and stabilizing chemically diverse binding sites (Zhang et al., 2023; Hu et al., 2025).

Recent MG adsorption studies indicate that the underlying mechanism is governed by multiple concurrent interactions rather than a single dominant pathway. Recurring contributions include pore filling, electrostatic attraction between cationic MG and deprotonated adsorbent surfaces, π - π stacking between the aromatic structure of MG and carbon domains, hydrogen bonding, hydrophobic interactions, n - π interactions, functional-group complexation, and, in some cases, ion exchange. Magnetic hydrochars further expand this mechanistic understanding by highlighting surface complexation and metal-assisted interfacial interactions as important contributors in magnetic carbon-based adsorbents. The most rigorous mechanistic hypothesis is that Fe-Co-N functionalization may enhance MG uptake through the combined effects of pore architecture, defect-rich N sites, aromatic carbon domains, pH-dependent electrostatic interactions, and metal-associated binding. At the same time, the magnetic phase may improve adsorbent recovery and reuse, rather than functioning merely as a passive additive (Meng et al., 2025).

This research aims to functionalize the hydrochar produced from pomegranate peel waste through hydrothermal carbonization followed by pyrolysis with Fe-Co-N to create a magnetic adsorbent that is highly surface reactive and simply recoverable using an external magnetic field. The efficacy of magnetic Fe-Co-N functionalized nanocomposite (Fe-Co-N/HCpp) in removing MG, a harmful and cationic dye, from aqueous environments in terms of adsorption capacity, kinetic behavior depending on contact time, equilibrium isotherms, thermodynamic behavior, and reusability after numerous uses will then be thoroughly assessed.

Materials and Experimentation

Iron(III) chloride hexahydrate ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$), cobalt(II) chloride hexahydrate ($\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$), urea ($\text{CO}(\text{NH}_2)_2$) and KOH were obtained from Merck (Darmstadt, Germany). Malachite Green (MG) dye was obtained from Acros Organics (New Jersey, USA). All chemicals used in the experiments were of analytical purity. The biomass was purchased from a local market in Turkey and used to prepare an adsorbent. A pH700 glass-electrode pH meter

from Apera Instruments, a PSU-10 orbital shaker from Biosan, and an FN 500 oven from Nüve were used to prepare the hydrochar. The concentration of MG was measured using a Shimadzu UV-1700 UV–Vis spectrophotometer. FT-IR spectra were recorded with a Thermo Scientific Nicolet iS20 spectrometer, while XRD analysis was performed using a Europe model X-ray diffractometer. The microstructure of the adsorbent was examined using a scanning electron microscope (SEM, Zeiss Gemini SEM 500).

Preparation of Raw Material and Hydrochar

Pomegranate peels (PP) were manually separated from the fruit, thoroughly washed with deionized water to remove surface impurities, and subsequently dried. The dried biomass was initially pulverized using a laboratory mill and passed through a sieve to ensure particle homogeneity. The resulting powder was repeatedly washed with 0.1 mol L⁻¹ HCl and subsequently rinsed with distilled water before being dried at room temperature for 24 h. Then, the dried biomass and deionized water were charged into a stainless-steel autoclave reactor. Hydrothermal carbonization was carried out at 200 °C for 8 h in a temperature-controlled oven. After cooling to room temperature, the obtained hydrochar sample was washed with 0.1 M HCl and rinsed with ultra-pure water until a neutral pH was reached. Finally, the product was oven-dried, ground in a laboratory grinder, and fractionated using a sieve to obtain a definitive particle size range of 200 µm for subsequent composite synthesis.

Synthesis of Adsorbent

The magnetic Fe–Co–N functionalized hydrochar nano-composite (Fe–Co–N/HCpp) was synthesized using a two-stage thermal method. In the first stage, a mixture of pomegranate-derived hydrochar, urea, FeCl₃·6H₂O, and CoCl₂·6H₂O in an aqueous solution was prepared, and this mixture was thermally treated at 300 °C for 1 h to convert the composite into a metal/nitrogen-doped hydrochar intermediate. In the second stage, the resulting intermediate was pyrolyzed in the presence of KOH at 700 °C for 1 h to successfully obtain a nano-composite structure with high porosity and strong magnetic susceptibility. Finally, the synthesized Fe–Co–N/HCpp was washed with pure water and dried in an oven at 60 °C (Figure 1.).

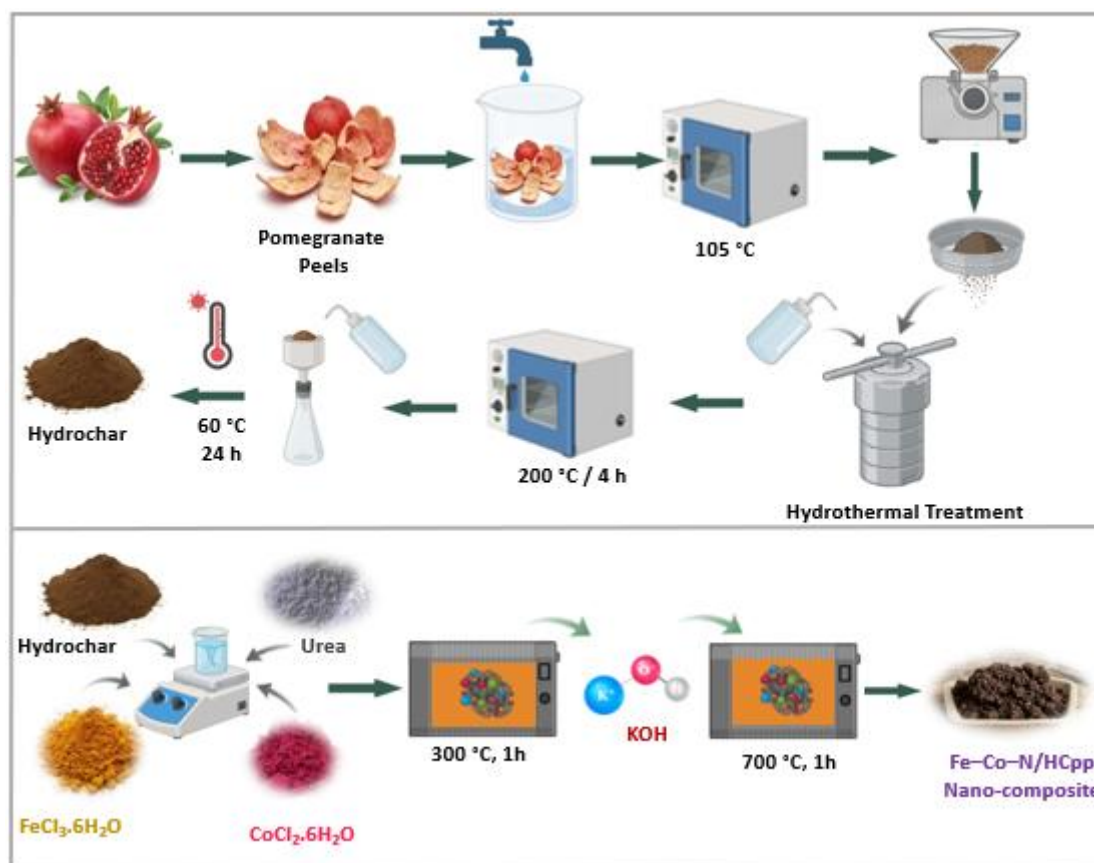


Figure 1. Fe-Co-N/HCpp nano-composite synthesis.

Batch Adsorption Experiments

Batch adsorption experiments for MG removal were systematically carried out in temperature-controlled batch reactors at 25 °C. All analyses were performed in duplicate to ensure the accuracy, reliability, and reproducibility of the experimental findings. Initially, a starting MG concentration of 200 ppm was used; subsequently, various operating parameters were optimized to evaluate their effects on the adsorption capacity and efficiency of Fe–Co–N/HCpp. In this study, the effects of solution pH (3–9), initial MG concentration (100–800 mg L⁻¹), adsorbent amount (0.005–0.04 g), contact time (5–240 min), and reaction temperature (25–45 °C) on MG removal were systematically investigated. After the completion of the adsorption process, the MG concentration remaining in the filtrate was measured at regular intervals using a UV-vis spectrophotometer. The equilibrium adsorption capacity (q_e , mg g⁻¹) and percentage removal efficiency (%) of the composites were determined based on the difference between the initial and final MG concentrations, as expressed in Eqs. (1) and (2).

$$q_e = \frac{(C_o - C_e)V}{m} \quad (1)$$

$$Removal(\%) = \frac{(C_o - C_e)100}{C_o} \quad (2)$$

Results and Discussion

Structural and Morphological Characterization of the Fe–Co–N/HCpp

The surface functional groups and crystal structure of the produced Fe–Co–N/HCpp nano-composite were determined by FTIR and XRD analyses, respectively. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) analyses were used to examine the surface morphology and elemental composition of the nano-composite. Furthermore, post-adsorption FTIR analyses were performed to confirm MG adsorption on the Fe–Co–N/HCpp surface and elucidate the adsorption by examining structural changes.

FT-IR Spectrum of Composite

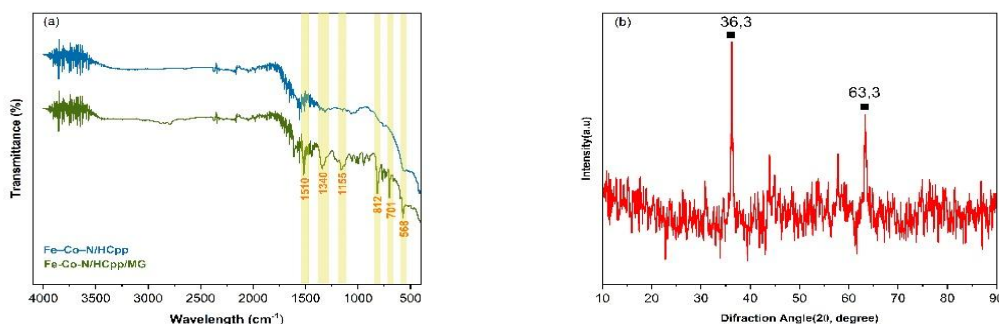


Figure 2. FT-IR diagram of Fe–Co–N/HCpp (a), XRD diagram of Fe–Co–N/HCpp (b).

Figure 2a. shows the FTIR spectra of the Fe–Co–N/HCpp composite before and after MG adsorption. The broad band observed at around 3200–3500 cm⁻¹ in the Fe–Co–N/HCpp composite is attributed to the stretching vibrations of surface hydroxyl (–OH) and amino (–NH) groups. After MG adsorption, the broadening of this band and the increase in its intensity indicate that hydroxyl- and nitrogen-containing functional groups participate in the adsorption mechanism through hydrogen bonding and electrostatic interactions. It has also been previously reported that these groups in hydrocarbon-based adsorbents can form hydrogen bonds and electrostatic interactions with cationic dyes (Hammud et al. 2023).

Distinct changes were observed in the 1700–1500 cm⁻¹ region after adsorption. The increase in the intensity of the peak located at approximately 1510 cm⁻¹ may be associated with aromatic C=C and/or C=N vibrations (Kohzadi et al., 2023). Since MG has a conjugated aromatic structure, this increase indicates that MG molecules are bound to the aromatic carbon structure of Fe–Co–N/HCpp through π – π interactions. Similarly, the increase in the intensity of the C–N stretching vibrations observed at 1340 cm⁻¹ indicates that the nitrogen-containing

functional groups introduced onto the Fe–Co–N/HCpp surface through urea modification interact with the dimethylamino groups in the MG molecule. This is consistent with the study reporting that nitrogen-doped carbon-based adsorbents exhibit higher adsorption performance toward MG molecules (Sun et al. 2015).

A distinct increase in intensity and a change in band shape were observed after adsorption in the band located at approximately 1155 cm^{-1} , which corresponds to C–O, C–O–C, and C–N stretching vibrations (Han et al. 2017). This change indicates that the oxygen-containing functional groups on the Fe–Co–N/HCpp surface directly interact with MG molecules (Zhang et al. 2017). In addition, the appearance of numerous new vibration bands and the formation of more distinct peaks in the spectrum after adsorption, particularly in the fingerprint region between 1500 and 600 cm^{-1} , confirm the presence of characteristic vibrations belonging to MG on the nano-composite surface (Coates, 2000; Zhang et al. 2017). The changes in this region are considered one of the important indicators of the highly effective interaction between Fe–Co–N/HCpp and MG.

The bands observed at approximately 812 and 701 cm^{-1} became more pronounced after adsorption, which can be associated with out-of-plane C–H bending vibrations of aromatic rings. The changes in these bands support the presence of characteristic aromatic vibrations of MG molecules on the composite surface and indicate that the dye molecules interact with the surface functional groups after adsorption (Ojediran et al. 2021). The change in the intensity of the Fe–O and Co–O vibration band observed at around 568 cm^{-1} indicates that Fe and Co active centers play a role in the adsorption mechanism (Oguntuyi et al. 2026; Tabassum et al. 2024). This change suggests the possible occurrence of coordination interactions between MG molecules containing electron-rich amino groups and the metal active centers. Similar FTIR changes have been reported in MG adsorption studies conducted with Fe-based magnetic adsorbents (Parlayıcı et al. 2026; Sun et al. 2015). Overall, the FTIR results indicate that the adsorption of MG onto the Fe–Co–N/HCpp nano-composite occurs through the combined effects of hydrogen bonding, electrostatic attraction, π – π interactions, coordination with Fe/Co centers, and pore-filling mechanisms.

XRD Spectrum of Composite

Examination of the XRD pattern of the Fe–Co–N/HCpp reveals prominent diffraction peaks at angles of $2\theta = 36.2^\circ$ and 63.3° in Figure 2b. These peaks indicate that Fe and Co species form crystalline structures on the carbon matrix during the pyrolysis process (Aboul-Enein et al. 2023). Along with the extensive amorphous structure derived from carbon, these observed diffraction peaks confirm the successful loading of metal species onto the hydrochar surface and their incorporation into the nano-composite structure. The results demonstrate the successful formation of Fe and Co-containing active centers on the carbon structure. Similarly, it has been reported in the literature that metal-containing crystalline phases form in Fe–Co modified biocarbon systems while the carbon structure largely retains its amorphous character (Rehman et al. 2024; Abdelrahman et al. 2024).

SEM–EDX Analysis of the Composite

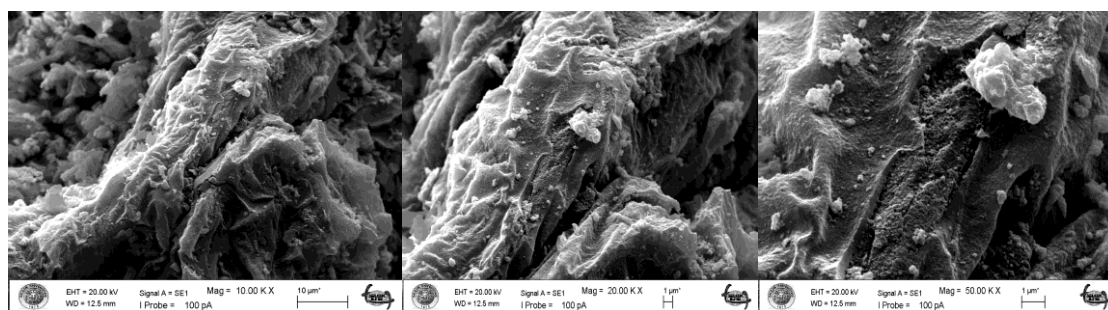


Figure 3. SEM image of Fe-Co-N/HCpp.

SEM images of the Fe–Co–N/HCpp reveal an irregular, heterogeneous, and distinctly rough surface morphology. Particle clusters of varying sizes are observed on the layered structure formed as a result of hydrothermal carbonization and subsequent modification processes (Figure 3.). The voids and irregular structures on the surface create additional active sites for adsorption, exhibiting properties that may facilitate the retention of dye molecules. Furthermore, the bright and dense regions observed on the surface are thought to indicate the successful dispersion of Fe and Co-containing metal species onto the hydrochar matrix. This morphological structure supports the finding of a high adsorption capacity.

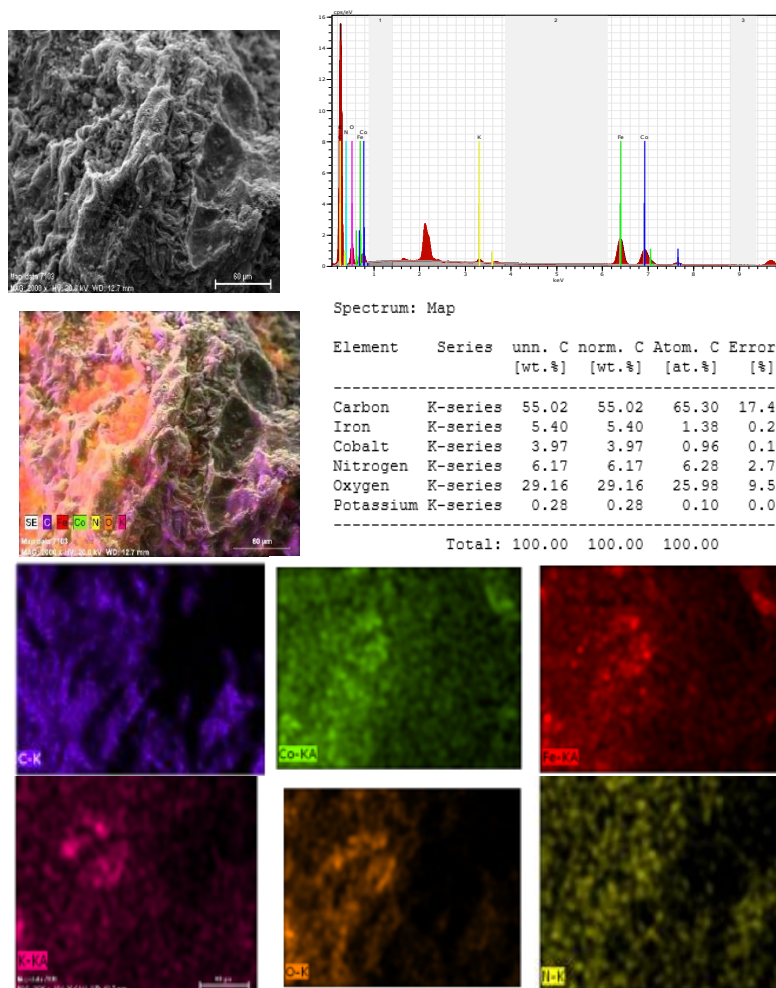


Figure 4. SEM-EDX mapping images of the Fe-Co-N/HCpp composite.

EDX analysis (Figure 4.) shows that the nano-composite is primarily composed of carbon (55.02%), oxygen (29.16%), nitrogen (6.17%), iron (5.40%) and cobalt (3.97%) elements. The high carbon content confirms the formation of a carbon-rich structure as a result of hydrothermal carbonization. The presence of oxygen indicates the presence of oxygen-containing functional groups such as hydroxyl, carbonyl, and carboxyl in the structure. The presence of nitrogen in the composite shows that nitrogen was successfully incorporated into the carbon structure as a result of urea modification. The detection of Fe and Co signals in the EDX spectrum confirms that Fe and Co species were successfully loaded onto the hydrochar surface. The presence of Fe not only confers magnetic properties to the composite but also affective during adsorption, improving dye removal performance. The low amount of K (0.28%) detected may originate from activation processes.

Results of the Batch Adsorption Experiments

Effect of pH

To investigate the effect of pH on MG adsorption, the initial pH values of the dye solutions were adjusted to a range of 3.0–9.0. The pH of the solution affects the functional groups on the Fe-Co-N/HCpp surface, causing changes in surface charge properties and thus significantly influencing adsorption performance. For the cationic dye MG, the decrease in adsorption capacity at low pH values is mainly associated with the abundance of H^+ ions, which compete with MG molecules for active adsorption sites on the Fe-Co-N/HCpp surface. In addition, protonation of the surface functional groups may generate a positively charged surface, thereby weakening the electrostatic attraction toward MG cations. As the pH increases, deprotonation of carboxyl and hydroxyl groups on the Fe-Co-N/HCpp surface enhances its negative surface charge, thereby strengthening the electrostatic attraction between the positively charged MG molecules and the hydrochar surface. This allows the dye molecules to bind more effectively to the Fe-Co-N/HCpp surface, contributing to an increase in adsorption capacity. In addition to electrostatic interactions, π - π interactions and hydrogen bonds can also contribute to the adsorption

mechanism. Similar results are supported by studies reporting that hydrochars obtained by hydrothermal carbonization exhibit pH-dependent increased adsorption performance in cationic dye removal (Hammud et al., 2023; Kohzadi et al., 2023). The presence of Fe in the Fe-Co-N/HCpp may contribute to MG adsorption by introducing additional surface-active sites, such as Fe-O, Fe-OH, or Fe-N functionalities, which can promote electrostatic interactions, surface complexation, and Lewis acid-base interactions with MG molecules, thereby enhancing the overall dye removal performance. Changes in the adsorption capacity of MG under different pH conditions are shown in Figure 5.

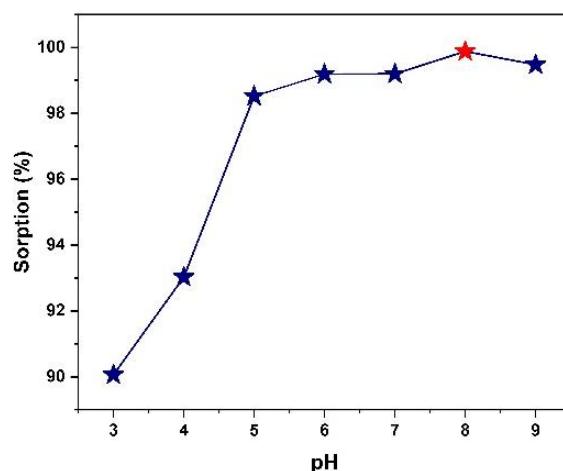


Figure 5. The effect of pH on MG adsorption.

Effect of Fe-Co-N/HCpp Amount

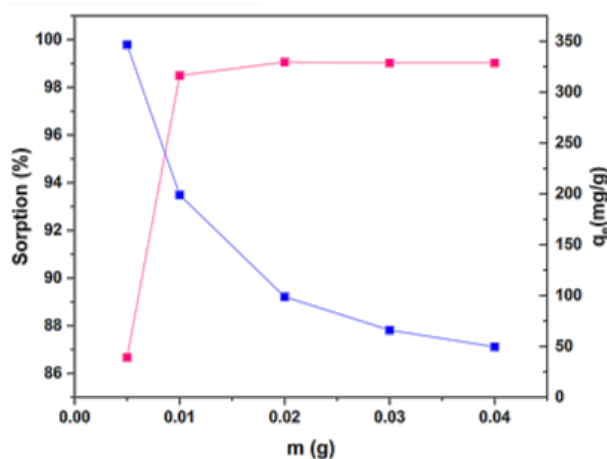


Figure 6. Effect of Fe-Co-N/HCpp composite amount.

The influence of adsorbent amount on MG adsorption was evaluated by varying the adsorbent mass from 0.005, 0.01, 0.02, 0.03, and 0.04 g. Adsorption performances obtained at different adsorbent amounts are presented in Figure 6. In general, a significant increase in MG removal efficiency was observed as the number of available active sites and the total surface area for adsorption increased with increasing Fe-Co-N/HCpp amount. Adsorption capacity increased up to an adsorbent mass of 0.01 g, and this value was determined as the optimum adsorbent amount. However, it was observed that the increase in removal efficiency remained quite limited at adsorbent doses above 0.01 g. Therefore, 0.01 g was used as the optimum adsorbent mass in subsequent experiments. This situation can be explained by the fact that the active sites approach saturation as a result of the large adsorption of MG molecules in the solution. Similar results have been reported in dye removal studies performed with hydrochar-based adsorbents, where no significant change in adsorption performance was observed after a certain optimum adsorbent dose (Qiao et al., 2024; Supee and Zaini, 2023).

Effect of Fe-Co-N/HCpp Contact Time

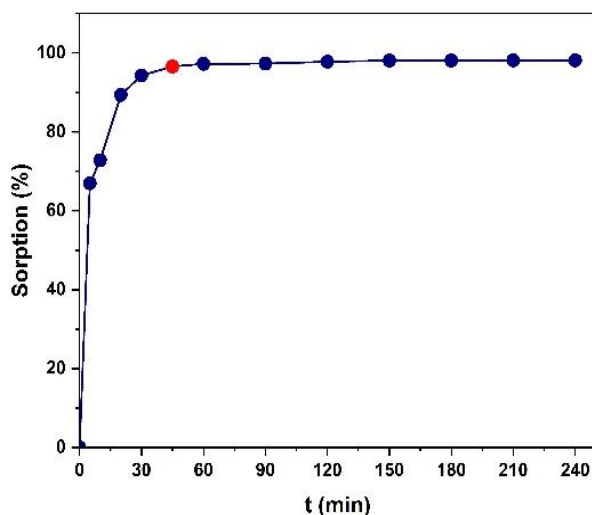


Figure 7. Effect of Fe-Co-N/HCpp contact time.

The effect of contact time on MG adsorption was investigated at intervals of 5, 10, 20, 30, 45, 60, 90, 120, 150, 180, 210, and 240 minutes. As shown in Figure 7, the adsorption capacity increased with increasing contact time, indicating that MG uptake by the Fe-Co-N/HCpp composite was time-dependent. The rapid increase in adsorption capacity during the initial stage can be attributed to the availability of numerous vacant active sites on the adsorbent surface, which facilitated the fast uptake of MG molecules within the first 5 min. As the contact time increased, the adsorption rate slowed down due to the gradual filling of the active sites and the decrease in MG concentration in the solution. In this study, it was observed that the change in adsorption capacity remained quite limited after a certain contact time, indicating that the system reached adsorption equilibrium. Therefore, 45 minutes was chosen as the optimum contact time in subsequent experiments. Similarly, studies conducted with hydrochar-based adsorbents have reported rapid dye retention in the initial stages of adsorption (Kohzadi et al., 2023).

Effect of Dye Initial Concentration

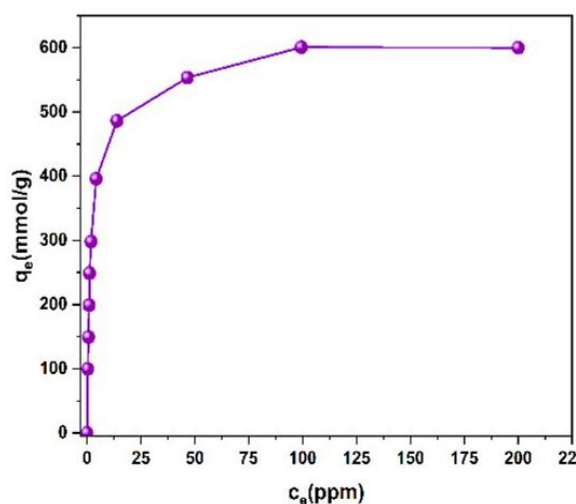


Figure 8. Effect of MG concentration.

To investigate the effect of initial dye concentration on adsorption performance, experiments were conducted using MG solutions prepared in the concentration range of 100–800 mg L⁻¹. As the initial concentration increased, the number of MG molecules in the solution increased, increasing the concentration gradient between the adsorbent and adsorbate and contributing to the improvement of the driving force required for mass transfer. Therefore, it was observed that the adsorption capacity increased with increasing initial concentration (Figure 8.). Similarly, studies on hydrothermal carbonization-derived carbon materials have also reported that high initial dye concentrations increase the adsorption capacity (Parlayıcı and Pehlivan, 2026). Langmuir, Freundlich, and Temkin isotherm models were applied to explain the adsorption mechanism of the equilibrium data. Analysis of the

obtained correlation coefficients revealed that the Langmuir model represented the experimental data more successfully than the Temkin and Freundlich models (Table 1.).

Table 1. Adsorption isotherm parameters for removal of MG dye.

Model	Equation	Parameters for dye			
Langmuir	$\frac{C_e}{q_e} = \frac{C_e}{A_s} + \frac{1}{K_b A_s}$	A_s	K_b	R^2	R_L
		333.40	1.77	0.987	0.003
Freundlich	$\ln q_e = \ln K_f + \frac{1}{n} \ln C_e$	K_f	n	R^2	
		198.98	3.86	0.854	
Temkin	$q_e = B_T \ln A_T + B_T \ln C_e$	B_T	A_T	R^2	
		83.13	14.09	0.961	

This indicates that MG adsorption occurs predominantly via a monolayer adsorption mechanism in active sites with homogeneous energy on the Fe–Co–N/HCpp surface. The maximum adsorption capacity ($q_{\max}$) calculated from the Langmuir model was found to be 333.40 mg g⁻¹, demonstrating the effectiveness of the adsorbent in MG removal. Furthermore, the calculation of the Langmuir separation factor (R_L) as 0.003 shows that the adsorption process is quite suitable and feasible. Similarly, it has been reported in various studies that the Langmuir model is dominant in cationic dye adsorption and that the adsorption exhibits a monolayer character (Pehlivan and Parlayıcı, 2024; Sorour et al., 2024).

Effect of Kinetic Studies

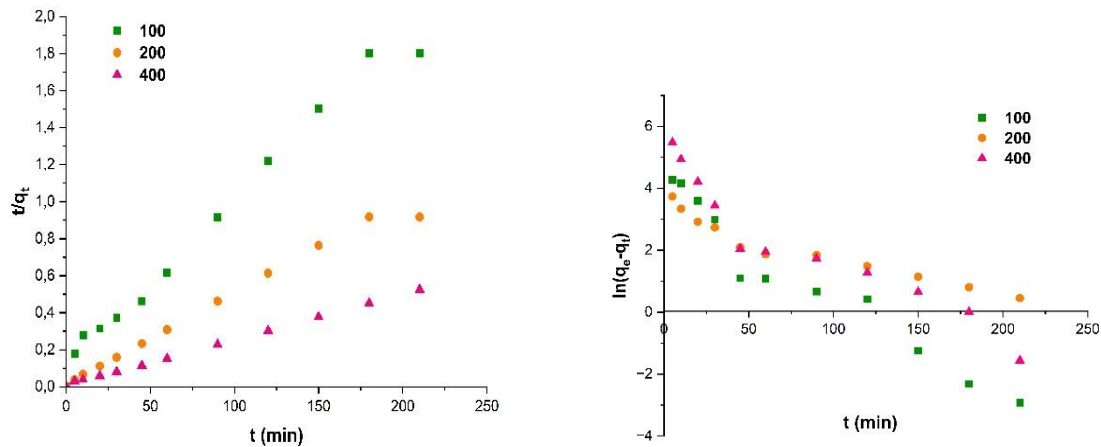


Figure 9. Kinetics for MG dye adsorption onto Fe-Co-N/HCpp nano-composite.

Adsorption kinetic curves for MG removal with Fe-Co-N/HCpp are shown in Figure 9. Table 2 presents the parameter results of both the pseudo-first-order and pseudo-second-order kinetic models used to evaluate the adsorption data. The pseudo-second-order model showed a better fit to the experimental results compared to the pseudo-first-order model. This is confirmed by the higher correlation coefficient (R^2) obtained for the pseudo-second-order model. In conclusion, the adsorption process is more accurately explained by so-called second-order kinetics, suggesting that chemical adsorption and electrostatic attraction are highly likely to be the dominant mechanisms (Yuan & Lu, 2024). Electrostatic attraction, π – π interactions, and hydrogen bonds occurring between carboxyl, hydroxyl, and other oxygen-containing functional groups on the hydrochar surface and MG molecules are thought to contribute to the adsorption mechanism (Qiao et al., 2024). These results reveal that the synthesized hydrochar develops strong surface interactions with MG molecules and that the adsorption process cannot be explained solely by physical diffusion.

Table 2. Comparison of the pseudo-first-order, pseudo-second-order adsorption rate constants and calculated and experimental q_e values obtained at different initial dye concentrations.

C_0 (ppm)	q_e Exp.	Pseudo-first-order			Pseudo-second-order		
		k_1	q_e	R^2	k_2	q_e	R^2
100	99.95	0.0011	50.30	0.947	0.0007	113.64	0.985
200	196.30	0.0014	60.34	0.911	0.0010	212.77	0.989
400	398.45	0.0013	143.70	0.901	0.0007	416.67	0.992

Thermodynamic Analysis of the Adsorption Process

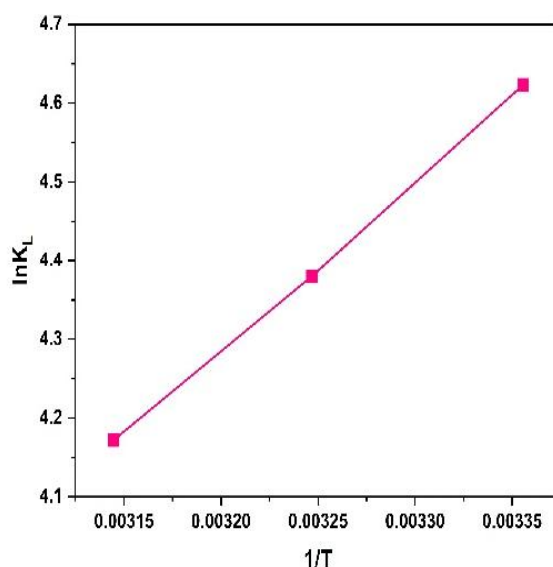


Figure 10. The impact of temperature on dye adsorption.

The effect of temperature on the adsorption of MG onto Fe-Co-N/HCpp was investigated (Figure 10.), and the obtained thermodynamic parameters are presented in Table 3. The negative Gibbs free energy change (ΔG°) values indicate that the adsorption process occurs spontaneously and is thermodynamically favorable (Akiode et al., 2023). Furthermore, the fact that the ΔG° values become less negative with increasing temperature reveals that adsorption is more advantageous at lower temperatures. The negative enthalpy (ΔH°) indicates that the adsorption of MG onto the Fe-Co-N/HCpp surface is exothermic. However, the negative entropy (ΔS°) values suggest that the system disorder at the adsorbent-adsorbate interface decreases during adsorption, and the MG molecules form a more ordered structure on the adsorbent surface. When these results are considered together, it is understood that MG adsorption is a spontaneous, exothermic process that is more favorable at low temperatures.

Table 3. Thermodynamic parameters for adsorption of MG.

$\Delta S^\circ (\text{J K}^{-1} \text{mol}^{-1})$	$\Delta H^\circ (\text{J mol}^{-1})$	$\Delta G^\circ (\text{J mol}^{-1})$			
		T=298.15K	T=308.15K	T=318.15K	R ²
-21.3	-17793.6	-11454.5	-11216.0	-11029.7	0.999

Regeneration and Reusability Performance of the Fe-Co-N/HCpp

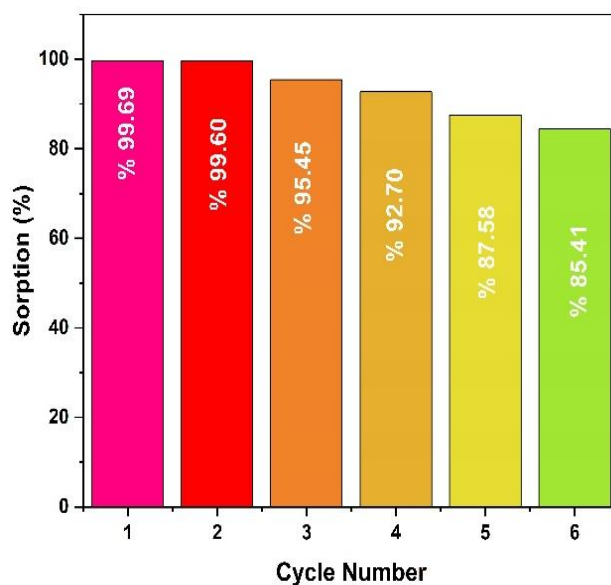


Figure 11. Desorption efficiency after recycle use.

Six consecutive adsorption-desorption cycles were performed to evaluate the reusability of the adsorbent. The results showed that the adsorption efficiency, which was 99.69% in the first cycle, decreased to 85.41% at the end of the sixth cycle (Figure 11.). This observed decrease can be attributed to the irreversible occupation of some of the active adsorption sites by MG molecules and small adsorbent losses occurring during the regeneration process. Nevertheless, the maintenance of high removal efficiency after six cycles reveals that the synthesized Fe-Co-N/HCpp exhibits good reusability and structural stability. These results demonstrate that the adsorbent has the potential to be used as an economical and sustainable alternative in wastewater treatment.

Conclusion

This study investigated the adsorption performance of an Fe-Co-N/HCpp nano-composite for the removal of MG from an aqueous medium. Utilizing plant waste through appropriate methods offers a significant approach in terms of both reducing environmental pollution and developing adsorbents with high economic value. In this context, the synthesized Fe-Co-N/HCpp nano-composite was characterized using FTIR, SEM, EDX, and XRD analyses, and the results confirmed the successful synthesis of the composite. The optimum conditions for adsorption studies were determined as: solution pH 8.0, temperature 25 °C, adsorbent amount 0.01 g, and contact time 45 minutes. The effect of initial MG concentration on adsorption was investigated, and equilibrium data were evaluated using different isotherm models. The results showed that the adsorption process best fit the Langmuir isotherm model. The maximum adsorption capacity calculated from the Langmuir model was found to be 333.40 mg g⁻¹, demonstrating that the synthesized composite exhibits high performance in MG removal. Kinetic studies, considering the obtained R², determined that the adsorption behavior better fits the pseudo-second-order kinetic model. This indicates that the adsorption process is largely controlled by surface interactions and chemical adsorption mechanisms. It was assessed that MG adsorption occurs through the combined effect of multiple mechanisms such as electrostatic attraction, π - π interactions, hydrogen bonds, and hydrophobic interactions. Temperature studies showed that the adsorption capacity decreased with increasing temperature. Thermodynamic parameters revealed that the adsorption process is exothermic and spontaneous. Furthermore, the iron content imparts magnetic properties to the composite, enabling facile separation of the adsorbent from the solution using a magnet after adsorption, without requiring filtration or centrifugation. In conclusion, the synthesized Fe-Co-N/HCpp composite has been evaluated as a promising adsorbent for the removal of cationic dyes from textile and other industrial wastewaters due to its high adsorption capacity, suitable kinetic and thermodynamic properties, easily recoverable structure, and the use of a sustainable raw material source. The development of such adsorbents derived from plant waste can make significant contributions to the dissemination of environmentally friendly and economical wastewater treatment technologies.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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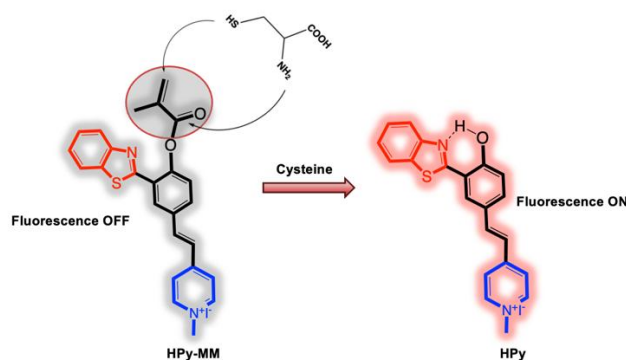
ICRETS 2026: International Conference on Research in Engineering, Technology and Science

Design, Synthesis, and Cytotoxicity Assessment of a Novel Fluorescent Probe for Cysteine Detection

Mehmet Oguz
Selcuk University

Abstract: Cysteine (Cys) is a sulfur-containing amino acid that plays a vital role in numerous biological processes, including protein synthesis, redox homeostasis, and cellular metabolism. Abnormal Cys levels have been associated with various diseases, creating a growing demand for the development of fluorescent probes for its detection. In this study, a new pyridinium–benzothiazole-based fluorescent probe was designed and synthesized as a potential molecular platform for Cys sensing. The structure of the synthesized compound was successfully confirmed by ^1H and ^{13}C NMR spectroscopy. To evaluate its suitability for biological applications, cytotoxicity studies were carried out, and the probe exhibited favorable biocompatibility under the tested conditions. These results demonstrate that the synthesized probe is a suitable candidate for further investigations in fluorescence-based sensing studies. Overall, the newly developed pyridinium–benzothiazole derivative provides a useful foundation for the future development of Cys-responsive fluorescent probes and related biological applications.

Keywords: Cysteine, Fluorescent probe, Cytotoxicity



Introduction

Cysteine (Cys) is a biologically important sulfur-containing amino acid that participates in a wide range of physiological processes (Fang et al., 2020; Jung et al., 2012). As a precursor of glutathione, it plays a central role in maintaining intracellular redox balance and protecting cells against oxidative stress. In addition, Cys contributes to protein biosynthesis, enzymatic regulation, metal ion coordination, and cellular signaling pathways through its highly reactive thiol group (Tang et al., 2026; Kim et al., 2026). Since the intracellular concentration of Cys is tightly regulated, its imbalance has been associated with the onset and progression of several pathological conditions, including neurodegenerative disorders, liver dysfunction, cardiovascular diseases, and cancer (Gao et al., 2011; Mahmoud et al., 2016). Therefore, the reliable detection of Cys has attracted considerable interest in biomedical research, clinical diagnostics, and analytical chemistry.

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A variety of analytical techniques have been developed for the determination of Cys, including high-performance liquid chromatography (HPLC), capillary electrophoresis, electrochemical methods, and mass spectrometry (Lalitha et al., 2026; Asghar et al., 2026). Although these techniques provide reliable analytical performance, they generally require sophisticated instrumentation, time-consuming sample preparation, or trained personnel, which may limit their use in routine and real-time analyses. Fluorescence-based methods have emerged as an attractive alternative because of their high sensitivity, rapid response, operational simplicity, and capability for non-invasive detection (Jiang et al., 2025; Luo et al., 2024). Furthermore, fluorescent probes enable real-time monitoring of biological analytes with high spatial and temporal resolution, making them valuable tools for biochemical research and the development of analytical sensing platforms.

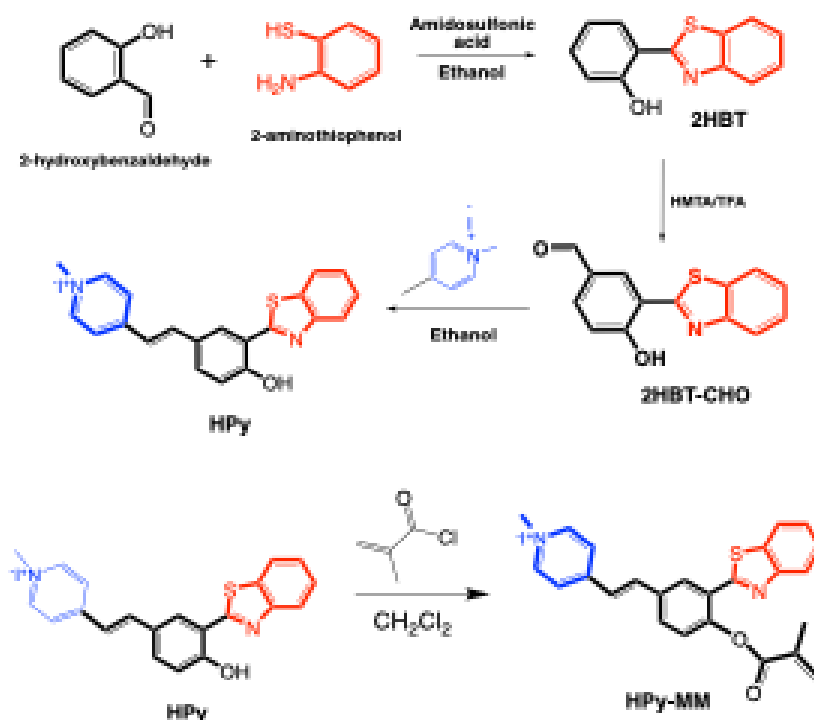
Among the various fluorophore scaffolds currently available, benzothiazole derivatives have attracted considerable attention owing to their favorable photophysical properties, synthetic accessibility, and structural versatility. Their conjugated framework enables efficient fluorescence emission, while the molecular structure can be readily modified to tailor the optical response toward specific analytes. Likewise, pyridinium derivatives are frequently incorporated into fluorescent probe design because of their strong electron-withdrawing character, good water compatibility, and ability to facilitate intramolecular charge transfer (ICT) processes (Lee et al., 2026; Erdemir et al., 2026; Kaur et al., 2024). The combination of benzothiazole and pyridinium moieties offers a rational molecular framework for the design of fluorescent probes with desirable optical characteristics and potential applicability in biological sensing.

In the present study, a new pyridinium–benzothiazole-based fluorescent probe was designed and synthesized as a potential platform for Cys sensing. The synthesized compound was structurally characterized by ^1H and ^{13}C NMR spectroscopy to confirm its molecular structure. Furthermore, cytotoxicity studies were performed using the Alamar Blue assay to evaluate its biocompatibility and assess its suitability for potential biological applications. The results of this work provide a useful foundation for the future development of Cys-responsive fluorescent probes and related biological studies.

Experimental Section

Materials and Methods

The intermediates 2HBT, 2HBT-CHO, and HPy were synthesized according to previously reported methods with slight modifications (Erdemir et al., 2022; Sahana et al., 2015). These intermediates were subsequently used for the synthesis of the target pyridinium–benzothiazole fluorescent probe (Scheme 1).



Scheme 1. Synthetic pathway for the preparation of HPy-MM

Synthesis of Hpy-MM

Hpy (1.0 mmol) and methyl methacrylate (1.1 mmol) were dissolved in dichloromethane (20 mL), and three drops of triethylamine were added to the reaction mixture. The reaction mixture was stirred at room temperature for 3 h. After extraction with water, the product was purified by column chromatography (CH_2Cl_2) to afford Hpy-MM in 65% yield. ^1H NMR (400 MHz, $\text{DMSO}-d_6$) δ 8.94 (d, 2H, $J=6.6$ Hz), 8.25-8.31 (m, 3H), 8.15-8.19 (m, 2H), 8.01 (d, 1H, $J=7.8$ Hz), 7.85 (d, 1H, $J=16.5$ Hz), 7.63-7.67 (m, 2H), 7.58 (t, 1H, $J=7.2$ Hz), 7.50 (t, 1H, $J=7.2$ Hz), 6.48 (s, 1H), 6.06 (s, 1H), 4.30 (s, 3H), 2.11 (s, 3H); ^{13}C NMR (100 MHz, $\text{DMSO}-d_6$) δ 165.7, 162.3, 152.9, 152.0, 146.9, 146.0, 135.4, 135.1, 133.0, 132.2, 130.8, 130.7, 129.8, 127.8, 127.3, 126.5, 124.6, 123.4, 122.7, 47.6, 18.7.

Cell Viability Assay

Cytotoxicity Assay. The biocompatibility of Hpy-MM was assessed in PNT1A and HeLa cells using the Alamar Blue assay. Briefly, cells were seeded into 96-well plates at a density of 1×10^4 cells per well and allowed to attach for 24 h at 37 °C. The cells were subsequently exposed to various concentrations of Hpy-MM (0–200 μM) for 48 h. Following the treatment period, Alamar Blue reagent was added at 10% of the culture medium volume, and the plates were incubated for an additional 4 h. Absorbance was recorded at 570 and 600 nm using a microplate reader. Cell viability was expressed relative to untreated control cells, and IC_{50} values were determined from dose–response curves generated from three independent experiments.

Results and Discussion

Synthesis and Structural Characterization of Hpy-MM

Hpy-MM was synthesized through a multistep synthetic route involving pyridinium and benzothiazole intermediates, as illustrated in Scheme 1. The final product was isolated by column chromatography and structurally characterized by ^1H and ^{13}C NMR spectroscopy (Figs. 1–2). The NMR data were consistent with the proposed molecular structure of Hpy-MM. In the ^1H NMR spectrum, the methyl protons of the pyridinium moiety appeared at δ 4.23 ppm, while the methyl protons of the methacryloyl group were observed at δ 2.15 ppm. In addition, the characteristic aromatic proton signals corresponding to the pyridinium unit were detected in the expected chemical shift region. Further structural confirmation was provided by the ^{13}C NMR spectrum, in which the carbonyl ($\text{C}=\text{O}$) carbon of the methacryloyl group was observed at δ 167.24 ppm, supporting the successful incorporation of the methacryloyl functionality into the target molecule.

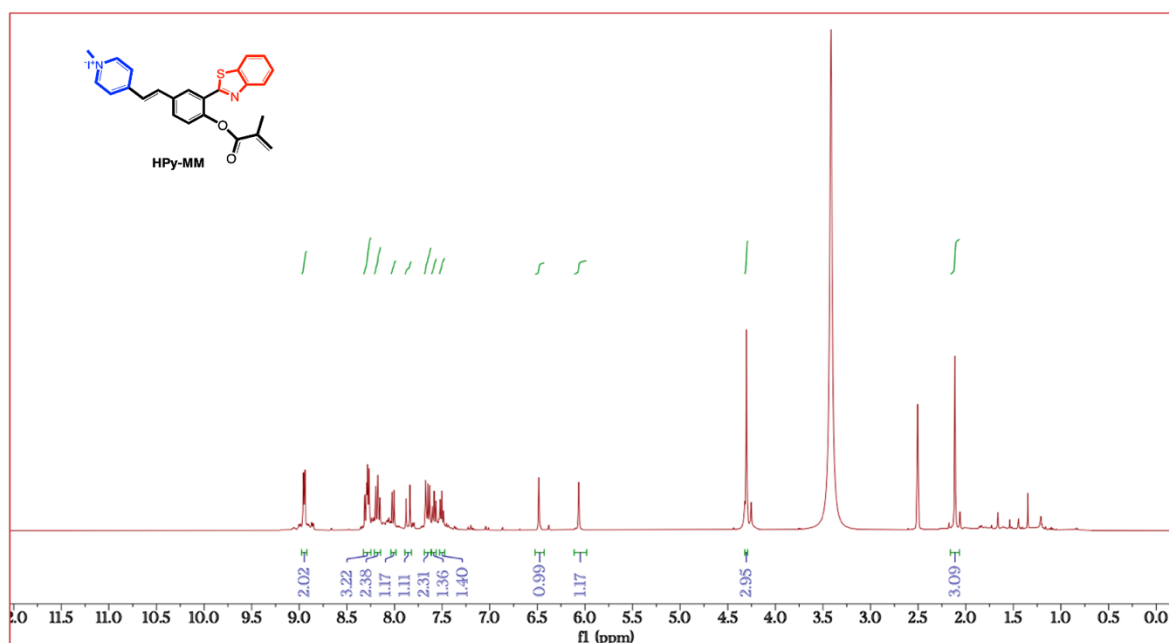
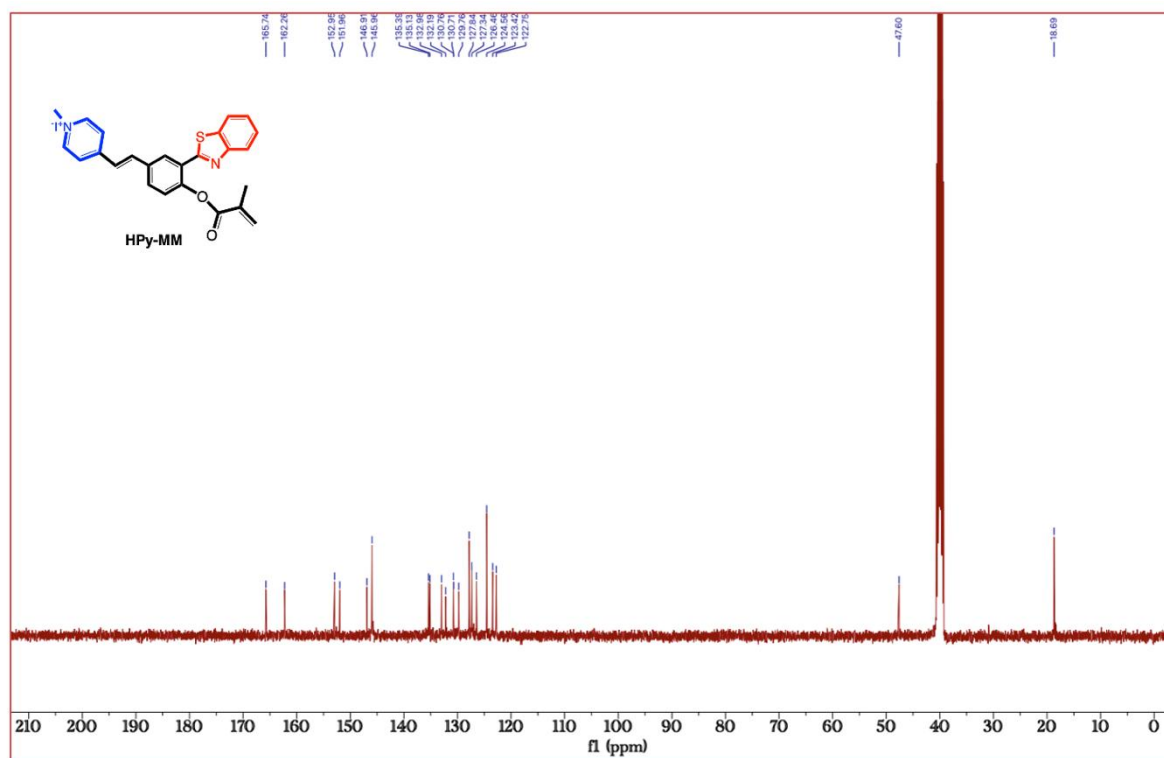
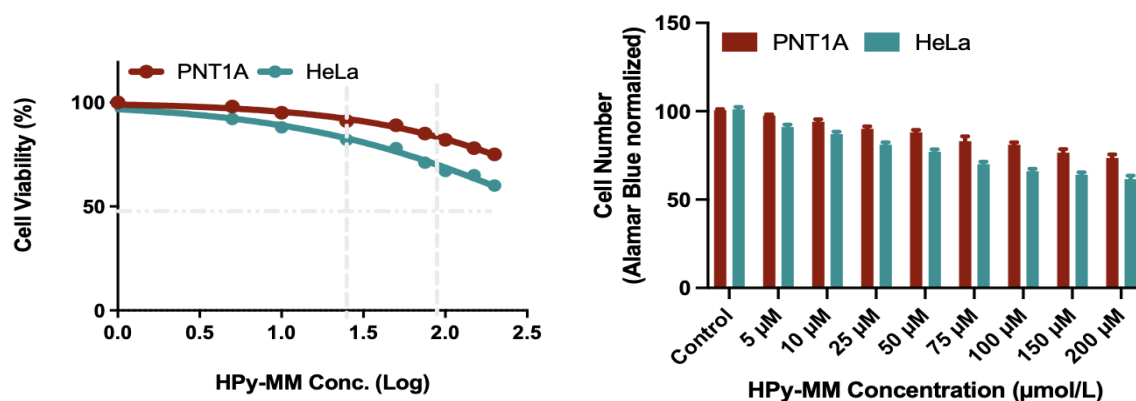


Figure 1. ^1H NMR spectrum of Hpy-MM ($\text{DMSO}-d_6$, 400 MHz)

Figure 2. ^{13}C NMR spectrum of **HPy-MM** ($\text{DMSO-}d_6$, 100 MHz)

Cytotoxicity Evaluation

Figure 3. IC_{50} values of the **HPy-MM** on PNT1A and HeLa

The cytotoxicity of HPy-MM was evaluated in PNT1A and HeLa cells using the Alamar Blue assay, and the results are presented in Fig. X. As the concentration of HPy-MM increased, a gradual reduction in cell viability was observed in both cell lines. Nevertheless, cell viability remained above approximately 85% in PNT1A cells and above 75% in HeLa cells, even at the highest tested concentration (200 μM), indicating that HPy-MM exerts only limited cytotoxic effects under the investigated conditions. The calculated IC_{50} values further supported these observations, with values exceeding 200 μM for PNT1A cells and 195.1 μM for HeLa cells (Table 1). These findings indicate that HPy-MM possesses good biocompatibility and may be considered suitable for further biological studies.

Table 1. Calculated IC_{50} values (μM) for **HPy-MM**.

Compound	PNT1A	HeLa
HPy-MM	> 200	195.1

Conclusion

In this study, a new pyridinium–benzothiazole-based fluorescent compound, HPy-MM, was successfully synthesized through a multistep synthetic route. The molecular structure of the synthesized compound was confirmed by ^1H and ^{13}C NMR spectroscopy, verifying the successful formation of the target molecule. To evaluate its potential for biological applications, the cytotoxicity of HPy-MM was investigated using the Alamar Blue assay in PNT1A and HeLa cell lines. The results demonstrated that the compound maintained high cell viability over the investigated concentration range, indicating favorable biocompatibility. These findings suggest that HPy-MM represents a suitable molecular platform for future studies involving cysteine-responsive fluorescent probe development and related biological applications.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Conflict of Interest

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Geospatial Causal Inference for Barangay-Level Maternal Care Assessment: A Causal Forest Framework on Antenatal Intervention Outcomes in Davao City

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Abstract: Maternal mortality is a critical concern globally, particularly in rural and economically disadvantaged countries. In the Philippines, despite national and local interventions, the situation remains a critical concern due to the country's reported Maternal Mortality Rate. This study develops a geospatial causal inference framework to assess the effectiveness of maternal care programs in Davao City, particularly in the barangay level, providing insights into local variations in maternal health outcomes. Using the Routine Health Information System dataset covering from 2020 to 2024, the usage of Causal Forest estimates heterogeneous treatment effects of antenatal interventions, including prenatal care, anemia management, skilled birth attendance, and laboratory screenings. Furthermore, Spatial cross-validation and falsification tests are applied to address spatial autocorrelation and validate causal robustness. Additionally, results are visualized through an interactive dashboard, enabling clear identification of high and low-impact areas for targeted interventions. The integration of causal machine learning with geospatial analysis demonstrates the potential to uncover localized intervention effectiveness, optimizing maternal care resource allocation and strategic planning, as well as improving maternal health outcomes in Davao City.

Keywords: Maternal health, Causal forest, Geospatial analysis, Antenatal care, Heterogeneous treatment effects

Introduction

Maternal health refers to the health of women during pregnancy, childbirth and the postnatal period (WHO, 2019). All three stages of pregnancy are critical so ensuring positive experiences at every stage is important for both maternal and newborn survival and well-being. Maternal health care and outcomes have improved globally over the recent decades, however maternal mortality remains alarmingly high, particularly in low- and middle-income countries. Maternal morbidity refers to those occurring during pregnancy, childbirth, or within the postpartum period. According to the World Health Organization, in 2020, there was a record of an estimated of 287,000 women died from pregnancy-related causes, many of which, could have been prevent with timely and appropriate healthcare. The leading causes of these maternal mortalities include direct causes such as severe bleeding, infections, high blood pressure during pregnancy, unsafe abortion, and obstructed labor (WHO, 2023).

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Maternal health care involves three stages, namely antenatal care (ANC), intrapartum care, and postnatal care (PNC). Antenatal care covers risk identification, prevention, and management of pregnancy-related conditions, and health education (WHO, 2016). Intrapartum care spans the onset of labor through delivery of the placenta, ensuring safe childbirth (Hutchison et al., 2025). Postnatal care extends for six to eight weeks after birth, covering maternal recovery and newborn care, which includes breastfeeding, immunizations, and mental health support (Lopez-Gonzalez & Kopparapu, 2022; UNICEF, 2025). These stages are often prone to failure, leading to poor maternal outcomes, where studies highlight diseases such as preeclampsia, intrauterine fetal demise (IUFD), and infections as leading causes of maternal morbidity and mortality (Amosco et al., 2019). These findings show the importance of early and effective interventions, and systematic maternal care programs.

In the Philippines, maternal health remains a major public health concern. Despite national programs like the Maternal, Neonatal, and Child Health and Nutrition (MNCHN) Strategy, which developed frameworks that promote access to antenatal, childbirth, and postnatal services, emphasizing measurable policy improvements and strengthening its health systems (Haakenstad et al., 2022; PMNCH), maternal mortality rates continue to challenge the health system of the country. The Philippine Statistics Authority (PSA) reports that the maternal mortality ratio (MMR) in the Philippines remains above the SDG 3 target of 70 per 100,000 live births, with significant disparities between urban and rural areas. According to Inquirer (2023), the PSA reported that there were 2,478 women who died from maternal causes in 2021, the MMR for that is 189.21 per 100,000 live births which is the third deadliest number of maternal mortalities next to 1951 and 1952. In Davao City, maternal health is still a multifaceted issue, particularly in inequalities in the quality and accessibility of maternal care across barangays. In 2021, the City Health Office (CHO) recorded 22 maternal mortalities, which were primarily caused by hemorrhage and eclampsia, both are preventable with timely and quality prenatal care (City Government of Davao, 2022).

A qualitative study conducted by Cagayan et al. (2022), in rural health units in Luzon revealed the systemic challenges faced by mothers in accessing maternal health services. The study reported the challenges that included long travel distances, lack of transportation, poor facility readiness, and intermittent availability of skilled health professionals. Many women also reported feeling disrespected or neglected during health visits, which discouraged regular check-ups and facility-based deliveries. These insights highlight the persistent socio-structural and accessibility barriers that limit the effectiveness of existing maternal health programs. The study also shows the importance of local health units providing maternal care, especially the need for capacity building, resource allocation, and localized decisions-making tools to better help rural communities.

In response to these recorded maternal mortalities, the CHO intensified their efforts through the Safe Motherhood Program, having multiple initiatives aimed at improving maternal health services. This program includes services such as 18 batches of consultative meetings for district health staff, District Facebook Pages for pregnant women to receive necessary prenatal updates and advocacy materials, a planned Safe Motherhood Hotline and, a mobile clinic services that aims to bring prenatal care, nutrition counseling, laboratory tests, and micronutrient supplementation directly to communities.

The barangay and district health centers currently provide prenatal services that include nutritional assessments via BMI, Tetanus-Diphtheria immunization, micronutrient supplementation specifically iron and folic acid, deworming, STI and laboratory testing, and gestational diabetes screening. Despite these efforts, a study by Matutino et al. (2024) revealed inconsistent perceptions of care quality among mothers in selected barangays, citing resource limitations, follow-up gaps, and variable patient experiences as ongoing challenges.

These disparities despite the current efforts emphasize the need for a data-driven approach to support evidence-based decision-making in maternal care. While these services are in place, there remains a gap in the ability to assess the effectiveness of maternal care interventions and identify areas that most need support. The absence of these tools makes it difficult to track the success of interventions across the Davao City barangays over time.

To address this, this study will begin with the collation of selected barangay-level data from Davao City's Routine Health Information System (RHIS). Although RHIS is an administrative dataset, in this study it is considered the primary dataset because it was obtained directly from the City Health Office (CHO) before any cleaning or processing. This step is data gathering of the relevant indicators of this study such as, antenatal care services, maternal outcomes, and interventions activities across the different health centers in Davao City. Consolidating these varied datasets into a structured and analyzable format, this study will be able to have a more granular analysis and make sure that both successful and underserved areas are properly captured.

To further support maternal healthcare decision-making, researchers have delved into data-driven methods. Using effective data acquisition and preprocessing are foundational for accurate epidemiological models. Related studies include an automated electronic health record (EHR) extraction (Lijovic et al., 2024), hybrid SEIR-neural models with external variables (Ziarelli et al., 2024), and wastewater-based surveillance (Meadows et al., 2025) illustrate how innovative data sources improve health forecasting. Furthermore, Geospatial analysis provides powerful tools to identify health disparities. Studies in Africa and Asia used spatial clustering and Bayesian networks to map out maternal mortality ratios and neonatal outcomes, which reveal hotspots of regions of high maternal risk (Yaya et al., 2021; Rubaiya et al., 2024; Liu et al., 2024). Machine learning integrated with geospatial data further enables predictive mapping of maternal and child health disparities (Rajuroy & Emmanuel, 2025).

There are numerous machine learning models that were developed for maternal care. For instance, a hybrid model combining Random Forest and XGBoost identified significant predictors of antenatal care uptake (Sani & Ahmed, 2023), whereas other hybrid models such as MaternalNET-RF, which integrates Artificial Neural Networks and Random Forest, achieve performance metrics exceeding 94% (Togunwa et al., 2023). Ensemble approaches, including gradient-boosted trees and stacked models, outperform single algorithms in classification accuracy (Khadidos et al., 2024; Macrohon et al., 2022). Other ensemble methods such as bagging are also widely recognized for improving model robustness and reducing prediction variance (Breiman, 1996). Performance metrics such as accuracy, precision, recall, F1-Score and Area under the Receiver Operating Characteristic Curve (AUROC) were commonly used to evaluate these models, with hybrid methods achieving the best balance between sensitivity and specificity (Bertini et al., 2022; Sani & Ahmed, 2023). Despite these advances, most studies rely on small localized, datasets, producing population biases which limits their generalizability across diverse populations and overlooks the full continuum of maternal care. To mitigate these issues, oversampling methods such as Synthetic Minority Over-sampling Technique (SMOTE) are commonly applied, which helps to balance high-risk and low-risk cases (Elreedy & Atiya, 2019).

This study focuses on using Causal Forest, which is a machine learning method that focuses more on the identification of heterogeneous causal effects of treatment and is unlike the conventional machine learning methods (Kakimoto et al., 2022). In recent years, causal forests have been applied in various studies such as economics, transportation, and agriculture to make site-specific or context-specific decisions. A study by Kakimoto et al. (2022) utilizes the causal forest approach in the agricultural context, specifically to generate economically optimal site-specific input management recommendations based on the gathered on-farm experimentation data. Similarly, in the medical field, studies by Raghavan et al. (2022) and Susukida et al. (2025) utilizes causal forest to explore sugar control for diabetic patients and examine in psychology substance use disorder treatments respectively. Another study focuses on economics which their program provides individuals to meet their basic needs and escape poverty (Wu et al., 2023). These studies mentioned show the strength of causal forest in giving insights on how treatment effects vary across different population subgroups. This capability is relevant to this study's focus on barangay-level variation in maternal health outcomes.

Two methods were taken into consideration to tackle this study, and while Causal Forest was selected by the researchers due to it having a distinct ability to estimate Conditional Average Treatment Effects (CATEs) at a granular level, another method was also considered which is the Double Machine Learning (DML). DML is a statistically strong and effective way for estimating average treatment effects, but is it not designed to capture the heterogeneity of effects across diverse settings. In contrast, Causal Forest can reveal how maternal health interventions perform differently depending on barangay specific factors like access to facilities, resource allocation, and personnel distribution. A study by Zheng and Yin (2023) explained how Causal Forest is particularly well-suited for observational studies, because it enables nuanced, interpretable causal analysis. Furthermore, another study by Credit and Lehnert (2023) highlighted that Causal Forest is especially effective in spatially distributed datasets, where treatment impacts are uneven across the geography, this is an ideal choice for this study's target of health disparities within Davao City's 182 barangays. These strengths from this selected model align closely with the goal of the study which is to generate localized, actionable insights for maternal healthcare planning and policy.

To ensure the reliability of the hybrid model's output, the study also includes an evaluation phase using both cross-validation and falsification tests. In geospatial datasets such as maternal health indicators across barangays, using standard random cross-validation can lead to an overestimated model performance due to spatial autocorrelation, this is the tendency for neighboring areas to exhibit similar characteristics. To address this, this study applies spatial cross-validation, which partitions the data based on geographic blocks, making sure that the training and test sets are spatially independent. A study by Sun et al. (2023) emphasized the important role of Spatial Cross-Validation in GeoAI applications, also showing that the traditional Cross-Validation techniques can produce overly optimistic results in spatial domains. Along with the Cross-Validation strategy, falsification tests

will also be employed to evaluate the causal validity of the model. These tests detect potential confounding or misspecification by applying the model to outcomes that should not be influenced by maternal interventions, such as health indicators not related to maternal health. A study from Liu et al. (2023) highlighted that assumption-lean falsification tests are vital when deploying double-robust machine learning estimators in any observational settings, making sure of credible causal inferences by identifying the false positives that may arise from unobserved biases.

Together with the hybrid model, this study also integrates a web-based platform as a visualization layer rather than a core contribution. Built with React with Vite for the frontend and Flask for the backend, the system allows users to interact with heatmaps representing each barangay in Davao City. Color gradients to indicate the severity or effectiveness of the maternal health interventions will be shown on these heatmaps. This is done to enhance the accessibility and the interpretability of the study's results.

This study aims to address the gaps of maternal health care in the Davao City barangays with the help of causal forest and geographic heterogeneity. This study proposes a data-driven system that integrates routinely collected and selected health data and applies causal inference and geospatial analysis. With this combination of statistical modeling and spatial mapping the system will help the workers and policymakers of the health sector to see and understand which interventions work effectively, and in which barangays. These insights generated by the hybrid model will serve as a valuable tool for evidence-based planning for resource planning and targeted response in district to barangay-level maternal healthcare efforts. Specifically, this study aims to:

1. To construct a collated dataset by consolidating data on antenatal care services, maternal health outcomes, and interventions from the records of the Davao City Routine Health Information System (RHIS)
2. To train a hybrid model that applies Causal Forest algorithm to estimate how the effects of maternal health interventions vary across barangay-level subgroups and incorporate geospatial heterogeneity to visualize these heterogeneous treatment effects.
3. To evaluate the maternal care interventions hybrid model using Spatial Cross-Validation and Falsification Tests.

Method

Research Design

This study employs a quantitative, ecological research design aimed at assessing the causal relationship between maternal healthcare interventions and maternal and neonatal health outcomes across barangays in Davao City. The approach will integrate spatial analysis with the Causal Forest algorithm; to investigate how geographic factors influence the effectiveness of interventions such as prenatal care, skilled birth attendance, and maternal supplementation. This study will utilize observational health records and historical data from routine monitoring data instead of randomized control trials. This study will leverage natural variation in intervention intensity across barangays. The study applies causal inference techniques to estimate both Average and Conditional Average Treatment Effects (ATE and CATE). Geospatial data, health service records, and demographic features are all incorporated to reveal heterogeneity in outcomes. This chapter outlines the research setting, data sources, data preparation process, model implementation, validation techniques, and the visualization system that translates findings into actionable insights. The unit of analysis comprises aggregated data at the Barangay level. For indicators with sparse or unreliable data at the barangay level, the district level serves as the alternative unit of analysis.

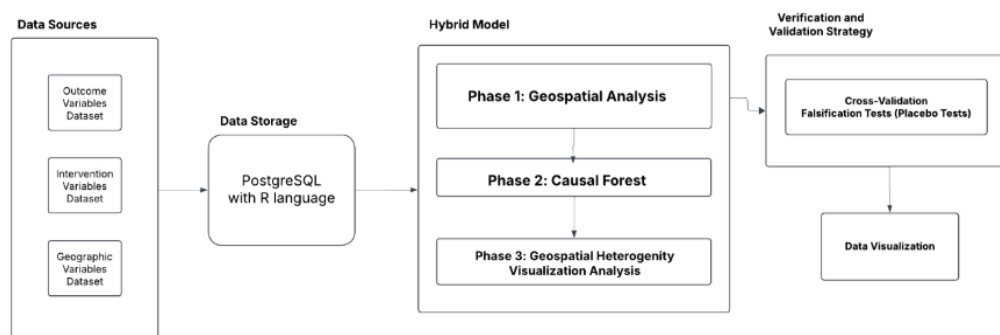


Figure 1. Conceptual framework

Figure 1 illustrates the overall conceptual framework of this study. It outlines the sequential and interconnected stages, beginning with the acquisition of primary and secondary data sources. These data then undergo rigorous processing and management, leading into a multi-phase analytical approach designed to investigate spatio-temporal trends in maternal health. The outputs of this analysis, including identified patterns and statistical models, culminate in the development of an interactive dashboard. Crucially, the framework emphasizes that verification and validation strategies are applied throughout the entire research process to ensure the credibility and utility of the findings.

Research Setting and Time Frame

The research setting is Davao City, Davao Region, Philippines, encompassing the 182 barangays across 11 administrative districts. Due to availability of data, this study spans a five-year period from January 2020 to December 2024 utilizing historical data.

Population and Locale

The study population does not use a fixed sample size. Instead, it is defined by the administrative boundaries of Davao City during the study period, with particular focus on women of reproductive age (15-49 years) and mothers/newborns represented in the maternal and child health (MCH) indicators. This encompasses all 182 barangays across the city's 11 districts.



Figure 2. Davao city districts

Data Sources

This study utilizes primary routine health information system (RHIS) to ensure comprehensive analysis. The selection of multiple complementary data sources is essential to capture the multidimensional nature of maternal health outcomes and their determinants.

Primary Data: Davao City RHIS

This study uses the Davao City Routine Health Information System (RHIS) data. Although RHIS is an administrative dataset, in this study it is considered as the primary dataset because it is the direct source collected from CHO before any cleaning or processing. This serves as the foundation of this study for several critical reasons: (1) It provides the most comprehensive, systematically collected data on maternal health services and

outcomes in Davao City. (2) It offers granular geographic detail (barangay-level). (3) It contains longitudinal data allowing variation in exposures of maternal health interventions. (4) It represents the actual operational data used by health administrators for decision-making, ensuring research-to-practice relevance. The study relies on obtaining aggregated reports based on the standardized 2025 RHIS covering the period 2020-2024, obtained from the Davao City Health Office (CHO) through formal data sharing agreements.

Key Datasets

These are the key datasets that were identified as integral parts of the analysis. They contain the most relevant indicators to identify the disparities in maternal health outcomes. Below are specific descriptions for each dataset describing the way these datasets are structured. These datasets are presented in a data dictionary to ease readability.

Outcome Variables Datasets

The primary outcome dataset contains maternal and neonatal health outcomes and indicators at the barangay level. This dataset provides the dependent variables necessary for causal inference. The stillbirth dataset missing specific causes is a key limitation, however, analysis is still possible to identify its association with interventions. Stillbirth counts will be used as an outcome variable in the causal forest analysis. However, due to the lack of cause-specific information, interpretation will be limited to overall associations between interventions and stillbirth prevalence, rather than causal pathways of specific conditions. For specific causes of morbidity/mortality the International Statistical Classification of Diseases and Related Health Problems 10th Revision (ICD-10) will be used to identify the diagnosed cause of morbidity or mortality.

Table 2. Neonatal morbidity/mortality dataset

Barangay	Sex	Cause Diagnosed	Age Group	Neonatal Cases
Barangay A	Male	A34	0 – 6 days	35
Barangay B	Female	O00-O95	7 – 28 days	160
Barangay C	Male	O98-O99	7 – 28 days ...	127 ...

Note. Barangay refers as the Geographic Unit. Sex is classified as “Male or Female”. Cause Diagnosed refers to the ICD-10 coded causes specifically on morbidity/mortality. Age_Group refers to the count between ‘0-6 days’ and ‘7-28 days’. Neonatal_Cases refers to the count of neonatal morbidity or mortality cases.

Table 3. Maternal morbidity/mortality dataset

Barangay	Age Group	Cause Diagnosed	Maternal Cases
Barangay A	<20	A34	35
Barangay B	20 - 34	O00-O95	160
Barangay C	≥35	O98-O99	127

Note. Barangay refers as the Geographic Unit. Age_Group refers to the defined reproductive age brackets. Cause Diagnosed refers to the ICD-10 coded causes of morbidity/mortality. Maternal_Cases refers to the count of maternal cases.

Table 4. Stillbirth dataset

Barangay	Stillbirth Count
Barangay A	74
Barangay B	256
Barangay C	182

Note. Barangay refers to the Geographic unit. Stillbirth_Count refers to the count of stillbirths.

Intervention Variables Datasets

These datasets capture the implementation intensity of maternal healthcare interventions across barangays. These provide the treatment variables for causal analysis. The natural variation in implementation intensity across barangays creates the necessary treatment variation for causal identification. The variation is primarily caused by the practical limitations of implementing interventions due to resources allocation, infrastructure and community engagement.

Table 5. Prenatal care coverage dataset

Barangay	Prenatal_Visits	Birth_Plan
Barangay A	132	75
Barangay B	634	344
Barangay C	243	180

Note. Barangay refers to the Geographic unit. Prenatal_Visits refers to the count of pregnant women completing recommended prenatal visits. Birth_Plan refers to the count of pregnant women who received counseling on preparing birth plans.

Table 6. Maternal vaccination and supplementation dataset

Barangay	Vaccination_Rate	Supplementation_Rate
Barangay A	274	287
Barangay B	104	404
Barangay C	468	269

Note. Barangay refers to the Geographic unit. Vaccination_Rate refers to the count of women who received Tetanus Vaccine. Supplementation_Rate refers to the count of women administered iodine and iron supplements.

Table 7. Birth attendant and delivery location dataset

Barangay	Facility_Delivery_Rate	Skilled_Attendant_Rate	Home_Delivery_Rate
Barangay A	201	192	9
Barangay B	237	48	168
Barangay C	273	269	4

Note. Barangay refers to the Geographic unit. Facility_Delivery_Rate refers to the count of births in health facilities. Skilled_Attendant_Rate refers to the count of births attended by skilled birth attendants. Home_Delivery_Rate refers to the count of births at home.

Table 8. Screening and diagnostic coverage dataset

Barangay	Lab_Exams_Coverage	CBC	Stool	Urinalyses	Screening_Coverage
Barangay A	431	151	86	108	86
Barangay B	496	124	74	99	199
Barangay C	549	220	55	165	109

Note. Barangay refers to the geographic unit. Lab_Exams_Coverage refers to the count of pregnant women who received the required laboratory tests. CBC, Stool, and Urinalyses refer to the number of conducted tests on pregnant women and correspond to the dataset variables “Lab_Exams_CBC, Lab_Exams_Stool, and Lab_Exams_Urinalyses” respectively. Screening Coverage refers to the count of pregnant women screened for key maternal health conditions.

Data Processing and Management

The study implements a systematic data processing workflow designed to transform raw administrative data into analysis-ready datasets while preserving data integrity and maximizing information extraction.

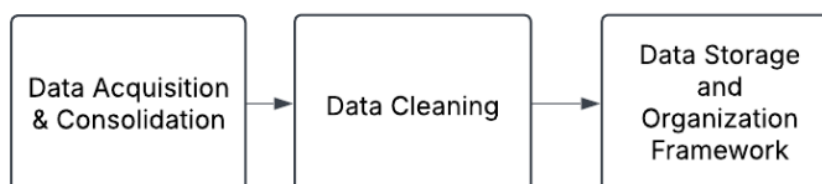


Figure 3. Data processing and management plan

Data Acquisition & Consolidation

The nature of the data requires extensive selection and removal of irrelevant data points. The RHIS dataset is a large and comprehensive report on all public health related data. There is a large amount of data within the dataset that serves no purpose to the thesis as our focus is on maternal health. The maternal health care dataset from RHIS is represented by nineteen Excel files for each of Davao City's districts. Within these files contain individual

sheets for every month of the year and all the relevant maternal health statistics subdivided into individual barangays. With five years of data from 2020-2024, there is a total of ninety-five individual Excel files. These files were created primarily to optimize data entry and readability. This results in structural issues that make it difficult to work with. Specifically, merged header cells, multiple header rows, embedded formatting, and references to external files. Steps need to be taken in order to manage these structural issues to ensure efficient data management.

There are 298 data rows in the excel file; however, most of these are subsets of other statistics that are divided by age-group or other subdivisions. There are also a significant number of rows that contain data that is irrelevant to study. These will need to be managed accordingly so that only relevant data is collected. The relevant data will be selected and transferred to a comprehensive database with all relevant data cleaned and ready for further analysis. These will then be compiled into more specific datasets to be implemented into causal forests.

A standardized script will be used to integrate the Excel files into R; the script includes importing the Excel files and managing the different sheets within them. Following that, the script will remove irrelevant formatting and fix column and row names. This step is essential for integrating data from disparate sources with different structures. Creating structured integration protocols ensures consistent merging methodology across temporal and spatial dimensions. These protocols include standardized naming conventions, assigning unique identifiers to barangays/districts, and ensuring the handling of different levels of granularity.

Data Cleaning

The RHIS dataset is already a comprehensive and aggregated report that is submitted to the national government as such. However, because it is primarily formatted for reporting instead of analysis, extensive formatting adjustments are required. However, due to RHIS being primarily a reporting system for decision makers, there is substantial formatting and redundant rows and columns for the sole purpose of readability and data entry. Before data cleaning when the Excel file is imported into R, there is a total of ~400 columns, most of these are just artifacts from the way it was formatted and presented in Excel.

These formatting artifacts will need to be carefully removed and excluded from the dataset. Column headers for each barangay are repeated multiple times within the dataset. There are multiple merged cells and entries that provide additional information to the data. Empty placeholder columns for each barangay that are used for data entry. The rows that exist solely to aggregate statistics that were divided by group such as age group, pregnancy trimester, or screened and diagnosed patients. After removing all the formatting data and data entry columns, the resulting data set now only has 298 rows and the correct number of columns for barangays that exist within each district.

Data Storage and Organization Framework

The aggregated dataset will then be stored to PostgreSQL, providing flexible data queries and seamless integration to the dashboard for data visualization. Data security and access control will remain under the discretion of the CHO.

Data Analysis

The analysis will be conducted in three sequential phases using robust statistical and computational methods. Each analytical method has been carefully selected based on its suitability for addressing specific research questions, handling the characteristics of maternal health data, and specifically, for identifying heterogeneous treatment effects in a spatial context. The overarching goal is to transform processed data into actionable insights regarding intervention effectiveness across Davao City.

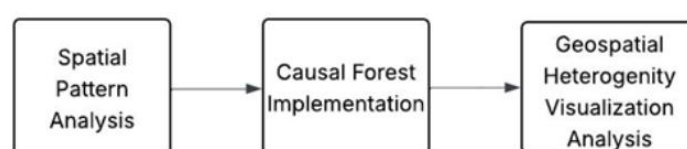


Figure 4. Data analysis plan

Phase 1: Spatial Pattern Analysis

This initial phase focuses on characterizing the spatial distribution of key variables and identifying underlying geographic patterns that may influence both intervention implementation and health outcomes. This allows for a deeper understanding of the research setting and informs the subsequent causal inference models.

A) Geographic Feature Engineering

This step involves creating new spatial variables that encapsulate critical aspects of access and infrastructure.

Healthcare Worker-to-Population Ratios: For each barangay, calculate the ratio of different types of healthcare personnel (e.g., doctors, nurses, midwives, Barangay Health Workers) to its total population.

B) Facility Density and Distribution Metrics

Spatial Density: The number of birthing facilities per Barangay.

Categorization of Facilities: Facilities will be categorized and their distributions analyzed to understand the types of services available within different geographic areas.

Spatial Clustering: This involves identifying areas with statistically significant concentrations of similar characteristics, which could indicate underlying spatial processes or disparities.

Phase 2: Causal Forest Implementation

This phase is the core of causal inference, leveraging the strengths of Causal Forests to estimate the heterogeneous impacts of interventions. Causal Forests are particularly suited for this study due to their ability to (1) handle high-dimensional data with numerous covariates without requiring strong assumptions about their functional forms, (2) robustly estimate causal effects in the presence of complex confounding, and most importantly, (3) directly estimate heterogeneous treatment effects (HTE), allowing for the identification of how intervention effectiveness varies across different barangays based on their unique characteristics. This machine learning approach provides a non-parametric way to uncover nuanced causal relationships that traditional linear models might miss. The model specifications are as follows:

A) Outcomes (Y):

- Maternal morbidity/mortality rates
- Neonatal mortality/morbidity rates
- Stillbirth rates

B) Treatments (W):

- Prenatal care coverage metrics
- Maternal vaccination rates
- Maternal supplementation rates
- Skilled birth attendant delivery rates
- Health facility delivery rates
- Screening and diagnostic test coverage rates

Below are the intervention variables, representing the "intensity" or coverage of maternal healthcare interventions within each barangay. Each intervention will be analyzed individually as a "treatment" variable against the outcomes.

C) Covariates (X):

- Demographic characteristics: Age distribution of birthing mothers, barangay population density, total barangay population.

- Facility access and geographic features: The engineered variables from Phase 1, including healthcare worker-to-population ratios, facility density, and barangay spatial categories. These are crucial for understanding geographic heterogeneity.
- Temporal indicators: Year and month fixed effects to account for time trends or seasonality in health data.

Furthermore, the following are the potential confounders and effect modifiers that influence both intervention uptake and health outcomes and are critical for achieving causal identification.

A) Causal Forest Training:

The Causal Forest model will be trained using the `grf` package in R (or `econml.grf` in Python), which implements Generalized Random Forests. This involves growing an ensemble of causal trees, where each tree is built by recursively partitioning the covariate space to minimize the variance of treatment effect estimates within each leaf node.

B) Hyperparameter Tuning:

Key hyperparameters such as the number of trees (`num.trees`), minimum node size (`min.node.size`), and subsampling rates (`sample.fraction`) will be tuned using cross-validation to optimize model performance and ensure robust estimation.

C) Treatment Effect Estimation:

- Average Treatment Effects (ATE): For each intervention, the overall average causal impact on the various maternal and neonatal health outcomes across all barangays will be estimated. This provides a general understanding of the intervention's efficacy.
- Conditional Average Treatment Effects (CATE): This is the primary output of interest for addressing the study's core question on heterogeneity. Causal Forests will estimate the CATE for each intervention at the individual barangay level, conditional on its unique profile of covariates (including all geographic features). This allows for a granular understanding of how the impact of a specific intervention varies from one barangay to another.
- Heterogeneous Treatment Effects across Geographic Features: The estimated CATEs will then be analyzed to explicitly identify how the effectiveness of interventions differs based on specific geographic features. This analysis will highlight which geographic contexts are most receptive or resistant to interventions.

Phase 3: Geospatial Heterogeneity Visualization Analysis

This delves into understanding the drivers of the heterogeneous treatment effects identified in the Causal Forest Model, focusing heavily on geographic factors.

A) Variable Importance Measures:

- Quantifying Predictive Power: The importance of each geographic feature in explaining the variation in estimated treatment effects will be formally assessed. This will be done by examining how much each covariate contributes to the heterogeneity in the estimated CATEs within the Causal Forest framework (e.g., using "feature importance" metrics specifically designed for HTE estimation in causal forests, which identify variables that predict differences in treatment effects).
- Comparison of Spatial vs. Non-Spatial Variables: A direct comparison will be made to ascertain whether spatial variables are more predictive of treatment effect variation than traditional demographic or socio-economic variables. This will highlight the unique contribution of the spatial dimension to understanding intervention effectiveness.

B) Interaction Analysis:

- Identifying Thresholds and Synergies: While causal forests implicitly account for complex interactions, this phase will explicitly analyze key interactions to provide actionable insights. This includes:

- **Role of Facility Type and Personnel Allocation:** Investigating if specific types of facilities or higher allocations of particular healthcare personnel amplify or diminish the effects of certain interventions, especially in remote or underserved areas.

Verification and Validation Strategy

Rigorous verification and validation strategies will be employed throughout the analysis to ensure the robustness, reliability, and generalizability of the study's findings, particularly concerning the causal claims in a spatial context.

A) Cross-Validation

- **Spatial Cross-Validation:** To accurately assess the model's performance and avoid overfitting due to spatial autocorrelation, blocked cross-validation will be implemented. This approach ensures that training and validation sets are geographically independent, providing a more conservative and realistic estimate of predictive accuracy and causal effect estimation.
- **Out-of-Sample Prediction Evaluation:** The performance of the causal forest models will be evaluated on unseen data using appropriate metrics. For continuous outcomes (rates), Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE) will be used. For binary outcomes or proportions, Area Under the Receiver Operating Characteristic Curve (AUC), precision, recall, and F1-score will be considered. The stability of estimated CATEs across different cross-validation folds will also be monitored.

B) Falsification Tests (Placebo Tests):

- **Applying Methodology to Unaffected Outcomes:** The causal forest methodology will be applied to outcomes that are theoretically unlikely to be affected by the maternal healthcare interventions (e.g., adult male mortality rates, incidence of non-maternal/neonatal specific communicable diseases that do not directly involve the maternal health system). If significant causal effects are detected for these "placebo" outcomes, it would indicate potential unobserved confounding or issues with the causal identification strategy.
- **Testing for Effects Before Intervention Implementation:** Where historical data allows, the methodology will be applied to data from a period before the substantial implementation of the interventions being studied. The absence of significant "treatment effects" during this pre-intervention period would provide stronger evidence that the observed effects are genuinely attributable to the interventions rather than pre-existing trends or unobserved factors.

Ethical Considerations

The study adheres to the highest ethical standards in health research, prioritizing data privacy, confidentiality, and responsible dissemination of findings. All data handling complied with the Data Privacy Act of 2012, ensuring confidentiality of patient records and ethical use of health information (Official Gazette, 2012).

- A) **Data Aggregation and De-identification:** The study will exclusively use aggregated, de-identified data at the barangay level. No individual patient information will be accessed, processed, or stored at any point. This ensures that the privacy of individuals is fully protected.
- B) **Formal Data Sharing Agreements:** A formal, Data Sharing Agreement (DSA) will be established with the Davao City Health Office (CHO). This agreement will explicitly outline the terms of data access, usage, storage, retention, and destruction, ensuring compliance with the CHO's data governance policies and national data privacy laws.
- C) **Responsible Reporting and Dissemination:** Research findings will be reported responsibly, focusing on public health implications and avoiding any form of stigmatization of specific geographic areas or populations. Results will be presented in a way that is culturally sensitive and promotes equitable health interventions. Complete findings, including the developed dashboard, will be shared proactively with the Davao City Health Office and other relevant public health stakeholders to inform evidence-based public health action and policy development.

Software and Tools

The analysis will primarily utilize powerful open-source programming languages and specialized libraries, complemented by Geographic Information System (GIS) software and robust data management tools.

- Programming Languages:
- Python 3.9+:

Data Manipulation: Pandas 1.4.0+ for efficient data cleaning, transformation, and aggregation.

Geospatial Analysis: GeoPandas 0.10.0+ for working with spatial dataframes, performing spatial joins, and manipulating geographic features.

Statistical Modeling: Statsmodels 0.13.0+ for complementary statistical tests and basic regression analysis.

Visualization: Matplotlib, Seaborn, and Plotly for creating static and interactive data visualizations to present the analysis results.

API Routing: Flask framework and Cross-Origin Resource Sharing (CORS) to route requests to and from the frontend framework.

- R 4.1.0+:

Data Processing: tidyverse suite (e.g., dplyr, ggplot2, tidyr) for efficient data manipulation, visualization, and consistent syntax.

Causal Inference: grf (Generalized Random Forests) package for robust implementation of Causal Forests and other causal machine learning methods.

- GIS Software:
- QGIS 3.22+: A free and open-source desktop GIS application for advanced geospatial processing, digitizing, geocoding health facility addresses, creating detailed basemaps, performing network analysis for distance calculations and cartographic production for thesis figures.
- Database:
- PostgreSQL: This will serve as the primary database to hold the aggregated dataset to fetch data to the dashboard.

Data Visualization



Figure 5. Davao City Barangays and Districts Shapefiles exported via GeoJSON from QGIS

Like other related studies, the best way to comprehend data is visualization through heatmaps by creating a dashboard. The dashboard consists of a map panel that only shows Davao City as well as its surrounding districts and barangays via GeoJSON shapefiles exported from QGIS, as well as card panels to display number statistics

of the dataset. The dataset, "philippines-psgc-shapefiles" by altcoder found on Github, is used for the shapefiles to trace out barangays found in Davao City, whereas OpenStreetMaps via overpass-turbo is used for tracing districts. This method saves performance on the app as the GeoJSON files are saved locally, rather than relying on APIs to fetch maps and shapefiles. In an administrative level to classify a country, barangays are classified as level 4, whereas districts are classified as level 2.

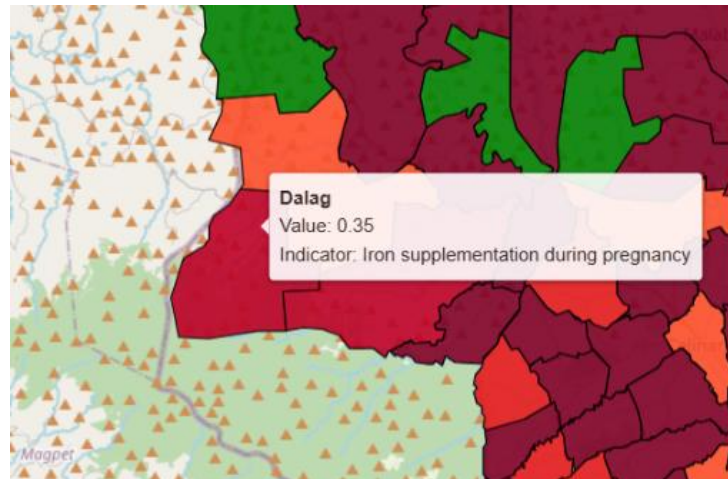


Figure 6. Sample Barangay heatmap with top indicator and value

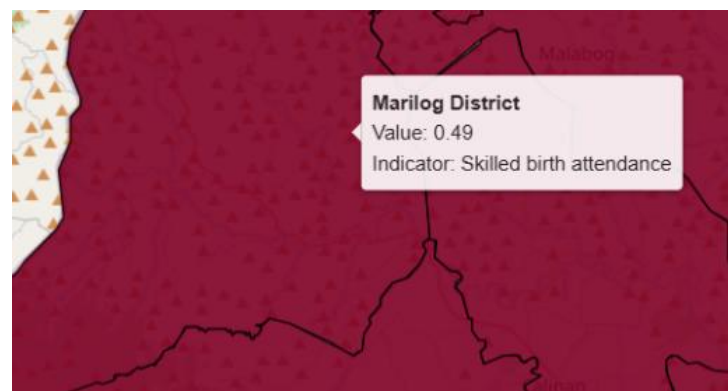


Figure 7. Sample district heatmap with top indicator and value

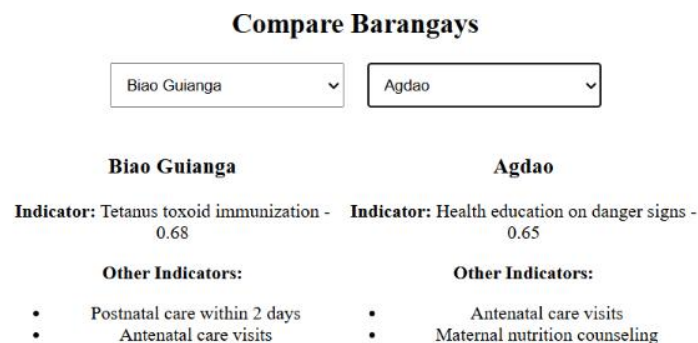


Figure 8. Comparing Barangay A and B

The frontend will be developed using JavaScript with the React framework under Vite, providing a lightweight and fast development environment. The backend will be powered by Python using the Flask framework, which is responsible for serving the GeoJSON shapefiles, handling API requests to fetch and process relevant data (e.g., maternal care indicators, barangay and district names, numerical data) and building the proposed model. These data values are bound to geographic units and visualized as color gradients on the map using heatmaps, allowing users to visually identify areas of concern or interest. Interactive features such as showing either barangays or districts on the map panel, as well as a component for comparing barangay A and B, will be implemented to enhance user engagement and support decision-making. Cards displayed on the right side of the map panel will provide an overview of the dataset, including numbers of total morbidity and mortality cases, along with other

relevant numerical indicators. The data presented in the figures above are for illustrative purposes only and do not represent the actual dataset to be used in the study.

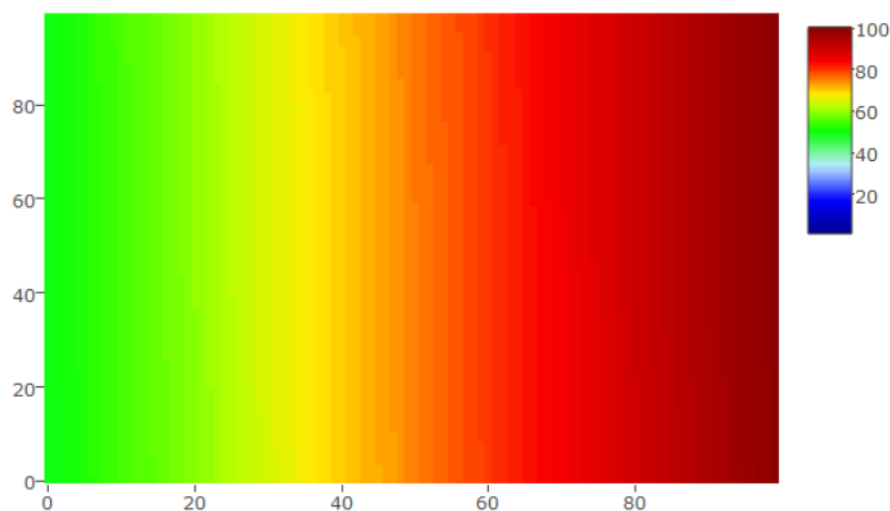


Figure 9. Sample green-to-red heatmap

The heatmaps will indicate the severity of predicted indicators based on the trained model. Each barangay will display the value of its top indicator, as well as other indicators based on its hierarchical value in descending order, and be classified as Safe (green), Caution (yellow), or Act (red).

Results and Discussion

This study analyzed 10,920 barangay-month records from January 2020 to December 2024, covering 182 barangays in Davao City. The primary outcome of interest is the pregnancy outcome, measured as a normalized ratio of stillbirths/abortions to live births. The treatments evaluated are a comprehensive suite of maternal health interventions, including prenatal checkups, anemia and tetanus management, counseling, birth planning, screening for diseases, and ensuring skilled attendance at facility-based deliveries. A causal forest model was utilized with district-level blocked spatial cross-validation to estimate the causal effects of these interventions while accounting for geographic dependencies. As these results are preliminary, further model refinement will be necessary to precisely identify the relevance of specific covariates in driving treatment effect heterogeneity.

Preliminary Analysis: Causal Impact of Outcomes

As a preliminary step before assessing the primary outcome, the causal forest was first applied to measure the effect of the interventions on key intermediate outcomes related to service utilization. This initial analysis is crucial for understanding *how* the program achieves its goals. The Average Treatment Effect (ATE) was estimated for various indicators, representing the intervention-driven increase in the probability of a pregnant woman receiving a specific service. The results show the interventions are highly effective in promoting foundational and planning-related aspects of prenatal care. The strongest causal impact was observed in the creation of birth plans (ATE: 0.301), followed by encouraging first-trimester prenatal visits (ATE: 0.234) and providing health information on danger signals (ATE: 0.216). These findings suggest the program successfully influences proactive health-seeking behaviors. Moderate effectiveness was observed in anemia management and supplementation protocols. The interventions led to a significant increase in the identification of anemic women among those tested (ATE: 0.186) and in the completion of iron with folic acid supplementation by the time of delivery (ATE: 0.127).

The program's impact on the uptake of specific laboratory screenings and tests was positive but more modest. Ensuring women receive three basic laboratory exams (ATE: 0.103) and hemoglobin determination (ATE: 0.092) were the most notable effects in this category. Conversely, screenings for specific diseases like Syphilis (ATE: 0.005), HIV (ATE: 0.004), and Hepatitis B (ATE: 0.001) showed the smallest causal impacts. A summary of these preliminary ATEs on service uptake is presented below.

Table 1. Average treatment effects (ATE)

Category	Indicator	ATE
Prenatal Care	No. of pregnant women with birth plan	0.301
	First prenatal visit (1st PNV)	2.34
	Provided with health info, advice, counsel	0.216
Anemia Management	Diagnosed with anemia	0.186
	Completed dose of iron with folic acid	0.127
Screening/Testing	With three (3) basic laboratory exams	0.103
	Hemoglobin determination	0.092
	Screened for gestational diabetes	0.046
	Screened for Syphilis	0.005

Conclusion

This study demonstrates the successful application of a geospatial causal forest framework to evaluate a complex set of maternal health interventions in Davao City. By analyzing their impact on service uptake as a preliminary step, this research provides a nuanced understanding of the mechanisms through which the program operates. The initial findings are highly relevant for our primary stakeholder, the Davao City Health Office. The results indicate that current interventions are exceptionally effective at improving process-oriented outcomes like birth planning, early-trimester checkups, and health counseling. These are critical successes. However, the more modest impact on specific disease screenings suggests that targeted strategies may be needed to overcome barriers related to these services, which could include supply-side constraints, provider training, or patient-level factors.

As this research is ongoing, these preliminary results on service utilization form the foundation for the next phase of analysis. Future work will directly link the uptake of these specific services to the primary outcome—the reduction of stillbirths and abortions. By estimating the heterogeneous treatment effects, we will identify which interventions, in which specific barangays, have the greatest causal impact on saving lives. This will ultimately provide the Davao City Health Office with a data-driven tool to optimize resource allocation, refine public health strategies, and advance the goal of ensuring safe and healthy pregnancy outcomes for every mother in the city.

Recommendations

To evaluate robustness across various methodological frameworks, future research should expand on this work by further honing the use of causal forests with alternative techniques like Bayesian causal inference and Double Machine Learning. An additional approach would be to broaden the analysis's scope to include other Philippine regions or comparable low- and middle-income country contexts. This would improve the findings' generalizability and offer comparative insights into the spatial heterogeneity of maternal health outcomes.

Researchers are also encouraged to incorporate individual-level datasets to complement barangay-level analyses and to allow deeper understanding of patient-level risk factors. Longitudinal validation with updated Routine Health Information System (RHIS) data is recommended to evaluate the temporal stability of treatment effects and to capture evolving patterns in maternal health care delivery. Moreover, integrating additional determinants such as socioeconomic indicators, transportation access, and cultural practices into causal frameworks may improve contextual interpretation. Lastly, future studies may explore the development of open-source, user-friendly geospatial decision-making support tools that extends beyond visualization to real-time predictive modeling, thereby proceeding its translational value of causal machine learning in maternal health research.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Radon Exposure Study in Underground Mine Sites

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Abstract: The seepage of radon from the bowels of the earth is practically a natural process, and the accumulation of this gas can be observed in any closed ground spaces, underground mines, tunnels, underground garages, etc. That is why the measurement of radon concentrations is of interest not only to the mining industry and underground mines. For the present study, experimental measurements have been carried out for radon exposure in three underground mines using two methods for measuring radon content - digital (with an electronic device) and analytical (by placing CD/DVD plates). The analytical method is the placement of CD/DVD plates for measuring radon/thoron in underground sites (mining galleries, caves, etc.). The principle of the CD/DVD method is that it combines the high absorption capacity of the polycarbonate material of the discs with its track properties. This makes it possible to clarify the contribution of thoron and radon to the irradiation of miners and above-ground personnel. The digital method was carried out with the help of an electronic device, with which continuous monitoring of the concentration (volume activity) of radon in one of the underground sites was carried out and the results were compared with those from CD/DVD plates.

Keywords: Radon, Thoron, Radon detectors, Underground mines, Radon exposure

Introduction

Radon is a radioactive gas discovered in 1900 by the German physicist Friedrich Dorn. As a member of the uranium-radium decay chain, it is distributed everywhere across the Earth – in soils, rocks, minerals, water, and air (Samson et al., 2026; Sapmaz Il & İçhedef., 2026). As a gas, radon migrates through air pores and fissures, reaches the Earth's surface, and is released into the ambient atmospheric air. Some materials used in construction, such as concrete structures and rock cladding and linings in metro tunnels and similar confined spaces, can also be a source of radioactive radiation (Borisov, 2021). In enclosed spaces, it has the property of accumulating. Radon is a dominant factor in the exposure of the global population to natural radioactive sources and activities related to the mining and processing of uranium-bearing minerals (Dai et al., 2026). In 2009, the World Health Organization identified radon as the second most significant cause of lung cancer after smoking. Recognized as the most consequential occupational hazard faced by underground workers, chronic inhalation of radon decay products emerged decades ago as the dominant driver of lung cancer among mining populations, contributing a substantial share of premature deaths recorded across major mining cohorts worldwide (WHO, 2009; WHO, 2021b). The International Commission on Radiological Protection (ICRP) recommended that national radiation protection authorities introduce reference levels for radon concentrations in dwellings and workplaces (ICRP 137, 2017). Because uranium-bearing rock continuously emits radon gas as part of its natural radioactive decay chain, underground workings frequently trap this invisible, odorless contaminant at concentrations far above surface background levels, placing every worker who enters such spaces at measurable

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risk of chronic radiation exposure (Li et al. 2026). As a consequence of this, reference levels for radon exposure have been introduced in many European countries (EU Council Directive 2013/59/EURATOM, 2013). When higher radon levels are detected, it is necessary to take appropriate measures. Determining the radon level is achieved through direct measurement.

Modern health assessments for radon and thoron follow the International Commission on Radiological Protection (ICRP) Publication 137. These guidelines updated and essentially doubled previous dose coefficients, adopting an advanced dosimetry model rather than older epidemiological approximations. Modern Dose Conversion Coefficients (ICRP 137) see Table 1. For both dwellings and most indoor workplaces, the ICRP uses a standardized dose coefficient: Radon (^{222}Rn) Coefficient: 3 mSv per mJ h m^{-3} (approx. 10 mSv/WLM or 6.7 nSv per Bq h m^{-3}). Worker Exposure: For physical activities in specific workplaces (like tourist caves or confined spaces), the coefficient increases to 6 mSv per mJ h m^{-3} . Thoron (^{220}Rn): Doses from thoron progeny are typically calculated via site-specific biokinetic and respiratory models outlined in the Occupational Intakes of Radionuclides (OIR) series (ICRP 137, 2017; Rani et al., 2026).

Table 1. Effective doses from inhalation of radon and thoron in workplaces by a reference worker with an average breathing rate of $1, 2 \text{ m}^3 \text{ h}^{-1}$ (ICRP 137, 2017)

Exposure/place*	Unattached fraction, f_p	F	Effective dose per exposure†		
			mSv per WLM	mSv per mJ h m ⁻³	mSv per Bq h m ⁻³
<i>Radon (²²²Rn) gas + progeny</i>					
Indoor workplace	0.08	0.4	20	5.7	1.3 × 10 ⁻⁵
Mine	0.01	0.2	12	3.3	—
Tourist cave	0.15	0.4	24	6.7	1.5 × 10 ⁻⁵
<i>Thoron (²²⁰Rn) progeny</i>					
Indoor workplace	0.02	—	5.6	1.6	1.2 × 10 ^{-4‡}
Mine	0.005	—	4.8	1.4	1.0 × 10 ^{-4‡}

Note. f_p , unattached fraction in terms of the potential alpha energy concentration; F , equilibrium factor.

* The assumed aerosol distributions for the different workplaces are given in Tables A.3 and A.4 of Annex A.

† For radon, 1 WLM = $(6.37 \times 10^5/F) \text{ Bq h m}^{-3}$; for thoron, 1 WLM = $4.68 \times 10^4 \text{ Bq h m}^{-3}$ of equilibrium equivalent concentration of ^{220}Rn ; 1 WLM = 3.54 mJ h m^{-3} .

‡ In terms of mSv per Bq h m^{-3} of equilibrium equivalent concentration of ^{220}Rn .

The working and microclimate conditions in underground mining sites are different from those in buildings and in open atmospheric conditions. This specifics should be considered by selecting the preferred measurement methods and tools appropriate to these conditions. Air quality in underground sites and deep open-pit mines depends on a number of factors such as: internal combustion engine (ICE) operation, blasting and underground fires. etc. (Dinchev et al, 2014). This requires constant monitoring and installation of fire-detection and fire-protection systems (Makedonska et al 2019, 2025). The obtained data in an underground mine from various process monitoring are very complex and often require further data post-processing (Mischio H., & Krichler T. 2022). The underground environment is challenging for the measuring with CD/DVD detectors due to:

- High humidity (close to 100%) leading to condensation on the detectors (Günther et al., 2026)
- Explosive gases (NO_x , forming of acidic substances with moisture)
- High concentration of dust
- Blast waves of various intensity and force (Mollova, 2025);
- Curious or malicious personnel causing loss (damage) of detectors;

To compile a detailed map of radon levels in the air of the mine galleries and diagnose the efficiency of ventilation, the points at which simultaneous measurements must be carried out are numerous and distributed throughout the mine. When selecting a method to assess radon exposure, several critical factors must be considered, namely cost-effectiveness, environmental adaptability, and accessibility. Recent trends show a diversification of materials employed for long-term cumulative radon monitoring, integrating with conventional alpha-track techniques (Rathebe & Kholopo, 2024).

Method

The present study evaluates the effectiveness of analytical method with CD/DVD polycarbonate discs for passive radon monitoring in three underground mine sites. The analytical method for cumulative measurements of radon (^{222}Rn) and thoron (^{220}Rn): consists of placing CD/DVD plates for measuring radon/thoron in underground spaces and mine workings (mining galleries, caves, etc.). This includes specifying the influence of underground conditions on the readings of these detectors and comparing them with other methods for radon measurement including electronic devices and diffusion chambers (Dimitrov D., Pressyanov D, 2018). The method is based on specific ability of polycarbonate material, used for commercial CD/DVDs. This material is highly radon absorbent and has track-etch properties (Figure 1). In 2011 and following, the capacity of the CD/DVD method was expanded (Pressyanov et al., 2018, 2019, 2022, 2026) with the possibility of differential measurements of thoron ^{220}Rn , using a development of the CD-disk method and application in distinct conditions indoors and outdoors.

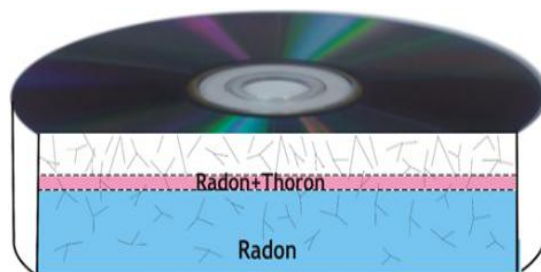


Figure 1. The principle of the CD/DVD method - Signal formation (Dimitrov D. 2020)

The main point of the method is that the time-integrated volumetric activity of radon can be determined from the density of α -particle traces at a strictly defined depth below the surface. At depth greater than $>76\mu\text{m}$, the signal is formed only from absorbed ^{222}Rn and its progeny (R-signal). Furthermore, at depth interval $64-76\mu\text{m}$ the signal is due to source connected to ^{220}Rn thoron (T –signal) namely ^{212}Po (decay product of ^{220}Rn) and from absorbed ^{222}Rn (R+T signal) (Figure 2). For the purpose of measuring ^{220}Rn the R-signal is used also to determine and subtract the ^{222}Rn contribution to the R+T signal in the first depth. The remaining “thoron component” (T-signal) is used to measure ^{220}Rn . This allows to eliminate the signal obtained from the progeny decay products in the environment and, after appropriate processing of the discs, to obtain a signal that is easy to register and read. The further treatment process of CD-DVDs like electrochemical etching (ECE) are described elsewhere (Pressyanov et al, 2022)

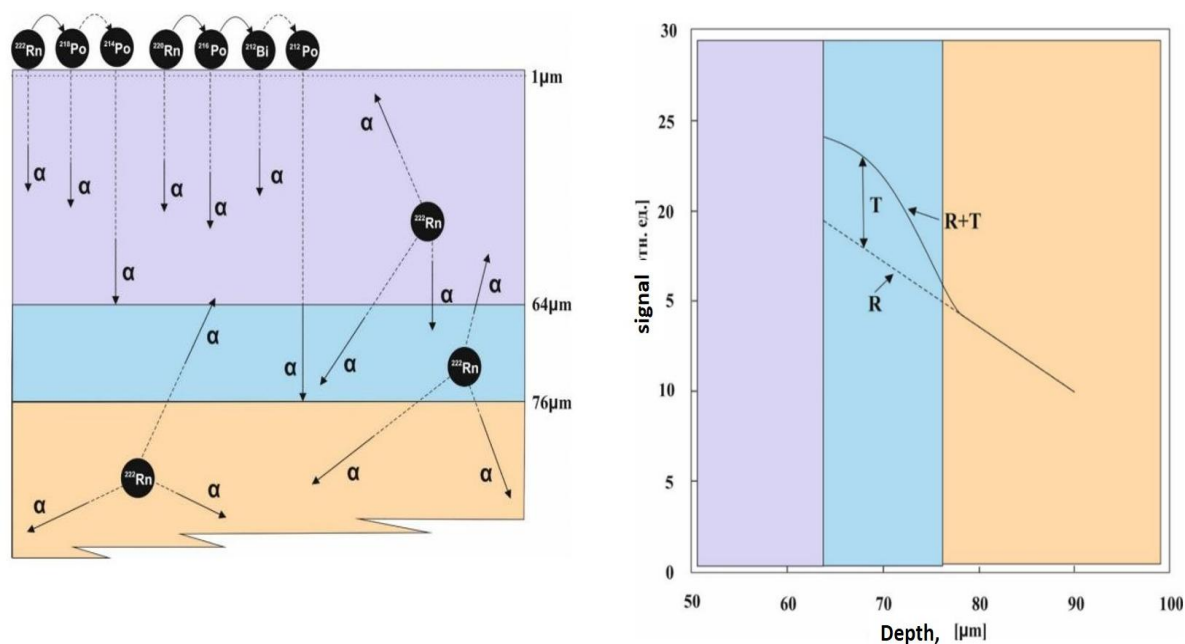


Figure 2. Radon and thoron signal depth distribution (Dimitrov D. 2020)

An important advantage of this method in an underground environment is that normal moisture condensation does not affect the measurement. The calibration factor depends on the temperature at the time of irradiation. The temperature influence can be reported, corrected if necessary. If it is not known, posteriori correction can be

applied. Other factors (pressure, dust, smoke, blast waves) do not affect the CD/DVD method. The CD/DVD method is sensitive and accurate enough to measure ^{222}Rn and ^{220}Rn in underground spaces and mines.

Experiments

Three study sites were selected for conducting the experiment: underground mines with distinct characteristics, varying geological conditions, and different types of extracted raw materials, mainly polymetallic ores (Table 2). Passive radon/thoron detectors were deployed across all three sites, with Site 3 featuring parallel measurements using an electronic radon monitor.

Table 2. Study sites characteristics

Mining site	Type	Ore extraction	CD number	Location
Site 1	Underground mine site	Gold - silver ores	28	Bulgaria
Site 2	Underground mine site	Lead – zinc ores	20	Bulgaria
Site 3	Underground mine site	Silver ore (Lead – zinc ores)	15	Germany

The geological conditions, as well as the characteristics of each mine site, are specific in terms of depth, type of ore, and microclimate characteristics (Table 3). The aim of the study is to compare the presence of radon/thoron under different conditions and to establish the applicability of the measurement method with CD/DVD discs.

Table 3. Experiment settings

Study site	Number of detectors	Exposition period	Temperature	Relative Humidity	Depth	Underground waters	Notes
Mine Site 1	28	6 months	11 – 14 °C	68 - 78% incl. shaft; 78 - 87 % galleries	From level 810 to 760	yes	
Mine site 2	20	3 months	15°C	dry	From level 460 to 240	no	
Mine site 3	15	3 months	10 °C	90% -95%	150 m	yes	*Digital Monitor

Description of Studied Mine Sites

Study Site 1 – Underground Mine Site for Extraction and Processing of Gold (Au) – Silver (Ag) Ores

Site 1 - is an underground mine located in the Western Srednogorje region, Western Bulgaria (Figure 3 and 4). The geological structure of the deposit area and its metallogenic specialization are determined by an Upper Cretaceous volcanic trough, filled with a thick layer of medium to basic volcanics and their tuffs, representing a small segment of the regional Banat-Srednogorje volcanogenic-metallogenic zone. The manifestations of mineralization of precious and non-ferrous metals are associated with partially exposed Upper Cretaceous porphyry stocks. Subsequently, the Upper Cretaceous volcanics and hydrothermal systems are covered by thicker Paleogene and Neogene sediments, folded into extensive synclinal structures. The occurrences of mineralization of precious and non-ferrous metals are associated with partially exposed Upper Cretaceous porphyry stocks. Subsequently, the Upper Cretaceous volcanics and hydrothermal systems were covered by thicker Paleogene and Neogene sediments, folded into extensive syncline structures..

An inclined shaft is used for the exploration and extraction. The entrance is at elevation 811 with slope 1/7 (14 degree). The inclined shaft is a rectilinear construction, and it is planned to use it to cut the ore veins at Chor. 760. The total length of the inclined shaft will be 380 m. During the period of normal operation and exploration of the mine, it is planned to use a flank suction ventilation system after the construction of the ventilation systems at two ventilation chimneys, located respectively at the eastern and western ends of the mine field. The clean air flow enters the opening workings located centrally in the mine field and through the central chimney will enter the respective horizon, where the mining operations are concentrated. The amount of air required to ventilate the mine is limited by the diesel-powered machinery intended for use in underground conditions, as modern trends in mining mechanization are towards the transition to electric vehicles and the use of autonomous

control methods (Gorbounov, 2025; Hristova, 2024). The designed main ventilation system ensures an air flow rate between 110 and 120 m³/s.



Figure 3. Site 1 – Underground mine site with Au – Ag deposits



Figure 4. CD/DVD positions on underground mine site 1

Study Site 2: Underground Mine for Extraction and Processing of Lead (Pb) – Zinc (Zn) Ores

Mining site 2 is located in the Southeastern part of Bulgaria, which is rich in ore and non-ore minerals. The greatest economic importance is given to lead-zinc and polymetallic ores (Madan, Rudozem, Lucky, Madzharovo and Zlatograd deposits). Lead-zinc deposits have a vein origin, with some ore-bearing veins having a length of up to several kilometers (Fig. 5) and sometimes in very hard-to-access areas (Aleksandrova et. al., 2025). In addition to lead and zinc, the ores contain copper, pyrite, gold, silver and other valuable components. Polymetallic ores are formed from hot mineralized solutions, which rose through the cracks of the rocks 20-30 million years ago. Chromium ore is found in Krumovgrad and Asenovgrad regions, and uranium ore - in Smolyan region. Tungsten is mined in Velingrad region. The deposits of fluorite (near Mihalkovo) and marble (Velingrad region) are of economic importance. Of the non-metallic minerals in the Eastern Rhodopes, asbestos, trass, perlite, and zeolites are of greatest importance. Figure 6 shows the position of CD/DVDs detectors in mine site 2.

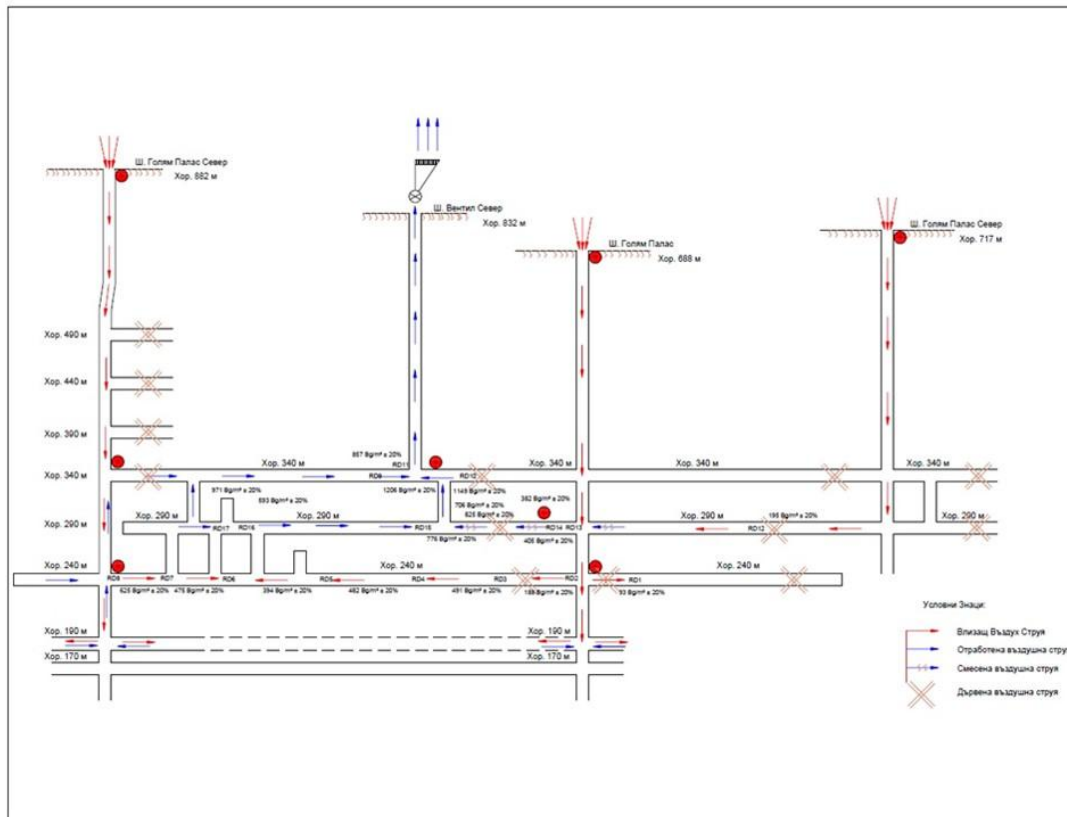


Figure 5. Site 2 – Underground mine site with Pb – Zn ore deposits

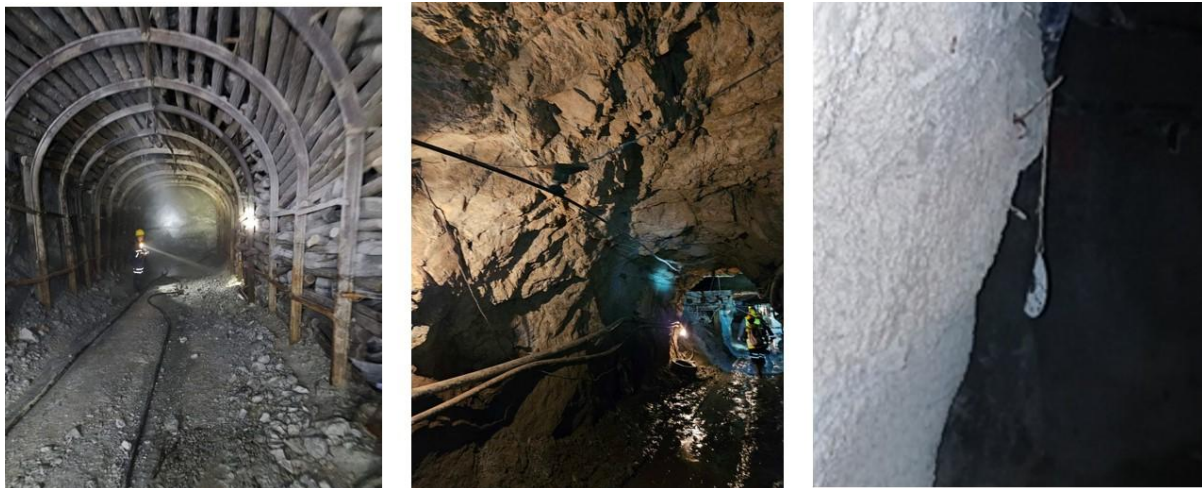


Figure 6. CD/DVD positions on underground mine site 2

Study Site 3: Underground Lead (Pb) – Zinc (Zn) Mine for Silver Ore (Ag) Extraction

The underground mine 3 is a lead-zinc deposit containing silver on the territory of Germany (Figure 7 and 8). The deposit is the most important ore deposit for the region in terms of its spatial extent, the quantities of ore mined and the metals extracted from it, its importance to the economic history of the region and the extent of geological research (Table 4). Geologically, it is a polymetallic, hydrothermal vein ore deposit of late Silurian to Silurian age with over 1100 known galleries. The galleries were the subject of mining activity from the late Middle Ages to the last third of the 20th century. Silver was the main extracted metal during most of the production periods. In addition, lead and zinc, as well as small amounts of copper, gold and trace metals, were of economic importance during the last periods of the mine's operation.

Table 4. Study site 3 – ore deposits composition

Ore type	Mineral	Chemical formula	Specific notes
Metallic ores	Galena	PbS	Basic Pb ore with high Ag content
	Sphalerite	ZnS	zinc sulfide mineral
	Pyrite	FeS ₂	Major raw material for sulfuric acid production; Low Au content – can be economically viable
	Arsenopyrite	FeAsS	
Silver (Ag) ores	Chalcopyrite	CuFeS ₃	Most abundant Cu content ore.
	Argentite	Ag ₂ S	Up to 87% Ag content
	Proustite	Ag ₃ [AsS ₃]	
	Argyrodite	Ag ₈ GeS ₆	Up to 74% Ag content and 6% Ge content
Non-metallic ores (rock minerals)	Quartz	SiO ₂	Nno economic importance; some of its variants are rock crystal, amethyst, agate, chalcedony
	Baryte	BaSO ₄	Due to high density is used as raw material for drilling
	Fluorite	CaF ₂	Collectable value – color variety and crystallisation
	Calcite	CaCO ₃	Collectable value



Figure 7. CD/DVD positions on underground mine site 3.

Results and Discussion

Figure 9 graphically presents the measured data for radon concentrations in the three underground mining sites compared to the maximum recommended threshold level of 300 Bq/m³ for homes and work exposure. In relation to this norm, radon fluctuations, as well as its exceedance, can be noted. The data obtained in Mine site 1 are with low radon content as presented on the graphic below. This low radon concentrations are caused by the positioning of the CD/DVDs near the entrance of the mine and the minor depth. The installed ventilation system ensures the necessary fresh air supply. The study mine site 1 is at the early stages of exploitation. Further radon exposure measurements are to be considered in the future.

Significant levels of radon were detected from the obtained data at Site 2, which is associated with the great depth and at places ineffective ventilation. In 85% of the disks, a radon signal accumulation above 300 Bq/m³ was reported, and in two of the points there was a detected signal values that surpass the 1000 Bq/m³ occupational threshold, especially in workings that lack robust mechanical ventilation or rely on natural airflow alone. Mine 2 has currently ceased operations

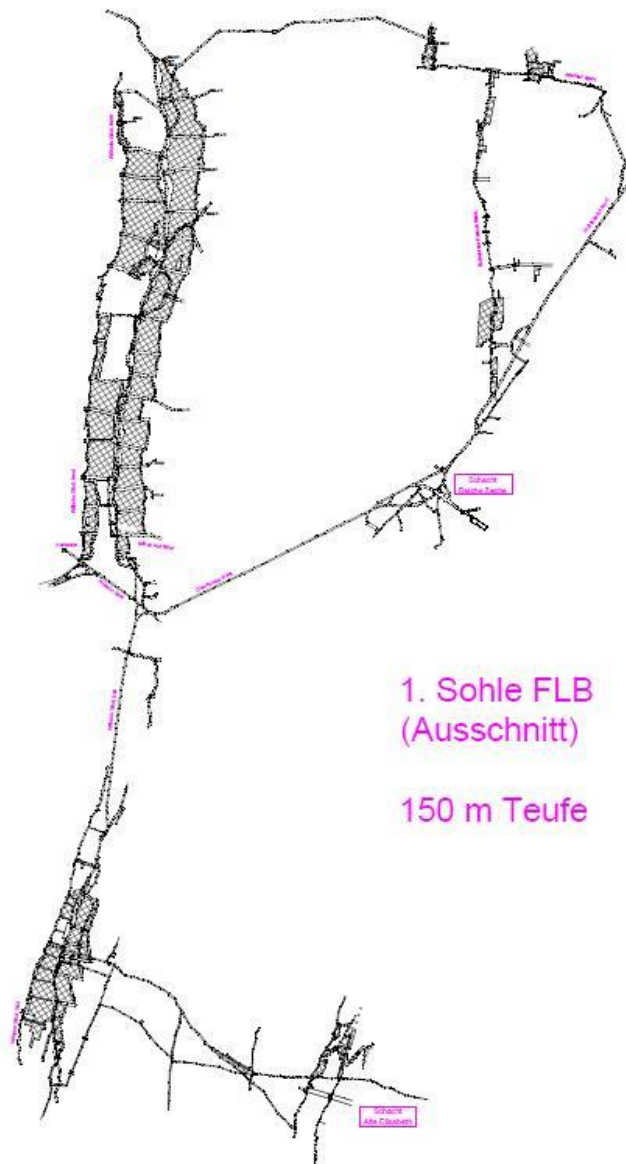


Figure 8. Site 3 – Underground mine site with Pb – Zn ore deposits and Ag extraction

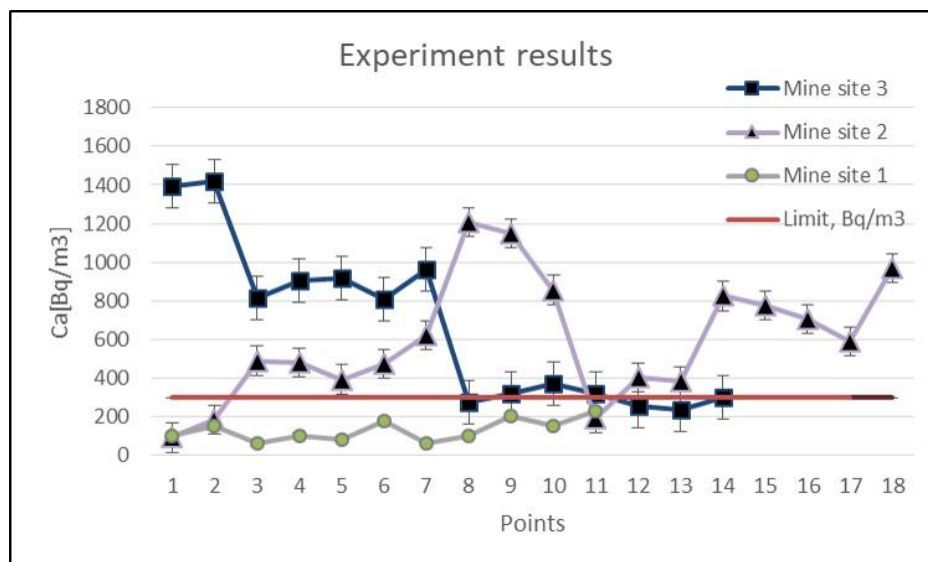


Figure 9. Result comparison for all experimental mine sites

Result Analyse for Mine Site 3

On particular interest are the data acquired in Site 3. The measured values are in wide range, from exceeding both 300 Bq/m³ and 1000 Bq/m³ thresholds. Due to the conditions in the mine 3 – low temperature (less than 10 degree Celsius) and high humidity (approximately 98 %), the radon signal (²²²Rn) on the CD/DVDs is considered relatively weak and hence the higher uncertainty of the radon measurement. In parallel with the passive time-integrated CD/DVD method independent control measurements were conducted using an active electronic device at four geographically randomized sampling points (Figure 10). The sampling points are in the proximity of corresponding polycarbonate detectors (Figure 11).

lfd. Nr.	Messort	Kurzzeichen	letzte Messung	C _{RN}	F	Dosis _h	Dosis ₂₀₀₀	Dosis _{0,4h}	Dosis _{0,4,2000}
				[Bq/m ³]		[μSv]	[mSv]	[μSv]	[mSv]
8	WMS 8		07.01.2020	419	0.02	0.06	0.13	1.33	2.67
9	WMS 9		03.12.2019	353	0.02	0.06	0.11	1.12	2.25
13	WMS 13		22.08.2019	1135	0.19	1.69	3.39	3.61	7.22
15	WMS 15		21.08.2019	836	0.25	1.65	3.31	2.66	5.32

Figure 10. Electronic device results

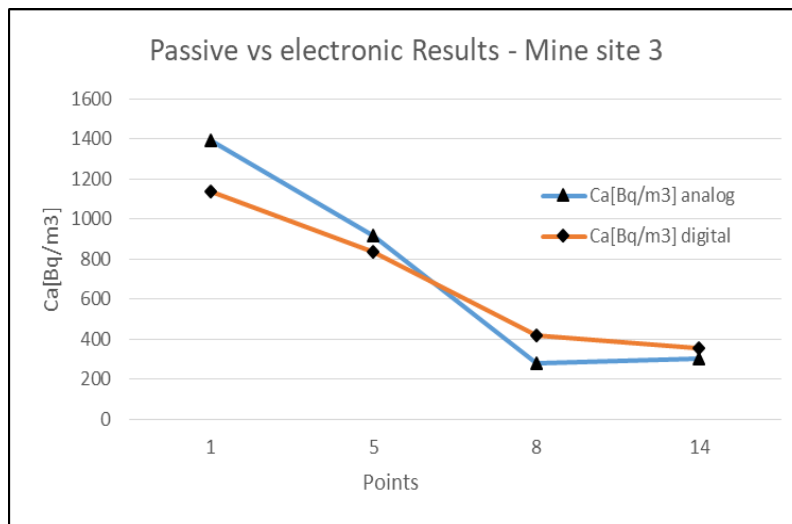


Figure 11. Results comparison - passive vs. electronic detector

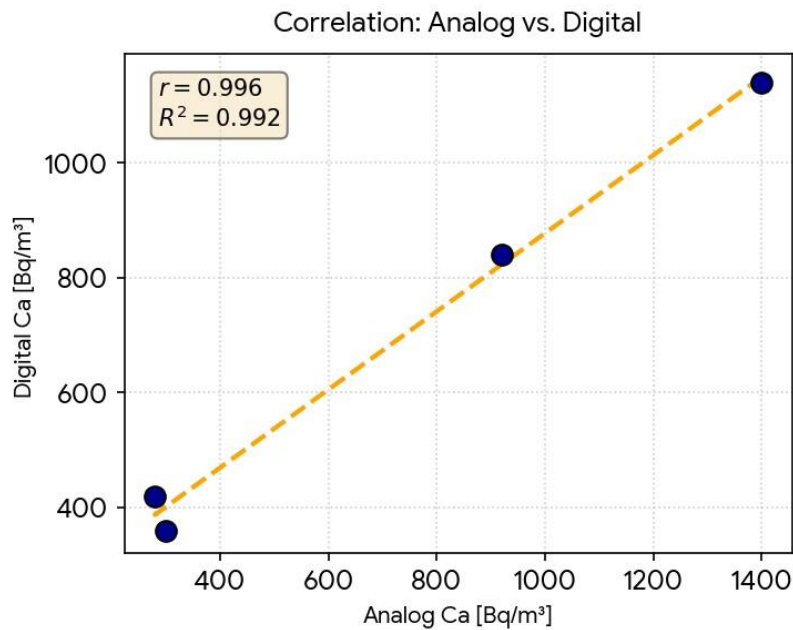


Figure 12. Result correlation - passive vs. electronic detector

These active readings were used to independently verify the accuracy of the passive CD/DVD method. Result comparison of the two independent measurement techniques (CD/DVD method vs. digital device) are in high agreement with $r = 0.996$, demonstrating the high validity of both approaches. (Figure 12). Furthermore, the analysis of thoron (^{220}Rn) concentrations results in notable findings. Radiometric evaluation of the passive detector disks revealed elevated (^{220}Rn) thoron signal. These data indicate that the atmospheric airborne radioactivity within this specific mine site is predominantly driven by a high contribution of thoron, as illustrated in Figure 13.

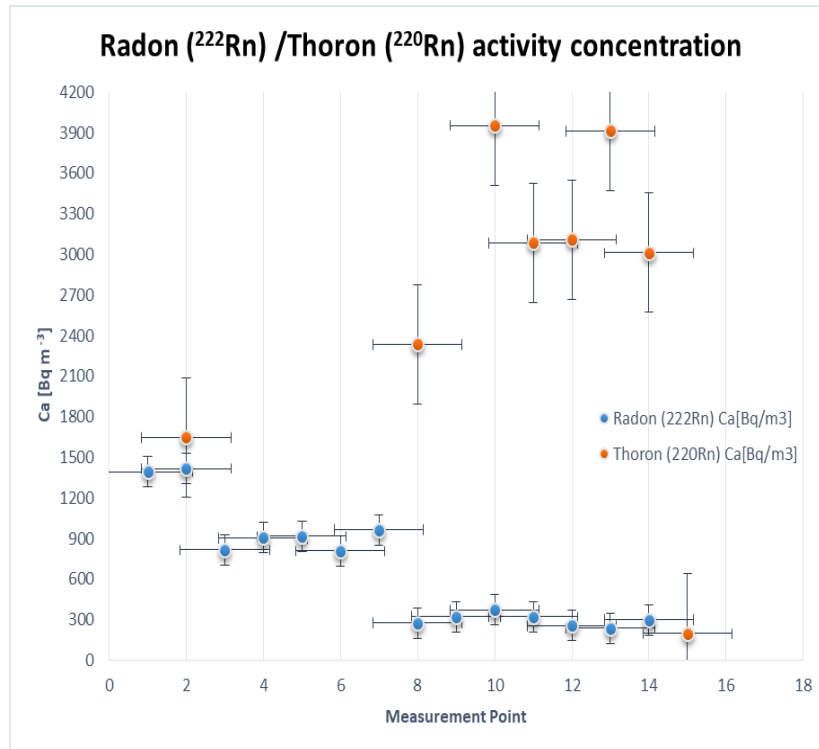


Figure 13. Radon/Thoron activity concentration

The measurement is based on tracking alpha particles from a short-lived progeny with decay energies between 7.8 and 8.8 MeV, recorded at a defined depth within the CD/DVD matrix. These tracks are assigned to (^{212}Po), a decay product of (^{220}Rn). Evaluation revealed an elevated track density in the DVDs exposed at site 3. This accumulation is presumably driven by the mineralogical profile of the mine rocks (Table 4). Consequently, it is pertinent to evaluate alternative techniques for thoron registration.

Conclusion

The application of CD/DVD polycarbonate discs as detectors for radon and thoron exposure demonstrates their capability to provide reliable results under extreme environmental conditions, including high humidity, dust, and smoke. This enables long-term cumulative measurements in underground mines, regardless of the severe conditions. Measuring radon and thoron levels in underground mines is of critical importance due to several key factors: the carcinogenicity of alpha radiation emitted by radon, the specific nature of the underground environment, restricted ventilation, and the rapid accumulation of hazardous concentrations.

Historically, thoron was overlooked as a radiological hazard due to its short half-life. Its half-life is approximately 56 seconds, compared to 3.8 days for radon, which led to the past assumption that it would decay before reaching the occupational zone. However, the actual risk of thoron manifests when the source material is in close proximity to the worker—as is typical in mining operations—allowing thoron to reach the breathing zone in substantial volumes. Its progeny are highly radiotoxic, and the resulting radiation workload can be comparable to, or even exceed, that of radon. One of the most effective mitigation strategies for reducing these underground gases is forced ventilation. Therefore, comprehensive measures to maintain safe radon and thoron levels in underground mines must integrate the control of ventilation systems, optimization of airflow dynamics, and continuous atmospheric monitoring.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Integrated Molecular Identification and Quantitative Analysis of Diet-Dependent Venom Variation in *Leiurus quinquestriatus* Scorpion Species

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Abstract: Scorpions are ancient and successful arthropods that have lived on Earth for millions of years. A key feature for their evolutionary success is the presence of specialized venom glands, which produce the venom. Scorpion venom is a complex mixture of bioactive compounds, and its composition and yield are influenced by various ecological factors. This study investigated the effect of prey type on venom yield and protein profile in the medically significant scorpion *Leiurus quinquestriatus* (the "deathstalker"), a species renowned for venom containing therapeutic peptides such as chlorotoxin. Specimens were molecularly identified using 16S and 12S rDNA sequencing to confirm species identity. A four-month feeding experiment (n = 50) was conducted to evaluate two different dietary regimes. The results demonstrated that the mitochondrial 16S and 12S rDNA markers are reliable tools for scorpion identification. Dietary variation significantly influenced venom yield; scorpions fed a super mealworm diet exhibited a 64% increase in venom yield compared to the alternative regime. Notably, no cannibalistic behavior was observed among the specimens studied during the experiment. Furthermore, SDS-PAGE analysis revealed distinct protein banding patterns between the dietary groups, indicating diet-induced alterations in venom protein composition. These findings highlight the critical impact of diet on scorpion venom production. Understanding these factors is essential for optimizing venom yield for ecological studies and venom-based biodiscovery.

Keywords: Scorpion, 16S, 12S rDNA genes, Scorpion venom, Prey, Venom yield, SDS-PAGE.

Introduction

Scorpions (phylum Arthropoda, class Arachnida) are ancient species, existing on earth for 430 million years. Distributed all over the earth, they are adaptive, venomous animals. 19 of scorpions, which include more than 2200 species, have been identified so far. Out of them, the Buthidae family is well known for its hazardous envenomation, which also possesses medicinal importance (Hassan et al., 2024; Lafnoute et al., 2022). Naturally, scorpions use the stinger at the end of their tail to inject venom into predators as a defense mechanism or into prey to paralyze and capture them. Scorpion venom—that produced from venom glands—is composed of a heterogeneous mixture of compounds, including varying concentrations of proteins, enzymes, lipids, free amino acids, and others (Nasr et al., 2023).

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In the last decades, scorpion venoms have been identified as a potential natural resource for designing antitumor, antibacterial drugs. Several lines of evidence have revealed that scorpion venoms and venom-derived peptides suppressed tumor cell proliferation, metastasis, and induced tumor cell apoptosis (Sadeghi et al., 2024). Understanding the factors that influence venom composition and yield is therefore essential for both ecological studies and venom-based biodiscovery.

The scorpion genus *Leiurus* is one of the most medically important species in North Africa and the Middle East. The *Leiurus quinquestriatus* species, commonly known as “death stalker,” found in upper Egypt and Sudan in dry habitats and is one of the most dangerous species; it causes severe envenoming and high death rates because its venom is highly neurotoxic (Borges & Lomonte, 2024; Salama & Sharshar, 2013).

Accurate species identification represents a fundamental step in venom research, as venom composition can vary significantly among closely related scorpion species. Traditional morphological identification is often limited by phenotypic similarity and intraspecific variation. Consequently, molecular approaches, particularly the use of mitochondrial markers such as the 16S and 12S rDNA gene, have become powerful tools for reliable species identification and phylogenetic analysis in scorpions.

By integrating molecular identification, quantitative venom analysis, and protein profiling, this work provides a comprehensive evaluation of diet-associated venom variation. The results contribute to a better understanding of how nutritional factors influence venom production and demonstrate the importance of combining experimental biology with statistical and data-oriented analysis in venom research.

In this study, mitochondrial 16S, 12S rDNA sequencing was employed to confirm species identity, while controlled dietary experiments were conducted to investigate the effects of different prey types on venom yield. Demonstrated scorpion behavior. Venom samples obtained under different feeding regimes were analyzed using SDS-PAGE to compare protein profiles. By integrating molecular, biochemical, and ecological approaches, this research aims to enhance our understanding of scorpion venom dynamics and contribute to optimized scorpion rearing practices and venom-based biomedical research.

Methods

Scorpion Collection

Adult scorpions, *L. quinquestriatus* (n=50), were collected at night by professional hunters in the Sinai region of Egypt using UV light and extra-long forceps. They were observed walking on sand or burying themselves beneath rocks and wood materials. After observation, the scorpions were placed in separate containers filled with sand and equipped with holes for adequate ventilation before being transported to the laboratory.

Molecular Identification

DNA Extraction

DNA was extracted from the muscle of the scorpion tail by using Nucleic Acids extraction RealBest-Vet Gamma, (Novosibirsk, Russia). According to the manufacturer's protocol, briefly, muscles were isolated and chopped, 400 µl of lysis buffer were added, and they were placed in a heat block at 65°C for 10 minutes. After adding 400 µl of precipitating solution, the mixture was pipetted and then transferred to the spin column and centrifuged at 10,000 xg for one minute. Then wash twice with buffer 1 and 2. Finally, 200 µl of elution buffer was used. Concentration and quality of the DNA was determined by nanodrop (Thermo Scientific NanoDrop 2000C Spectrophotometer).

Real-Time Polymerase Chain Reaction

Amplification of 16S rDNA gene by using primer pairs, Sc- 16F 5'-CGATTTGAACTCAGATCA-3' and Sc-16R 5'- GTGCAAAGGTAGCATAAT-3, For amplification of 12S rDNA, the primers Sc-12F 5'-AGAGTGACGGGCAATATGTG-3' and Sc-12R 5'- CAGCGGCTGCGGTTATAC-3' were used. (Macrogen, Seoul, South Korea). (Soltan-Alinejad et al., 2021). The qPCR amplification reaction was performed with a final

mixture of 20 µl, 5 µl of 4X CAPITAL qPCR Green Master Mix (Berlin, Germany), 5 µl of purified DNA, 1.5 µl of each forward and reverse primers, and completed to 20 µl with PCR-grade water.

The amplification conditions for all fragments were as follows: Hold the temperature at 95°C for 2 minutes, then 45 cycles of 95°C for 10 seconds and 46°C for 30 seconds. Then the melt setup conditions were a ramp from 50°C to 90°C raised by 1 degree at each step, wait for 90 seconds of pre-melt conditioning on the first step and 5 seconds for each step afterwards to measure the fluorescence.

Gradient PCR

For the PCR amplification reaction performed in 50 µl of the final mixture, consisting of 25 µl COSMO PCR red master mix (Birmingham, UK), 2 µl of each primer, 5 µl of the purified DNA, and completed to 50 µl with 16 µl of PCR-grade water. Confirmation for amplifications and purity of the genes were electrophoresed on 1.5 agarose gel and then properly sized PCR product were sent for sequencing.

Sequence Analysis

The sequence obtained from 16S rRNA was trimmed using Bioedit Software and then compared to sequences from the GenBank, Blast (<https://blast.ncbi.nlm.nih.gov/Blast.cgi>), to find the similarity. All the sequences received from the NCBI database together with the sequences from the present study, were aligned by ClustalW implanted in MEGA12 software. Phylogenetic trees were inferred by using the Maximum Likelihood (ML) tree, and the best-fit nucleotide substitution model of each was selected by using the Bayesian information criterion (BIC).

For 16S and 12S, genes from *Leiurus. quinquestriatus*, the phylogeny was inferred using the Maximum Likelihood method and Tamura (1992) model, with the evolutionary rate differences among sites modeled using a discrete Gamma distribution across 4 categories. The initial tree for the heuristic search was selected by choosing the tree with the superior log-likelihood between a Neighbor-Joining (NJ) tree and a maximum parsimony tree (MP). The NJ tree was generated using a matrix of pairwise distances computed using the Tamura model. The partial deletion was applied to eliminate all positions with less than 90% site coverage. The robustness of the inferred tree topology was assessed by bootstrap analysis with 1000 replicates, for the evolutionary history of 12S gene from *L. quinquestriatus* was inferred using the Neighbor-Joining method (NJ), the evolutionary distances were computed using the Tamura 3-parameter method.

Scorpion Rearing

In the laboratory, scorpions were transferred to wide, clean boxes, filled with 2 inches of sand. Properly sized stones and leaves were placed in each box. The boxes and their lids were designed to provide sufficient adequate ventilation for the scorpions and were positioned away from direct sunlight. conduct daily monitoring of environmental conditions such as temperature and 12:12 light cycle. Females bearing small juveniles were each placed in separated clean boxes. After 2-3-week period, once the young scorpions were off their mother's back, the young were separated into another boxes, fed with mealworms.

Behavioral Observation

During the first two weeks following the arrival of the scorpion species, a group of 20 scorpions were assembled to observe their interactions with one another. There were three boxes designated for *L. quinquestriatus*, accommodating a total of 50 scorpions. During this observation period, minimal interference was implemented to avoid any external influences on their natural behavior while keeping records of cannibalism incidents and their movements.

Impact of Dietary Intake on Venom Yield

Scorpion species had received two types of prey: live super mealworms and live red runner roaches once a week. Fifty scorpions were divided into two independent dietary groups (n = 25 each). One group was fed on

super mealworms, while the other was fed on roaches for four months. Venom volume data were expressed as mean $\pm$ and standard deviation (SD). Differences between dietary groups were analyzed using independent two-sample t-test assuming equal variances to compare venom yield between dietary groups, with statistical significance set at $p < 0.05$. Water sources were ad libitum. Sand must be changed monthly; any remnants of food must be removed; and the boxes should be in a hygienic condition.

Extraction and Preparing the Venom

Venom was collected by applying electrical stimulation (10– 12 V) to the articulation of the telson while carefully holding the scorpion with the left hand and gripping the stinger at the end of its tail between the index finger and thumb. Venom was extracted twice per month. The extracted venom collected in a clean Eppendorf tube, solubilized in distilled water in 1:4 ratio, centrifuged at 10,000 xg, 4°C, for 15 min to remove debris, and then the supernatant. The supernatants were pooled, lyophilized, and stored at -80 °C until use (Yoshimoto et al., 2019).

Sodium Dodecyl Sulfate–Polyacrylamide Gel Electrophoresis (SDS-PAGE):

SDS-PAGE was performed following the method from Laemmli 1970 (Laemmli, 1970), Venom samples were collected from scorpion species with different diets; the first venom sample was obtained from scorpions that consumed super mealworms, while the second sample was from scorpions that were fed with red runner roaches. the two venom samples were analyzed using a Tris-glycine running buffer system under reducing conditions. Samples were mixed with 3x loading dye and Bio- HELIX IRIS11 prestained as the protein ladder (3-260 KDa). 15%, resolving gel (29% acrylamide:1% bis acrylamide mix) and 5% stacking gel was carried out for protein bands' molecular weight analysis. The gels were stained overnight with Coomassie Brilliant blue R250, and the molecular weight of the separating bands was determined by GelAnalyzer 23.1.1 software.

Results and Discussion

Molecular Identification

Real-Time PCR Amplification

The DNA extracted from the tail muscle of scorpion species was analyzed first on Nanodrop, the concentration of the DNA was 200 ng/μl. Real-time PCR amplification was performed by using SYBR green. The melting curve, as in (Figure 1), showed a single distinct peak indicating amplification specificity for the gene without primer dimers or non-specific products.

Gradient PCR

The PCR product of the gene was electrophoresed on a 1.5% agarose gel, as shown in Figure 2; single, clear, distinct bands resulted with sizes of about 452 kDa and 563 kDa for 16S and 12S rDNA, respectively, which indicate the purity of the amplified gene.

Sequence Analysis

Molecular identification for *Leiurus quinquestriatus* was performed using 16S and 12S rRNA. The obtained sequences, which were made with triplicates, from the scorpion species were aligned with the sequences obtained from the GenBank. Blast analyses revealed 100% sequence identity, as in (Figure 3A). Regarding the 16S phylogenetic tree, the resulting ML tree consisted of thirty-three sequences formed from multiple *Leiurus quinquestriatus* together with outgroup taxa such as *Androctonus*, *Buthus*, and *Odontobuthus*. The scorpion specimen formed a basal lineage relative to *L. quinquestriatus* sequences; it was clearly separated from *Buthus* and *Androctonus* species. however, the deeper node of the specimen connected with the *L. quinquestriatus* lineage with a 100% bootstrap value (Figure 3B). For the 12S gene phylogenetic analysis, it was found to be directly clustered within the *L. quinquestriatus* clade with 78% bootstrap support, clearly separated from *Buthus* and *Androctonus* species (Figure 3 C).

Behavior of the Scorpions

In the study of the scorpion *L. quinquestriatus*, no aggression was observed among individuals, and cannibalism did not occur. They tend to hide under rocks and leaves during the day and do not exhibit vigorous movement at night. Consequently, we house every 10 scorpions together in the same box.

Dietary Intake Effect on Venom Yield

After offering the two different types of prey for scorpion species, venom yield after consuming super mealworms was higher than after roaches. Scorpions fed on super mealworms produced significantly higher venom volumes compared to those fed on roaches. The mean venom volume for the Super mealworms group was 137.5 μ L, while the roaches group produced a mean of 83.75 μ L. Statistical analysis revealed a highly significant difference between the two dietary treatments (independent t-test, $t = 11.93$, $df = 14$, $p < 0.0001$), table 1, (Figure 4).

SDS-PAGE

Lane L1, which was venom from the *L. quinquestriatus* scorpion, fed with super mealworms; lane L2, which was from the same scorpion species but fed with red runner roaches. Two protein bands appear in both venom samples, common between L1, and L2 samples, of sizes 213, 50 kDa. A bulk of Unseparated small peptides appear in both samples (Figure 5).

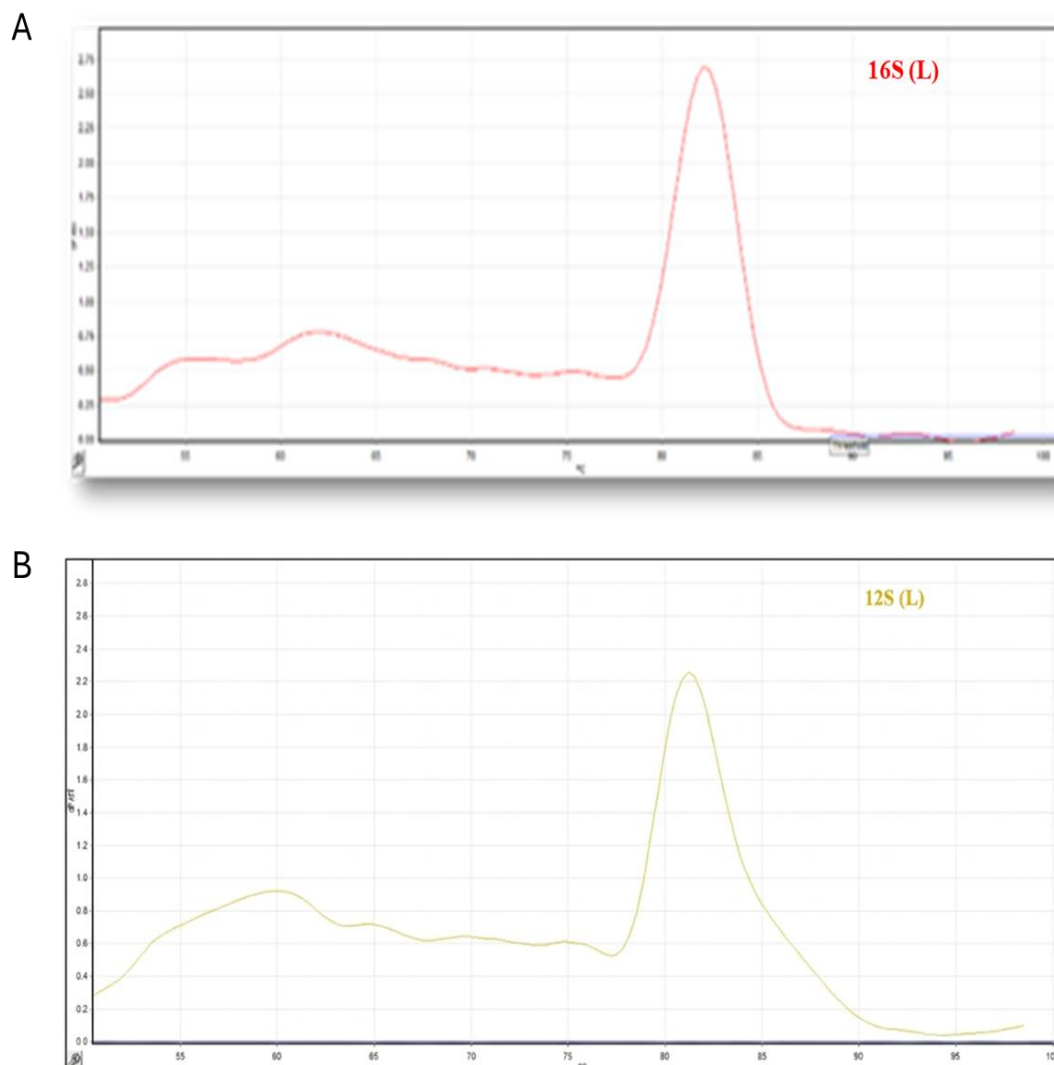


Figure 1. A: Melting curve of 16S rDNA. B: 12S rDNA for *L. quinquestriatus*

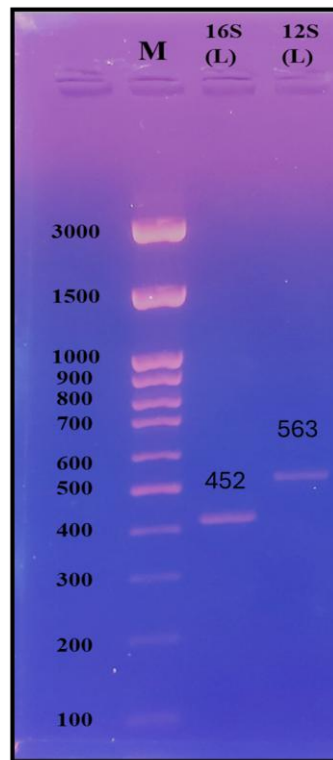


Figure 2. 1.5 agarose gel of the PCR product, M: marker protein. 16S (L): 16S and 12S rRNA gene of *L. quinquestriatus* scorpion.



Figure 3. A: Studied scorpions (*L. quinquestriatus* highlighted in yellow color) occur within leirus lineage: 16S rRNA gene sequences analysis, the yellow arrow is the tested scorpion (labelled Scorpion 1 16S), clustered with 100% bootstrap support with leirus lineage. C: 12S rRNA gene sequences analysis of the tested scorpion (yellow arrow) clustered within *L. quinquestriatus* clade.

Table 1. Comparison of mean venom yield between *L. quinquestriatus* scorpions fed on super worms androaches over a four-month period.

Dietary group	Super mealworms	Roaches
Standard Deviation (SD)	10.35	7.44
Variance	107.14	55.36
Mean yield (μL)	137.5	83.75
N (Sessions)	8	8
P-value	< 0.001	

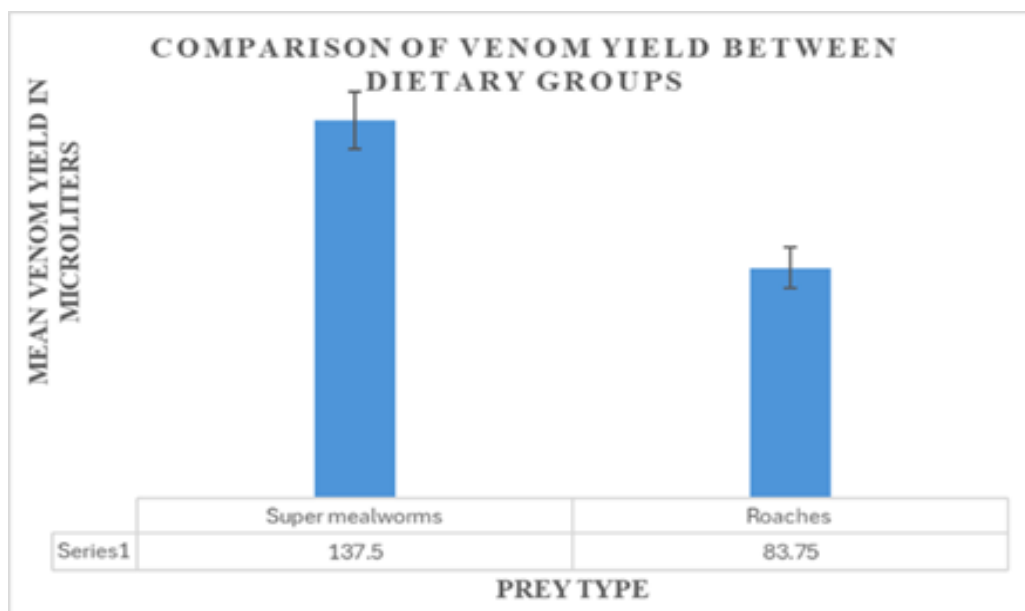


Figure 4. Comparison of mean venom yield between scorpions fed on superworms and those fed on cockroaches over a 4-month period. Data is presented as mean $\pm$ standard deviation (SD) of 8 milking sessions per group.

Statistical significance was determined using an independent two-sample t-test assuming equal variances

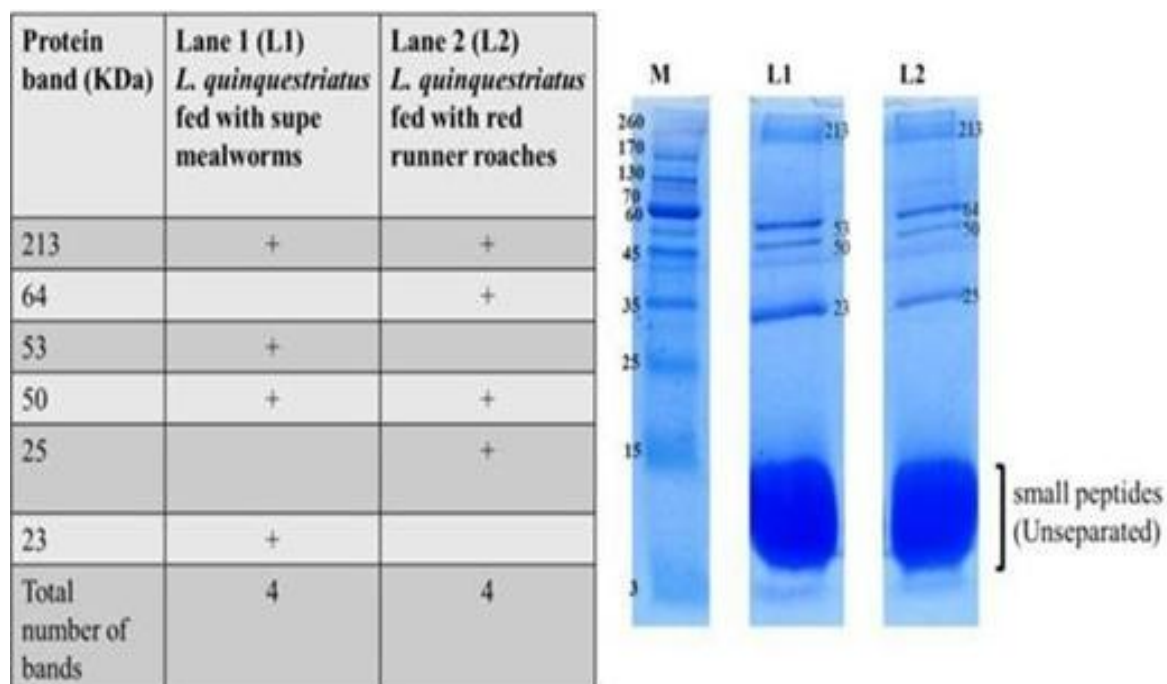


Figure 5. The table on the left showed protein profile of the separated crude venom from scorpion species. B: protein bands separation by using 15% resolving gel. L1 for *L. quinquestriatus* fed with super mealworms, L2 for *L. quinquestriatus* fed with red runner roaches, M is the protein marker.

This study successfully combined molecular, behavioral, and physiological approaches to provide an integrated understanding of scorpion biology and venom production. Molecular identification using the mitochondrial 16S rRNA marker proved to be a reliable and effective tool for accurate species. Identification, particularly in cases where morphological differentiation may be challenging. Accurate molecular identification is essential for venom studies, as even closely related species may exhibit substantial variation in venom composition and potency. Confirming its suitability for taxonomic and evolutionary studies of scorpions, the scorpion specimens studied were confirmed to belong to a single species, *Leiurus quinquestriatus*, ensuring that observed differences in venom profiles were not due to taxonomic misidentification.

Dietary variation was found to have a significant influence on venom yield, highlighting the role of nutritional factors in venom production. Scorpions fed on different prey types exhibited measurable differences in venom quantity; scorpions that were fed on super mealworms produced significantly higher venom volumes compared to those fed on roaches. This difference was supported by statistical analysis. This finding suggests that nutritional composition plays a crucial role in venom synthesis and replenishment, likely due to differences in protein and energy availability required for venom production. Such results are consistent with previous studies indicating that venom is metabolically expensive and closely linked to feeding efficiency and prey quality, as in (Tobassum et al., 2018), where it was found that grasshopper nymphs and adults were the best diet for the scorpions to get a higher yield of venom as compared to house crickets, moths, and house flies.

In addition, behavioral observations revealed distinct feeding, defensive, and activity patterns associated with each diet, indicating a close relationship between nutrition, behavior, and venom utilization. Scorpions subjected to different feeding regimes exhibited variations in feeding behavior, activity levels, and defensive responses. These behavioral changes may reflect adaptive strategies aimed at optimizing venom use in relation to prey types and availability. The association between diet, behavior, and venom characteristics underscores the importance of considering ecological factors when studying venom dynamics. Biochemical analysis using SDS-PAGE and the comparative analysis revealed distinct banding patterns and variations in protein abundance between individuals fed super mealworms and those fed red runner roaches, indicating that prey type can modulate venom expression.

Overall, the integration of molecular, biochemical, and behavioral data provides a comprehensive understanding of how dietary variation influences scorpion venom expression. These findings have important implications for scorpion rearing protocols, venom extraction efficiency, and venom-based biodiscovery. Understanding venom variability under controlled conditions may enhance the reproducibility and biomedical relevance of future venom research.

Conclusion

In conclusion, this research bridges molecular taxonomy, nutritional ecology, and toxicology, highlighting the need to consider dietary history in both basic venom studies and applied bioprospecting efforts. *L. quinquestriatus* fed on super mealworms produced significantly higher venom volumes compared to those fed on roaches, indicating a strong diet-dependent effect on venom yield. SDS-PAGE analysis revealed observable differences in band intensity between the two dietary groups, suggesting potential variation in venom protein profile.

Furthermore, the use of 16S and 12S rRNA molecular barcoding proved to be an efficient and reliable tool for species identification of venomous scorpions. This technique enabled accurate taxonomic classification of collected specimens, which is critical for ensuring reproducibility in venom research and avoiding misidentification-related errors in downstream pharmacological applications.

Recommendations

Future studies are recommended to apply Tris-Tricine SDS-PAGE to achieve better resolution of low-molecular weight peptides present in scorpion venom. This technique would allow more accurate separation and characterization of venom peptides, which are often biologically active and of high pharmacological interest. Incorporating Tris-Tricine analysis alongside conventional SDS-PAGE may provide deeper insights into venom peptide diversity and enhance the potential for identifying novel bioactive compounds relevant to therapeutic applications.

And future work should expand to functional assays (e.g., antimicrobial or cytotoxic activity) to determine whether dietary-induced changes in venom also translate into altered biological activity.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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PNPS α -Open Sets and PNPS α -Continuous, Irresolute, Open, Closed and Homeomorphic Mappings in Pentapartitioned Neutrosophic Pythagorean Topological Spaces

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Prince Mohammad Bin Fahd University

Abstract: Pentapartitioned Neutrosophic Pythagorean Topological Spaces (PNP-Top-Spaces) provide an effective mathematical framework for handling uncertainty, indeterminacy, inconsistency, contradiction, and ignorance in complex decision-making and information systems. Motivated by the development of generalized open sets in neutrosophic topology, this paper introduces and studies the concepts of Pentapartitioned Neutrosophic Pythagorean Semi- α -open (PNPS α -open) and PNPS α -closed sets. Fundamental definitions are established, and several basic properties and characterizations of these sets are obtained. The relationships between PNPS α -open sets and existing classes of PNP open, α -open, semi-open, and closed sets are investigated, and inclusion relations among these classes are discussed. Using these newly defined sets, the notions of PNPS α -continuous, PNPS α -irresolute, PNPS α -open, PNPS α -closed, and PNPS α -homeomorphic mappings are introduced. Various properties and characterizations of these mappings are derived by using PNPS α -open and PNPS α -closed sets. Several fundamental properties concerning preservation and composition of mappings are established. In addition, relationships among ordinary continuous mappings, PNPS α -continuous mappings, and PNPS α -irresolute mappings are examined. The behavior of PNPS α -open and PNPS α -closed mappings under composition and homeomorphic equivalence is also investigated.

Keywords: Pentapartitioned Neutrosophic Pythagorean Topological Space, PNPS α -open set, PNPS α -closed set, PNPS α -continuous mapping, PNPS α -irresolute mapping, PNPS α -open mapping, PNPS α -closed mapping, PNPS α -homeomorphism

Introduction

The theory of neutrosophic sets, introduced by Smarandache, has become an important framework for modeling uncertainty, indeterminacy, and inconsistency encountered in real-world problems. By incorporating the independent components of truth-membership, indeterminacy-membership, and falsity-membership, neutrosophic sets provide a more comprehensive representation of uncertain information than classical fuzzy and intuitionistic fuzzy models. Consequently, neutrosophic topology has emerged as an active area of research, leading to the introduction of numerous generalized topological concepts and mappings that extend classical topological theory.

Among the recent developments, Pythagorean fuzzy sets have attracted considerable attention due to their greater flexibility in handling uncertainty by allowing the squared sum of membership and non-membership degrees to be bounded by one. The integration of neutrosophic and Pythagorean concepts has given rise to Pentapartitioned Neutrosophic Pythagorean Sets (PNP-sets), which provide a richer mathematical structure for representing complex information. These sets partition uncertainty into five independent components, enabling a more refined description of positive, neutral, contradictory, incomplete, and negative information. Such an extension has opened new directions for the study of topological structures under highly generalized uncertainty environments.

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The investigation of generalized open sets occupies a central position in topology because they provide deeper insights into continuity, separation axioms, compactness, connectedness, and decomposition of mappings. Since the introduction of α -open sets by Njåstad, many generalized open sets, including semi-open, pre-open, β -open, regular open, generalized α -open, and their corresponding closed sets, have been studied extensively in classical, fuzzy, intuitionistic fuzzy, and neutrosophic topological spaces. These generalized classes have significantly enriched the theory of continuous and irresolute mappings and have found applications in decision analysis, information systems, artificial intelligence, and uncertainty modelling.

Motivated by these developments, this paper introduces and investigates a new class of generalized open sets, called Pentapartitioned Neutrosophic Pythagorean α -open sets (PNPS α -open sets), in Pentapartitioned Neutrosophic Pythagorean Topological Spaces (PNPS-Top-Spaces). The proposed class extends several existing notions of generalized openness and provides a broader framework for studying topological properties in pentapartitioned neutrosophic environments. Fundamental properties of PNPS α -open and PNPS α -closed sets are established, together with their relationships with other generalized open and closed sets already available in the literature.

Furthermore, based on the newly introduced PNPS α -open sets, several important classes of mappings are defined and studied, namely PNPS α -continuous mappings, PNPS α -irresolute mappings, PNPS α -open mappings, PNPS α -closed mappings, and PNPS α -homeomorphisms. Characterizations of these mappings are obtained through inverse images and direct images of PNPS α -open and PNPS α -closed sets. Various preservation results, equivalent conditions, composition properties, and interrelationships among these mappings are also established, thereby extending several well-known results from classical topology and neutrosophic topology to the framework of Pentapartitioned Neutrosophic Pythagorean Topological Spaces.

The results presented in this paper contribute to the theoretical development of generalized neutrosophic topology by providing a unified framework for studying generalized openness and continuity in PNPSTs. It is expected that the concepts introduced here will serve as a foundation for further investigations into separation axioms, compactness, connectedness, quotient spaces, decomposition of mappings, and applications of Pentapartitioned Neutrosophic Pythagorean structures in intelligent decision-making, information sciences, data analysis, and computational uncertainty.

2. Preliminaries

Definition 2.1. Let X be a universe. A Pentapartitioned Neutrosophic Pythagorean (briefly PNP-set) set M with T, F, C , and U as dependent neutrosophic components and I as an independent component for M on X is an object of the form $M = \{ \langle x, T_M, C_M, I_M, U_M, F_M \rangle : x \in X \}$ where $T_M + F_M \leq 1$, $C_M + U_M \leq 1$ and $(T_M)^2 + (C_M)^2 + (I_M)^2 + (U_M)^2 + (F_M)^2 \leq 3$. We note that $T_M(x)$ is the truth membership, $C_M(x)$ is contradiction membership, $U_M(x)$ is ignorance membership, $F_M(x)$ is the false membership, and $I_M(x)$ is an unknown membership.

Definition 2.2. Let X be a non-empty set. A PNP-set M over X characterizes each element x in X : a truth membership function T_M , a contradiction membership function C_M , an ignorance membership function G_M , unknown membership function U_M and a false membership function F_M , such that for each x in X . $T_M + C_M + G_M + U_M + F_M \leq 5$.

Definition 2.3. The complement of a PNP-set M on X denoted by M^c and is defined as $M^c = \{ \langle x, F_M(x), U_M(x), 1 - G_M(x), C_M(x), T_M(x) \rangle : x \in X \}$.

Definition 2.4. Let $M = \{ \langle x, T_M(x), C_M(x), G_M(x), U_M(x), F_M(x) \rangle : x \in X \}$ and $Q = \{ \langle x, T_Q(x), C_Q(x), G_Q(x), U_Q(x), F_Q(x) \rangle : x \in X \}$ are PNP-sets Then

$$M \cup Q = \left\{ \left\langle x, \max(T_M(x), T_Q(x)), \max(C_M(x), C_Q(x)), \min(G_M(x), G_Q(x)), \min(U_M(x), U_Q(x)), \min(F_M(x), F_Q(x)) \right\rangle : x \in X \right\}$$

$$M \cap Q = \left\{ \left\langle x, \min(T_M(x), T_Q(x)), \min(C_M(x), C_Q(x)), \max(G_M(x), G_Q(x)), \max(U_M(x), U_Q(x)), \max(F_M(x), F_Q(x)) \right\rangle : x \in X \right\}$$

Definition 2.5. A pentapartitioned neutrosophic Pythagorean topology on a nonempty set X is a family T_{PNP} of PNP-sets in X satisfying the following axioms

- (1) $0, 1 \in T_{PNP}$
- (2) $M_1 \cap M_2 \in T_{PNP}$ for any $M_1, M_2 \in T_{PNP}$
- (3) $\bigcup_{i \in I} M_i \in T_{PNP}$ for any $\{M_i : i \in I\} \subseteq T_{PNP}$

The pair (X, T_{PNP}) is called a PNP-Top-Space.

Definition 2.6. Let (X, T_{PNP}) be a PNP-Top-Space and $M \in T_{PNP}$. Then M is called a PNP-open set in X . The complement of a PNP-open set M is called a PNP-closed set in X and it is denoted by M^c .

Definition 2.7. Let (X, T_{PNP}) be a PNP-Top-Space and

$M = \left\{ \left\langle x, T_M(x), C_M(x), G_M(x), U_M(x), F_M(x) \right\rangle : x \in X \right\}$ be a PNP-set in X . Then the PNP-interior and the PNP-closure of M are denoted by $PNP-Int(M)$ and $PNP-CI(M)$ respectively and are defined as follows.

$$PNP-Int(M) = \bigcap \{Q : Q \text{ is a PNP-open set and } M \subseteq Q\} \text{ and}$$

$$PNP-CI(M) = \bigcup \{K : K \text{ is a PNP-closed set and } K \subseteq M\}$$

Theorem 2.8. Let (X, T_{PNP}) be a PNP-Top-Space and let M and Q be PNP-set subset of X . Then the following statements hold.

- (i) $PNP-Int(M)$ is a PNP-open set in X .
- (ii) $PNP-Int(\phi) = \phi$ and $PNP-Int(X) = X$.
- (iii) $PNP-CI(M)$ is a PNP-closed set in X .
- (iv) $PNP-CI(\phi) = \phi$ and $PNP-CI(X) = X$.
- (v) M is PNP-open set if and only if $M = PNP-Int(M)$
- (vi) M is PNP-closed set if and only if $M = PNP-CI(M)$
- (vii) $PNP-Int[PNP-Int(P)] = PNP-Int(M)$
- (viii) $PNP-CI[PNP-CI(P)] = PNP-CI(M)$
- (ix) $M \subseteq Q$ implies that $PNP-Int(M) \subseteq PNP-Int(Q)$
- (x) $M \subseteq Q$ implies that $PNP-CI(M) \subseteq PNP-CI(Q)$
- (xi) $PNP-Int(M \cap Q) = [PNP-Int(M)] \cap [PNP-Int(Q)]$
- (xii) $PNP-CI(M \cap Q) \subseteq [PNP-CI(M)] \cap [PNP-CI(Q)]$
- (xiii) $[PNP-Int(M)] \cup [PNP-Int(Q)] \subseteq PNP-Int(M \cup Q)$

Definition 2.9. Let (X, T_{PNP}) be a PNP-Top-Space and M be a PNP-set. M is said to be a Pentapartitioned Neutrosophic Pythagorean Pre-open (briefly PNPP-open) set if $M \subseteq PNP-Int(PNP-CI(M))$.

The family of all PNPP-open sets in (X, T_{PNP}) is denoted by $\text{PNPP-O}(X, T_{\text{PNP}})$. The complement of a PNPP-open set is called a $\text{Pentapartitioned Neutrosophic Pythagorean Pre-closed}$ (briefly PNPP-closed) set in X .

Definition 2.10. Let (X, T_{PNP}) be a PNP-Top-Space and M be a PNP-set . M is said to be a $\text{Pentapartitioned Neutrosophic Pythagorean Semi-open}$ (briefly PNPS-open) set if $M \subseteq \text{PNPP-Cl}(\text{PNP-Int}(M))$. The family of all PNPS-open sets in (X, T_{PNP}) is denoted by $\text{PNPS-O}(X, T_{\text{PNP}})$. The complement of a PNPS-open is called a $\text{Pentapartitioned Neutrosophic Pythagorean Semi-closed}$ (briefly PNPS-closed) set in X .

Definition 2.11. Let (X, T_{PNP}) be a PNP-Top-Space and M be a PNP-set . M is said to be a $\text{Pentapartitioned Neutrosophic Pythagorean } \alpha\text{-open}$ (briefly $\text{PNP}\alpha\text{-open}$) set if $M \subseteq \text{PNP-Int}(\text{PNPP-Cl}(\text{PNP-Int}(M)))$. The family of all $\text{PNP}\alpha\text{-open}$ sets in (X, T_{PNP}) is denoted by $\text{PNP}\alpha\text{-O}(X, T_{\text{PNP}})$. The complement of a $\text{PNP}\alpha\text{-open}$ set is called a $\text{Pentapartitioned Neutrosophic Pythagorean } \alpha\text{-closed}$ (briefly $\text{PNP}\alpha\text{-closed}$) set in X .

Proposition 2.12. A PNP-open subset M of a PNP-Top-Space (X, T_{PNP}) is a $\text{PNP}\alpha\text{-open}$ set in X if and only if M is a PNPS-open set and PNPP-open set.

Definition 2.13. Let (X, T_{PNP}) be a PNP-Top-Space and $M = \{ \langle x, T_M(x), C_M(x), G_M(x), U_M(x), F_M(x) \rangle : x \in X \}$ be a PNP-set in X . Then the $\text{PNP}\alpha\text{-interior}$ and the $\text{PNP}\alpha\text{-closure}$ of M are denoted by $\text{PNP}\alpha\text{-Int}(M)$ and $\text{PNP}\alpha\text{-Cl}(M)$, and are defined as follows.

$$\begin{aligned} \text{PNP}\alpha\text{-Int}(M) &= \bigcup \{ Q : Q \text{ is a } \text{PNP}\alpha\text{-open set and } Q \subseteq M \} \text{ and} \\ \text{PNP}\alpha\text{-Cl}(M) &= \bigcap \{ K : K \text{ is a } \text{PNP}\alpha\text{-closed set and } M \subseteq K \} \end{aligned}$$

Theorem 2.14. Let (X, T_{PNP}) be a PNP-Top-Space and M be a PNP-set in X . Then M is a $\text{PNP}\alpha\text{-open}$ set in X if and only if there exists a PNP-open set Q in X such that $Q \subseteq M \subseteq \text{PNP-Int}(\text{PNP-Cl}(Q))$.

Proof. Let M be a $\text{PNP}\alpha\text{-open}$ set in X . Then $M \subseteq \text{PNP-Int}[\text{PNP-Cl}(\text{PNP-Int}(M))]$. Then this implies that $\text{PNP-Int}(M) \subseteq M \subseteq \text{PNP-Int}[\text{PNP-Cl}(\text{PNP-Int}(M))]$. Let $Q = \text{PNP-Int}(M)$. Then there exists a PNP-open set Q such that $Q \subseteq M \subseteq \text{PNP-Int}[\text{PNP-Cl}(Q)]$.

Conversely, suppose that there is a PNP-open set Q such that $Q \subseteq M \subseteq \text{PNP-Int}[\text{PNP-Cl}(Q)]$. Then $Q = \text{PNP-Int}(Q) \subseteq \text{PNP-Int}(M)$. Hence $\text{PNP-Cl}(Q) \subseteq \text{PNP-Cl}(\text{PNP-Int}(M))$, then we obtain $\text{PNP-Int}(\text{PNP-Cl}(Q)) \subseteq \text{PNP-Int}[\text{PNP-Cl}(\text{PNP-Int}(M))]$. But by hypothesis, we have $Q \subseteq M \subseteq \text{PNP-Int}[\text{PNP-Cl}(Q)]$. Then $M \subseteq \text{PNP-Int}[\text{PNP-Cl}(\text{PNP-Int}(M))]$. Therefore, M is a $\text{PNP}\alpha\text{-open}$ set in X .

Theorem 2.15. The union of any family of $\text{PNP}\alpha\text{-open}$ sets in a PNP-Top-Space (X, T_{PNP}) is a $\text{PNP}\alpha\text{-open}$ set in X .

Proof. Let $\{M_i : i \in I\}$ be a family of $\text{PNP}\alpha$ -open sets in X . Then $M_i \subseteq \text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M_i)))$, for each $i \in I$. Since $\bigcup_{i \in I} \text{PNP-Int}(M_i) \subseteq \text{PNP-Int}(\bigcup_{i \in I} M_i)$ and $\bigcup_{i \in I} \text{PNP-Cl}(M_i) \subseteq \text{PNP-Cl}(\bigcup_{i \in I} M_i)$. We have $\bigcup_{i \in I} M_i \subseteq \bigcup_{i \in I} \text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M_i))) \subseteq \text{PNP-Int}(\bigcup_{i \in I} \text{PNP-Cl}(\text{PNP-Int}(M_i)))$
 $\subseteq \text{PNP-Int}(\text{PNP-Cl}(\bigcup_{i \in I} \text{PNP-Int}(M_i))) \subseteq \text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(\bigcup_{i \in I} M_i)))$. Hence, we conclude that $\bigcup_{i \in I} M_i$ is a $\text{PNP}\alpha$ -open set in X .

Theorem 2.16. Let (X, T_{PNP}) be a PNP-Top-Space . Then the following statements hold.

- (i) Every PNP-open (resp. PNP-closed) set is a $\text{PNP}\alpha$ -open (resp. $\text{PNP}\alpha$ -closed) set.
- (ii) Every $\text{PNP}\alpha$ -open (resp. $\text{PNP}\alpha$ -closed) set is a PNPS-open (resp. PNPS-closed) set.
- (iii) Every $\text{PNP}\alpha$ -open (resp. $\text{PNP}\alpha$ -closed) set is a PNPP-open (resp. PNPP-closed) set.

Lemma 2.17. Let (X, T_{PNP}) be a PNP-Top-Space and let M be a PNP-set in X .

- (i) If M is a PNP-open set, then $\text{PNPS-Cl}(M) = \text{PNP-Int}(\text{PNP-Cl}(M))$.
- (ii) $\text{PNPS-Int}(\text{PNP-Cl}(M)) = \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(M)))$.

3. PNPS α -Open Sets in Pentapartitioned Neutrosophic Pythagorean Topological Spaces

Definition 3.1. Let $(U, \mathfrak{T}_{\text{PNP}})$ be a PNP-Top-Space and M be a PNP-set . M is said to be a Pentapartitioned Neutrosophic Pythagorean semi α -open (briefly $\text{PNPS}\alpha$ -open) set if there exists a $\text{PNP}\alpha$ -open set H in U such that $H \subseteq M \subseteq \text{PNP-Cl}(H)$ or equivalently if $M \subseteq \text{PNP-Cl}(\text{PNP}\alpha\text{-Int}(M))$. The family of all $\text{PNPS}\alpha$ -open sets in $(U, \mathfrak{T}_{\text{PNP}})$ is denoted by $\text{PNPS}\alpha\text{-O}(U, \mathfrak{T}_{\text{PNP}})$. The complement of a $\text{PNPS}\alpha$ -open set is called a Pentapartitioned Neutrosophic Pythagorean semi α -closed (briefly $\text{PNPS}\alpha$ -closed) set in U .

Theorem 3.2. Let $(U, \mathfrak{T}_{\text{PNP}})$ be a PNP-Top-Space .

- (i) Every PNP-open (resp. PNP-closed) set is a $\text{PNPS}\alpha$ -open (resp. $\text{PNPS}\alpha$ -closed) set.
- (ii) Every $\text{PNP}\alpha$ -open (resp. $\text{PNP}\alpha$ -closed) set is a $\text{PNPS}\alpha$ -open (resp. $\text{PNPS}\alpha$ -closed) set.

Theorem 3.3. Let $(U, \mathfrak{T}_{\text{PNP}})$ be a PNP-Top-Space and M be a PNP-set . The following properties are equivalent:

- (i) $M \in \text{PNPS}\alpha\text{-O}(U, \mathfrak{T}_{\text{PNP}})$.
- (ii) There exists a PNP-open set H such that $H \subseteq M \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(H)))$.
- (iii) $M \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M))))$.

Proof. (i) $\Rightarrow$ (ii). Let M be a $\text{PNPS}\alpha$ -open set in $(U, \mathfrak{T}_{\text{PNP}})$. Then there exists a $\text{PNP}\alpha$ -open set Q such that $Q \subseteq M \subseteq \text{PNP-Cl}(Q)$. Hence there exists a PNP-open G such that $G \subseteq Q \subseteq \text{PNP-Int}(\text{PNP-Cl}(G))$ (by Theorem 2.14). Therefore, $\text{PNP-Cl}(G) \subseteq \text{PNP-Cl}(Q) \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(G)))$. This implies

that $\text{PNP-Cl}(Q) \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(G)))$. Then we obtain $G \subseteq Q \subseteq M \subseteq \text{PNP-Cl}(Q) \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(G)))$. Therefore, $G \subseteq M \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(G)))$, for some PNP-open set G .

(ii) $\Rightarrow$ (iii). Suppose that there exists PNP-open set G such that $G \subseteq M \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(G)))$. We know that $\text{PNP-Int}(M) \subseteq M$. On the other hand, $G \subseteq \text{PNP-Int}(M)$ since $\text{PNP-Int}(M)$ is the largest PNP-open set contained in M . Hence $\text{PNP-Cl}(G) \subseteq \text{PNP-Cl}(\text{PNP-Int}(M))$. Then $\text{PNP-Int}(\text{PNP-Cl}(G)) \subseteq \text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M)))$. Therefore, we obtain $\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(G))) \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M))))$. But by hypothesis, $M \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(M)))$. Hence $M \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(G))) \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M))))$. Then $M \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M))))$.

(iii) $\Rightarrow$ (i). Let $M \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M))))$. To prove M is $\text{PNPS}\alpha\text{-open}$ set. Let $Q = \text{PNP-Int}(M)$; we know that $\text{PNP-Int}(M) \subseteq M$. We need to prove $M \subseteq \text{PNP-Cl}(\text{PNP-Int}(M))$. Since $\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M))) \subseteq \text{PNP-Cl}(\text{PNP-Int}(M))$. So $\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M)))) \subseteq \text{PNP-Cl}((\text{PNP-Cl}(\text{PNP-Int}(M)))) = \text{PNP-Cl}(\text{PNP-Int}(M))$. But by hypothesis $M \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M))))$. Hence, $M \subseteq \text{PNP-Cl}((\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M)))) \subseteq \text{PNP-Cl}(\text{PNP-Int}(M))$. This implies $M \subseteq \text{PNP-Cl}(\text{PNP-Int}(M))$. Thus, there exists a PNP-open set, say Q , such that $Q \subseteq M \subseteq \text{PNP-Cl}(M)$. On the other hand, Q is a $\text{PNP}\alpha\text{-open}$ set (since Q is a PNP-open set). Hence M is a $\text{PNP}\alpha\text{-open}$ set in U .

Corollary 3.4. Let $(U, \mathfrak{T}_{\text{PNP}})$ be a PNP-Top-Space and M be a PNP-set . Then the following statements are equivalent:

- (i) M be a $\text{PNPS}\alpha\text{-closed}$ set.
- (ii) There exists a PNP-closed set H such that $\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(H))) \subseteq M \subseteq H$.
- (iii) $\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(M)))) \subseteq M$.

Proof. (i) $\Rightarrow$ (ii). Let M be a $\text{PNPS}\alpha\text{-closed}$ set in $(U, \mathfrak{T}_{\text{PNP}})$. Then M^c is a $\text{PNPS}\alpha\text{-open}$ set in U . Hence, by Theorem 3.3, there is a PNP-open set Q such that $Q \subseteq M^c \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(Q)))$. Hence $(\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(Q))))^c \subseteq (M^c)^c \subseteq Q^c \Rightarrow \text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(Q^c))) \subseteq M \subseteq Q^c$. Put $H = Q^c$. Then H is a PNP-closed set in U . This implies that $\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(H))) \subseteq M \subseteq H$, for some PNP-closed set H in U .

(ii) $\Rightarrow$ (iii). Assume there exists a PNP-closed set Q such that $\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(Q))) \subseteq M \subseteq Q$, but $\text{PNP-Cl}(M)$ is the smallest PNP-closed set containing M . Then $\text{PNP-Cl}(M) \subseteq Q$, and therefore, we get $\text{PNP-Int}(\text{PNP-Cl}(M)) \subseteq \text{PNP-Int}(Q)$. Thus $\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(M))) \subseteq \text{PNP-Cl}(\text{PNP-Int}(Q))$. Then

this implies $\text{PNP-Int}\left(\text{PNP-Cl}\left(\text{PNP-Int}\left(\text{PNP-Cl}(M)\right)\right)\right) \subseteq \text{PNP-Int}\left(\text{PNP-Cl}\left(\text{PNP-Int}(Q)\right)\right) \subseteq M$. Therefore we obtain $\text{PNP-Int}\left(\text{PNP-Cl}\left(\text{PNP-Int}\left(\text{PNP-Cl}(M)\right)\right)\right) \subseteq M$.

(iii) $\Rightarrow$ (i). Assume that $\text{PNP-Int}\left(\text{PNP-Cl}\left(\text{PNP-Int}\left(\text{PNP-Cl}(M)\right)\right)\right) \subseteq M$. Then it follows that $M^c \subseteq \left(\text{PNP-Int}\left(\text{PNP-Cl}\left(\text{PNP-Int}\left(\text{PNP-Cl}(M)\right)\right)\right)\right)^c = \text{PNP-Cl}\left(\text{PNP-Int}\left(\text{PNP-Cl}\left(\text{PNP-Int}(M^c)\right)\right)\right)$. Therefore, we obtain $M^c \subseteq \text{PNP-Cl}\left(\text{PNP-Int}\left(\text{PNP-Cl}\left(\text{PNP-Int}(M^c)\right)\right)\right)$. Hence M^c is a $\text{PNPS}\alpha$ -open set in U . Thus M is a $\text{PNPS}\alpha$ -closed set in U .

Theorem 3.5. The union of any family of $\text{PNPS}\alpha$ -open sets in a $\text{PNP-Top-Space } (U, \mathfrak{T}_{\text{PNP}})$ is a $\text{PNPS}\alpha$ -open set in U .

Proof. Let $\Omega = \{M_\lambda : \lambda \in \Lambda\}$ be a family of $\text{PNPS}\alpha$ -open sets in $(U, \mathfrak{T}_{\text{PNP}})$. Since for each $\lambda \in \Lambda$, M_λ is $\text{PNPS}\alpha$ -open set, there exists a $\text{PNP}\alpha$ -open set Q_λ in U such that $Q_\lambda \subseteq M_\lambda \subseteq \text{PNP-Cl}(Q_\lambda)$. This implies that $\bigcup_{\lambda \in \Lambda} Q_\lambda \subseteq \bigcup_{\lambda \in \Lambda} M_\lambda \subseteq \bigcup_{\lambda \in \Lambda} \text{PNP-Cl}(Q_\lambda) \subseteq \text{PNP-Cl}\left(\bigcup_{\lambda \in \Lambda} Q_\lambda\right)$. By Theorem 2.13, $\bigcup_{\lambda \in \Lambda} Q_\lambda$ is $\text{PNP}\alpha$ -open set in U . Therefore, $\bigcup_{\lambda \in \Lambda} M_\lambda$ is a $\text{PNPS}\alpha$ -open set in U .

Proposition 3.6. The intersection of any family of $\text{PNPS}\alpha$ -closed sets in a $\text{PNP-Top-Space } (U, \mathfrak{T}_{\text{PNP}})$ is a $\text{PNPS}\alpha$ -closed set in $(U, \mathfrak{T}_{\text{PNP}})$.

Proof. This follows directly from Theorem 3.5.

Definition 3.7. Let $M = \{\langle x, T_M(x), C_M(x), G_M(x), U_M(x), F_M(x) \rangle : x \in X\}$ be a PNP-set in a $\text{PNP-Top-Space } (U, \mathfrak{T}_{\text{PNP}})$. Then the $\text{PNPS}\alpha$ -interior and the $\text{PNPS}\alpha$ -closure of M are denoted by $\text{PNPS}\alpha\text{-Int}(M)$ and $\text{PNPS}\alpha\text{-Cl}(M)$, and are defined as follows.

$$\text{PNPS}\alpha\text{-Int}(M) = \bigcup \{Q : Q \text{ is a } \text{PNPS}\alpha\text{-open set and } Q \subseteq M\} \text{ and}$$

$$\text{PNPS}\alpha\text{-Cl}(M) = \bigcap \{K : K \text{ is a } \text{PNPS}\alpha\text{-closed set and } M \subseteq K\}$$

Theorem 3.8. Let $(U, \mathfrak{T}_{\text{PNP}})$ be a PNP-Top-Space and M be PNP-set in U . Then the following statements are true:

- (i) $\text{PNPS}\alpha\text{-Int}(M) = M$ if and only if M is $\text{PNPS}\alpha$ -open set.
- (ii) $\text{PNPS}\alpha\text{-Cl}(M) = M$ if and only if M is $\text{PNPS}\alpha$ -closed set.
- (iii) $\text{PNPS}\alpha\text{-Int}(M)$ is the largest $\text{PNPS}\alpha$ -open set contained in M .
- (iv) $\text{PNPS}\alpha\text{-Cl}(M)$ is the smallest $\text{PNPS}\alpha$ -closed set containing M .

Proof. (i), (ii), (iii) and (iv) are obvious.

Theorem 3.9. Let $(U, \mathfrak{T}_{\text{PNP}})$ be a PNP-Top-Space and M be a PNP-set in U . Then the following statements are true

$$(i) \text{PNPS}\alpha\text{-Int}(1_{\text{PNP}} - M) = 1_{\text{PNP}} - (\text{PNPS}\alpha\text{-Cl}(M)).$$

$$(ii) \text{PNPS}\alpha\text{-Cl}(1_{\text{PNP}} - M) = 1_{\text{PNP}} - (\text{PNPS}\alpha\text{-Int}(M)).$$

Proof. (i) By definition, $\text{PNPS}\alpha\text{-Cl}(M) = \bigcap \{K : K \text{ is a } \text{PNPS}\alpha\text{-closed set and } M \subseteq K\}$

$$\begin{aligned} 1_{\text{PNP}} - (\text{PNPS}\alpha\text{-Cl}(M)) &= 1_{\text{PNP}} - \bigcap \{K : K \text{ is a } \text{PNPS}\alpha\text{-closed set and } M \subseteq K\} \\ &= \bigcup \{1_{\text{PNP}} - K : K \text{ is a } \text{PNPS}\alpha\text{-closed set and } M \subseteq K\} = \bigcup \{Q : Q \subseteq 1_{\text{PNP}} - M, Q \text{ is a } \text{PNPS}\alpha\text{-open set}\} \\ &= \text{PNPS}\alpha\text{-Int}(1_{\text{PNP}} - M). \end{aligned}$$

(ii) The proof is similar to (i).

Theorem 3.10. Let $(U, \mathfrak{T}_{\text{PNP}})$ be a PNP -Top-Space and M and Q be PNP -sets in X . Then the following statements are true:

- (i) $\text{PNPS}\alpha\text{-Int}(0_{\text{PNP}}) = 0_{\text{PNP}}$, $\text{PNPS}\alpha\text{-Int}(1_{\text{PNP}}) = 1_{\text{PNP}}$.
- (ii) $\text{PNPS}\alpha\text{-Int}(M) \subseteq M$.
- (iii) $M \subseteq Q \Rightarrow \text{PNPS}\alpha\text{-Int}(M) \subseteq \text{PNPS}\alpha\text{-Int}(Q)$.
- (iv) $\text{PNPS}\alpha\text{-Int}(M \cap Q) \subseteq (\text{PNPS}\alpha\text{-Int}(M)) \cap (\text{PNPS}\alpha\text{-Int}(Q))$.
- (v) $(\text{PNPS}\alpha\text{-Int}(M)) \cup (\text{PNPS}\alpha\text{-Int}(Q)) \subseteq \text{PNPS}\alpha\text{-Int}(M \cup Q)$.
- (vi) $\text{PNPS}\alpha\text{-Int}(\text{PNPS}\alpha\text{-Int}(M)) = \text{PNPS}\alpha\text{-Int}(M)$.

Proof. (i), (ii), (iii), (iv), (v) and (vi) are obvious.

Theorem 3.11. Let $(U, \mathfrak{T}_{\text{PNP}})$ be a PNP -Top-Space and M and Q be PNP -sets in U . Then the following statements are true:

- (i) $\text{PNPS}\alpha\text{-Cl}(0_{\text{PNP}}) = 0_{\text{PNP}}$, $\text{PNPS}\alpha\text{-Cl}(1_{\text{PNP}}) = 1_{\text{PNP}}$.
- (ii) $M \subseteq \text{PNPS}\alpha\text{-Cl}(M)$.
- (iii) $M \subseteq Q \Rightarrow \text{PNPS}\alpha\text{-Cl}(M) \subseteq \text{PNPS}\alpha\text{-Cl}(Q)$.
- (iv) $\text{PNPS}\alpha\text{-Cl}(M \cap Q) \subseteq (\text{PNPS}\alpha\text{-Cl}(M)) \cap (\text{PNPS}\alpha\text{-Cl}(Q))$.
- (v) $(\text{PNPS}\alpha\text{-Cl}(M)) \cup (\text{PNPS}\alpha\text{-Cl}(Q)) \subseteq \text{PNPS}\alpha\text{-Cl}(M \cup Q)$.
- (vi) $\text{PNPS}\alpha\text{-Cl}(\text{PNPS}\alpha\text{-Cl}(M)) = \text{PNPS}\alpha\text{-Cl}(M)$.

Proof. (i) and (ii) are evident.

(iii) By part (ii), $Q \subseteq \text{PNPS}\alpha\text{-Cl}(Q)$. Since $M \subseteq Q$, we have $M \subseteq \text{PNPS}\alpha\text{-Cl}(Q)$. But $\text{PNPS}\alpha\text{-Cl}(Q)$ is a $\text{PNPS}\alpha\text{-closed}$ set. Thus $\text{PNPS}\alpha\text{-Cl}(Q)$ is a $\text{PNPS}\alpha\text{-closed}$ set containing M . Since $\text{PNPS}\alpha\text{-Cl}(M)$ is the smallest $\text{PNPS}\alpha\text{-closed}$ set containing M , we have $\text{PNPS}\alpha\text{-Cl}(M) \subseteq \text{PNPS}\alpha\text{-Cl}(Q)$. Hence $M \subseteq Q$ implies that $\text{PNPS}\alpha\text{-Cl}(M) \subseteq \text{PNPS}\alpha\text{-Cl}(Q)$.

(iv) We know that $M \cap Q \subseteq M$ and $M \cap Q \subseteq Q$. Therefore, by part (iii), $\text{PNPS}\alpha\text{-Cl}(M \cap Q) \subseteq \text{PNPS}\alpha\text{-Cl}(M)$ and $\text{PNPS}\alpha\text{-Cl}(M \cap Q) \subseteq \text{PNPS}\alpha\text{-Cl}(Q)$. Hence, we obtain $\text{PNPS}\alpha\text{-Cl}(M \cap Q) \subseteq \text{PNPS}\alpha\text{-Cl}(M) \cap \text{PNPS}\alpha\text{-Cl}(Q)$.

(v) Since $M \subseteq M \cup Q$ and $Q \subseteq M \cup Q$, it follows from part (iii) that $\text{PNPS}\alpha\text{-Cl}(M) \subseteq \text{PNPS}\alpha\text{-Cl}(M \cup Q)$ and $\text{PNPS}\alpha\text{-Cl}(Q) \subseteq \text{PNPS}\alpha\text{-Cl}(M \cup Q)$. Hence we obtain $\text{PNPS}\alpha\text{-Cl}(M) \cup \text{PNPS}\alpha\text{-Cl}(Q) \subseteq \text{PNPS}\alpha\text{-Cl}(M \cup Q)$.

(vi) Since $\text{PNPS}\alpha\text{-Cl}(M)$ is a $\text{PNPS}\alpha\text{-closed}$ set, we have by Theorem (3.8) part (ii), $\text{PNPS}\alpha\text{-Cl}(\text{PNPS}\alpha\text{-Cl}(M)) = \text{PNPS}\alpha\text{-Cl}(M)$.

Theorem 3.12. Let $(U, \mathfrak{T}_{\text{PNP}})$ be a PNP-Top-Space and M be PNP-set in U . Then the following statements are true:

- (i) $\text{PNP-Int}(M) \subseteq \text{PNP}\alpha\text{-Int}(M) \subseteq \text{PNPS}\alpha\text{-Int}(M) \subseteq \text{PNPS}\alpha\text{-Cl}(M) \subseteq \text{PNP}\alpha\text{-Cl}(M) \subseteq \text{PNP-Cl}(M)$.
- (ii) $\text{PNP-Int}(\text{PNPS}\alpha\text{-Int}(M)) = \text{PNPS}\alpha\text{-Int}(\text{PNP-Int}(M)) = \text{PNP-Int}(M)$.
- (iii) $\text{PNP}\alpha\text{-Int}(\text{PNPS}\alpha\text{-Int}(M)) = \text{PNPS}\alpha\text{-Int}(\text{PNP}\alpha\text{-Int}(M)) = \text{PNP}\alpha\text{-Int}(M)$.
- (iv) $\text{PNP-Cl}(\text{PNPS}\alpha\text{-Cl}(M)) = \text{PNPS}\alpha\text{-Cl}(\text{PNP-Cl}(M)) = \text{PNP-Cl}(M)$.
- (v) $\text{PNP}\alpha\text{-Cl}(\text{PNPS}\alpha\text{-Cl}(M)) = \text{PNPS}\alpha\text{-Cl}(\text{PNP}\alpha\text{-Cl}(M)) = \text{PNP}\alpha\text{-Cl}(M)$.
- (vi) $\text{PNPS}\alpha\text{-Cl}(M) = M \cup \text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(M))))$.
- (vii) $\text{PNPS}\alpha\text{-Int}(M) = M \cap \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M))))$.
- (viii) $\text{PNP-Int}(\text{PNP-Cl}(M)) \subseteq \text{PNPS}\alpha\text{-Int}(\text{PNPS}\alpha\text{-Cl}(M))$.

Proof. We shall prove only (ii), (iii), (iv), (vii) and (viii). The proofs of (i), (v) and (vi) are easy.

(ii) Since $\text{PNP-Int}(M)$ is a PNP-open set. Then $\text{PNP-Int}(M)$ is a $\text{PNPS}\alpha\text{-open}$ set. Hence (by Theorem (3.8)), $\text{PNP-Int}(M) = \text{PNPS}\alpha\text{-Int}(\text{PNP-Int}(M))$. Thus $\text{PNP-Int}(M) = \text{PNPS}\alpha\text{-Int}(\text{PNP-Int}(M))$. ----(*)

Since $\text{PNP-Int}(M) \subseteq \text{PNPS}\alpha\text{-Int}(M)$. This implies $\text{PNP-Int}(\text{PNP-Int}(M)) \subseteq \text{PNP-Int}(\text{PNPS}\alpha\text{-Int}(M))$. Therefore $\text{PNP-Int}(M) \subseteq \text{PNP-Int}(\text{PNPS}\alpha\text{-Int}(M))$. Also $\text{PNPS}\alpha\text{-Int}(M) \subseteq M$ implies that $\text{PNP-Int}(\text{PNPS}\alpha\text{-Int}(M)) \subseteq \text{PNP-Int}(M)$. Hence, $\text{PNP-Int}(M) = \text{PNP-Int}(\text{PNPS}\alpha\text{-Int}(M))$(**). Therefore by (*) and (**), we get $\text{PNP-Int}(\text{PNPS}\alpha\text{-Int}(M)) = \text{PNPS}\alpha\text{-Int}(\text{PNP-Int}(M)) = \text{PNP-Int}(M)$.

(iii) Since $\text{PNP}\alpha\text{-Int}(M)$ is a $\text{PNP}\alpha\text{-open}$ set. Then $\text{PNP}\alpha\text{-Int}(M)$ is a $\text{PNPS}\alpha\text{-open}$ set. Therefore (by Theorem (3.8)), it follows that $\text{PNP}\alpha\text{-Int}(M) = \text{PNPS}\alpha\text{-Int}(\text{PNP}\alpha\text{-Int}(M))$. -----(*). Since $\text{PNP}\alpha\text{-Int}(M) \subseteq \text{PNPS}\alpha\text{-Int}(M)$. This implies $\text{PNP}\alpha\text{-Int}(\text{PNP}\alpha\text{-Int}(M)) \subseteq \text{PNP}\alpha\text{-Int}(\text{PNPS}\alpha\text{-Int}(M))$. Therefore $\text{PNP}\alpha\text{-Int}(M) \subseteq \text{PNP}\alpha\text{-Int}(\text{PNPS}\alpha\text{-Int}(M))$. Also $\text{PNPS}\alpha\text{-Int}(M) \subseteq M$ implies that $\text{PNP}\alpha\text{-Int}(\text{PNPS}\alpha\text{-Int}(M)) \subseteq \text{PNP}\alpha\text{-Int}(M)$. So, $\text{PNP}\alpha\text{-Int}(M) = \text{PNP}\alpha\text{-Int}(\text{PNPS}\alpha\text{-Int}(M))$(**). Hence by (*) and (**), we get $\text{PNP}\alpha\text{-Int}(\text{PNPS}\alpha\text{-Int}(M)) = \text{PNPS}\alpha\text{-Int}(\text{PNP}\alpha\text{-Int}(M)) = \text{PNP}\alpha\text{-Int}(M)$.

(iv) We know that $\text{PNP-Cl}(M)$ is a PNP-closed set, so its is a $\text{PNPS}\alpha\text{-closed}$ set. Hence by Theorem (3.8), we obtain $\text{PNP-Cl}(M) = \text{PNPS}\alpha\text{-Cl}(\text{PNP-Cl}(M))$(1) Since $\text{PNPS}\alpha\text{-Cl}(M) \subseteq \text{PNP-Cl}(M)$. (by part(i)). Then $\text{PNP-Cl}(\text{PNPS}\alpha\text{-Cl}(M)) \subseteq \text{PNP-Cl}(\text{PNP-Cl}(M)) = \text{PNP-Cl}(M)$. This implies that $\text{PNP-Cl}(\text{PNPS}\alpha\text{-Cl}(M)) \subseteq \text{PNP-Cl}(M)$. Since $M \subseteq \text{PNPS}\alpha\text{-Cl}(M) \subseteq \text{PNP-Cl}(\text{PNPS}\alpha\text{-Cl}(M))$, then $M \subseteq \text{PNP-Cl}(\text{PNPS}\alpha\text{-Cl}(M))$. Therefore $\text{PNP-Cl}(M) \subseteq \text{PNP-Cl}(\text{PNP-Cl}(\text{PNPS}\alpha\text{-Cl}(M))) = \text{PNP-Cl}(\text{PNPS}\alpha\text{-Cl}(M))$. This implies $\text{PNP-Cl}(M) \subseteq \text{PNP-Cl}(\text{PNPS}\alpha\text{-Cl}(M))$ and therefore we obtain

$\text{PNP}-Cl(M) = \text{PNP}-Cl(\text{PNPS}\alpha - Cl(M)) \dots\dots\dots(2)$. Now by (1) and (2), it follows that $\text{PNP}-Cl(\text{PNPS}\alpha - Cl(M)) = \text{PNPS}\alpha - Cl(\text{PNP}-Cl(M)) = \text{PNP}-Cl(M)$.

(vii) Since $\text{PNPS}\alpha - Int(M)$ is a $\text{PNPS}\alpha - open$ set. Therefore we obtain $\text{PNPS}\alpha - Int(M) \subseteq \text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(\text{PNPS}\alpha - Int(M)))) = \text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M))))$ by (ii) $\text{PNPS}\alpha - Int(M) \subseteq \text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M))))$, also $\text{PNPS}\alpha - Int(M) \subseteq M$. Then we obtain $\text{PNPS}\alpha - Int(M) \subseteq M \cap (\text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M)))) \dots\dots\dots(1)$ Now we prove that $M \cap (\text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M))))$ is a $\text{PNPS}\alpha - open$ set contained in M . It is evident that $M \cap (\text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M)))) \subseteq \text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M))))$ and also it is clear that $\text{PNP}-Int(M) \subseteq \text{PNP}-Cl(\text{PNP}-Int(M))$. This implies that $\text{PNP}-Int(\text{PNP}-Int(M)) \subseteq \text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M)))$. This implies that $\text{PNP}-Int(M) \subseteq \text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M)))$. Then this implies that $\text{PNP}-Cl(\text{PNP}-Int(M)) \subseteq \text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M))))$ and $\text{PNP}-Int(M) \subseteq \text{PNP}-Cl(\text{PNP}-Int(M))$. This implies that $\text{PNP}-Int(M) \subseteq \text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M))))$ and $\text{PNP}-Int(M) \subseteq M$. Therefore we get $\text{PNP}-Int(M) \subseteq M \cap (\text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M)))) \subseteq \text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M))))$. Hence $M \cap (\text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M))))$ is a $\text{PNPS}\alpha - open$ set by Theorem (3.8). We also know that $M \cap (\text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M)))) \subseteq M$. Since $\text{PNPS}\alpha - Int(M)$ is the largest $\text{PNPS}\alpha - open$ set contained in M . Therefore we get $M \cap (\text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M)))) \subseteq \text{PNPS}\alpha - Int(M)$. $\dots\dots\dots(2)$

Now by (1) and (2). It follows that $\text{PNPS}\alpha - Int(M) = M \cap (\text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M))))$.

(viii) Since $\text{PNPS}\alpha - Cl(M)$ is a $\text{PNPS}\alpha - closed$ set. Therefore by Corollary (3.4), it follows that $\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNPS}\alpha - Cl(M)))) \subseteq \text{PNPS}\alpha - Cl(M)$. Hence we get $\text{PNP}-Int(\text{PNP}-Cl(M)) \subseteq \text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(M)))) \subseteq \text{PNPS}\alpha - Cl(M)$. (by part (iv)). Therefore it follows that $\text{PNPS}\alpha - Int(\text{PNP}-Int(\text{PNP}-Cl(M))) \subseteq \text{PNPS}\alpha - Int(\text{PNPS}\alpha - Cl(M))$. By part (ii), it follows that $\text{PNP}-Int(\text{PNP}-Cl(M)) \subseteq \text{PNPS}\alpha - Int(\text{PNPS}\alpha - Cl(M))$.

Theorem 3.13. Let $(U, \mathfrak{T}_{\text{PNP}})$ be a $\text{PNP}-Top-Space$ and M be $\text{PNP}-set$ in X . Then the following statements are equivalent:

- (i) M is $\text{PNPS}\alpha - open$ set.
- (ii) $Q \subseteq M \subseteq \text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(Q)))$, for some $\text{PNP}-open$ set Q .
- (iii) $Q \subseteq M \subseteq \text{PNPS}-Int(\text{PNP}-Cl(Q))$, for some $\text{PNP}-open$ set Q .
- (iv) $M \subseteq \text{PNPS}-Int(\text{PNP}-Cl(\text{PNP}-Int(M)))$.

Proof. (i) $\Rightarrow$ (ii). Let M be a $\text{PNPS}\alpha - open$ set. Then $M \subseteq \text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(\text{PNP}-Int(M))))$ and $\text{PNP}-Int(M) \subseteq M$. Hence $Q \subseteq M \subseteq \text{PNP}-Cl(\text{PNP}-Int(\text{PNP}-Cl(Q)))$, where $Q = \text{PNP}-Int(M)$.

(ii) $\Rightarrow$ (iii). Suppose $Q \subseteq M \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(Q)))$, for some PNP-open set Q . But $\text{PNP-Int}(\text{PNP-Cl}(Q)) = \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(Q)))$. (by Lemme (2.17)). Then we have $Q \subseteq M \subseteq \text{PNP-Int}(\text{PNP-Cl}(Q))$, for some PNP-open set Q .

(iii) $\Rightarrow$ (iv). Suppose that $Q \subseteq M \subseteq \text{PNP-Int}(\text{PNP-Cl}(Q))$, for some PNP-open set Q . Since Q is a PNP-open set contained in M . Then $Q \subseteq \text{PNP-Int}(M)$ implies that $\text{PNP-Cl}(Q) \subseteq \text{PNP-Cl}(\text{PNP-Int}(M))$. This implies that $\text{PNP-Int}(\text{PNP-Cl}(Q)) \subseteq \text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M)))$. But by hypothesis $M \subseteq \text{PNP-Int}(\text{PNP-Cl}(Q))$, then $M \subseteq \text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M)))$.

(iv) $\Rightarrow$ (i). Let $M \subseteq \text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M)))$. But $\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M))) = \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M))))$ (by Lemma 2.17). Hence it follows that $M \subseteq \text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(M))))$. This implies that M is $\text{PNP}\alpha$ -open set.

Corollary 3.14. Let $(U, \mathfrak{T}_{\text{PNP}})$ be a PNP-Top-Space and M be PNP-set in X . Then the following statements are equivalent:

- (i) M is $\text{PNP}\alpha$ -closed set.
- (ii) $\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(Q))) \subseteq M \subseteq Q$, for some PNP-closed set Q .
- (iii) $\text{PNP-Cl}(\text{PNP-Int}(Q)) \subseteq M \subseteq Q$, for some PNP-closed set Q .
- (iv) $\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(M))) \subseteq M$.

Proof. (i) $\Rightarrow$ (ii). Let M be a $\text{PNP}\alpha$ -closed set in U . Then by Corollary (3.4), we have $\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(M)))) \subseteq M$. Since $M \subseteq \text{PNP-Cl}(M)$. Therefore we obtain $\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(M)))) \subseteq M \subseteq \text{PNP-Cl}(M)$. Put $Q = \text{PNP-Cl}(M)$. Then we get $\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(Q))) \subseteq M \subseteq Q$.

(ii) $\Rightarrow$ (iii). Let $\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(Q))) \subseteq M \subseteq Q$, for some PNP-closed set Q . By Lemma (2.17), $\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(Q))) = \text{PNP-Cl}(\text{PNP-Int}(Q))$. Hence $\text{PNP-Cl}(\text{PNP-Int}(Q)) \subseteq M \subseteq Q$, for some PNP-closed set Q .

(iii) $\Rightarrow$ (iv). Let $\text{PNP-Cl}(\text{PNP-Int}(Q)) \subseteq M \subseteq Q$, for some PNP-closed set Q . Since $M \subseteq Q$ (by hypothesis), hence $\text{PNP-Cl}(M) \subseteq Q$. This implies $\text{PNP-Int}(\text{PNP-Cl}(M)) \subseteq \text{PNP-Int}(Q)$. Then this implies $\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(M))) \subseteq \text{PNP-Cl}(\text{PNP-Int}(Q)) \subseteq M$. Therefore it follows that $\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(M))) \subseteq M$.

(iv) $\Rightarrow$ (i). Let $\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(M))) \subseteq M$. But by Lemma (2.17), we get $\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(M))) = \text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(M))))$. Therefore it follows that $\text{PNP-Int}(\text{PNP-Cl}(\text{PNP-Int}(\text{PNP-Cl}(M)))) \subseteq M$. This shows that M is $\text{PNP}\alpha$ -closed set in $(U, \mathfrak{T}_{\text{PNP}})$.

4. Pentapartitioned Neutrosophic Pythagorean Semi Alpha –Continuous Mappings

In this section, we introduce the concepts of Pentapartitioned Neutrosophic Pythagorean Semi Alpha-continuous (briefly, PNPS α –continuous) mappings in PNP–Top–Spaces. Also, we study some of the main results depending on PNPS α –open sets.

Definition 4.1. Let $\xi:(U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ be a mapping. Then ξ is called a PNPS α –continuous mapping if $\xi^{-1}(Q)$ is a PNPS α –open set in U for every PNP –open set Q in W .

Theorem 4.2. Every PNP –continuous mapping is a PNPS α –continuous mapping.

Proof. Let $\xi:(U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ be PNP –continuous mapping. Let Q be a PNP –open set in (W, Γ_{PNP}) . Then $\xi^{-1}(Q)$ is PNP –open set in $(U, \mathfrak{T}_{\text{PNP}})$. Since every PNP –open set is PNPS α –open, $\xi^{-1}(Q)$ is PNPS α –open set in $(U, \mathfrak{T}_{\text{PNP}})$. Hence ξ is PNPS α –continuous mapping.

Theorem 4.3. Let $(U, \mathfrak{T}_{\text{PNP}})$, (W, Γ_{PNP}) and (Z, Ψ_{PNP}) be PNP –Top –Spaces. If $\xi:(U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ and $\eta:(W, \Gamma_{\text{PNP}}) \rightarrow (Z, \Psi_{\text{PNP}})$ are PNPS α –continuous mappings, then $\eta \circ \xi:(U, \mathfrak{T}_{\text{PNP}}) \rightarrow (Z, \Psi_{\text{PNP}})$ is a PNPS α –continuous mapping.

Proof. Let Q be a PNP –open set in Z . Since $\eta:(W, \Gamma_{\text{PNP}}) \rightarrow (Z, \Psi_{\text{PNP}})$ is PNP –continuous, $\eta^{-1}(Q)$ is PNP –open set in W . Since ξ is a PNPS α –continuous mapping, $\xi^{-1}[\eta^{-1}(Q)]$ is a PNPS α –open set in U . But $\xi^{-1}[\eta^{-1}(Q)] = (\eta \circ \xi)^{-1}(Q)$. Then $(\eta \circ \xi)^{-1}(Q)$ is a PNPS α –open set in U . Hence, $\eta \circ \xi$ is a PNPS α –continuous mapping.

Theorem 4.4. Let $(U, \mathfrak{T}_{\text{PNP}})$ and (W, Γ_{PNP}) be two PNP –Top –Spaces. Then prove that $\xi:(U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is PNPS α –continuous if and only if $\xi^{-1}(Q)$ is PNPS α –closed set in U for every PNP –closed set Q in W .

Proof. Let Q be a PNP –closed set in W . Then Q^c is PNP –open set in W . Since ξ is PNPS α –continuous. Therefore $\xi^{-1}(Q^c)$ is a PNPS α –open set in U . Since $\xi^{-1}(Q^c) = [\xi^{-1}(Q)]^c$, $\xi^{-1}(Q)$ is a PNPS α –closed set in U .

Conversely, Let Q be a PNP –open set in W . Then Q^c is PNP –closed set in W . By assumption $\xi^{-1}(Q^c)$ is PNPS α –closed set in U . Since $\xi^{-1}(Q^c) = [\xi^{-1}(Q)]^c$, $\xi^{-1}(Q)$ is PNPS α –open set in U . Hence ξ is PNPS α –continuous.

Theorem 4.5. Let $(U, \mathfrak{T}_{\text{PNP}})$ and (W, Γ_{PNP}) be two PNP –Top –Spaces and $\xi:U \rightarrow W$ be a mapping. Then ξ is a PNPS α –continuous mapping if and only if $\xi(\text{PNPS}\alpha\text{-Cl}(M)) \subseteq \text{PNP-Cl}(\xi(M))$ for every PNP –set M in U .

Proof. Let M be a PNP –set in U and ξ be a PNPS α –continuous mapping. We note that evidently $\xi(M) \subseteq \text{PNPS}\alpha\text{-Cl}[\xi(M)]$. Then we obtain $M \subseteq \xi^{-1}[\xi(M)] \subseteq \xi^{-1}[\text{PNPS}\alpha\text{-Cl}(\xi(M))]$ and $\text{PNPS}\alpha\text{-Cl}(M) \subseteq \text{PNPS}\alpha\text{-Cl}[\xi^{-1}(\text{PNPS}\alpha\text{-Cl}(\xi(M)))]$. Since ξ is a PNPS α –continuous mapping and

$\text{PNPS}\alpha\text{-Cl}[\xi(M)]$ is a $\text{PNPS}\alpha$ -closed set. Thus we have $\text{PNPS}\alpha\text{-Cl}[\xi^{-1}(\text{PNPS}\alpha\text{-Cl}(\xi(M)))] = \xi^{-1}[\text{PNPS}\alpha\text{-Cl}(\xi(M))]$. Hence, we have $\xi[\text{PNPS}\alpha\text{-Cl}(M)] \subseteq \text{PNP}\text{-Cl}[\xi(M)]$.

Conversely, let $\xi[\text{PNPS}\alpha\text{-Cl}(M)] \subseteq \text{PNP}\text{-Cl}[\xi(M)]$, for each PNP -set M in U . Let Q be a PNP -closed set in W . Then $\text{PNPS}\alpha\text{-Cl}[\xi(\xi^{-1}(Q))] \subseteq \text{PNPS}\alpha\text{-Cl}(Q) = Q$. By assumption, $\xi[\text{PNPS}\alpha\text{-Cl}(\xi^{-1}(Q))] \subseteq \text{PNP}\text{-Cl}[\xi(\xi^{-1}(Q))] \subseteq Q$ and hence $\text{PNPS}\alpha\text{-Cl}[\xi^{-1}(Q)] \subseteq \xi^{-1}(Q)$. Since $\xi^{-1}(Q) \subseteq \text{PNPS}\alpha\text{-Cl}[\xi^{-1}(Q)]$. Thus $\text{PNPS}\alpha\text{-Cl}[\xi^{-1}(Q)] = \xi^{-1}(Q)$. This implies that $\xi^{-1}(Q)$ is a $\text{PNPS}\alpha$ -closed set in U . Therefore by Theorem 4.4, ξ is a $\text{PNPS}\alpha$ -continuous mapping.

Theorem 4.6. Let $\xi:(U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ be a mapping. Then ξ is a $\text{PNPS}\alpha$ -continuous mapping if and only if $\text{PNPS}\alpha\text{-Cl}[\xi^{-1}(Q)] \subseteq \xi^{-1}[\text{PNP}\text{-Cl}(Q)]$ for each PNP -set Q in W .

Proof. Suppose that $\xi:(U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is a $\text{PNPS}\alpha$ -continuous mapping. Take Q be any PNP -set in W . Clearly $Q \subseteq \text{PNP}\text{-Cl}(Q)$ implies $\xi^{-1}(Q) \subseteq \xi^{-1}[\text{PNPS}\alpha\text{-Cl}(Q)]$. Then $\text{PNPS}\alpha\text{-Cl}[\xi^{-1}(Q)] \subseteq \text{PNPS}\alpha\text{-Cl}[\xi^{-1}(\text{PNP}\text{-Cl}(Q))]$. Since $\text{PNP}\text{-Cl}(Q)$ is PNP -closed set in W . So by Theorem 4.4, $\xi^{-1}[\text{PNP}\text{-Cl}(Q)]$ is a $\text{PNPS}\alpha$ -closed set in U . Therefore, $\text{PNPS}\alpha\text{-Cl}[\xi^{-1}(\text{PNP}\text{-Cl}(Q))] = \xi^{-1}[\text{PNP}\text{-Cl}(Q)]$. Hence, we have $\text{PNPS}\alpha\text{-Cl}[\xi^{-1}(Q)] \subseteq \xi^{-1}[\text{PNP}\text{-Cl}(Q)]$.

Conversely, let $\text{PNPS}\alpha\text{-Cl}[\xi^{-1}(Q)] \subseteq \xi^{-1}[\text{PNP}\text{-Cl}(Q)]$ for every PNP -set Q in W . Let F be a PNP -closed set in W . Since every PNP -closed set is $\text{PNPS}\alpha$ -closed set, $\text{PNPS}\alpha\text{-Cl}[\xi^{-1}(F)] \subseteq \xi^{-1}[\text{PNP}\text{-Cl}(F)] = \xi^{-1}(F)$. This implies that $\xi^{-1}(F)$ is a $\text{PNPS}\alpha$ -closed set in U . Thus by Theorem 4.4, ξ is a $\text{PNPS}\alpha$ -continuous mapping.

Theorem 4.7. Let $(U, \mathfrak{T}_{\text{PNP}})$ and (W, Γ_{PNP}) be two PNP -Top-Spaces and $\xi:U \rightarrow W$ be a mapping.. Then ξ is a $\text{PNPS}\alpha$ -continuous mapping if and only if $\xi^{-1}[\text{PNP}\text{-Int}(B)] \subseteq \text{PNPS}\alpha\text{-Int}[\xi^{-1}(B)]$ for every PNP -set B in W .

Proof. Let B be any PNP -set in W and ξ be a $\text{PNPS}\alpha$ -continuous mapping. Then $\text{PNP}\text{-Int}(B) \subseteq B$ implies $\xi^{-1}[\text{PNP}\text{-Int}(B)] \subseteq \xi^{-1}(B)$. Therefore we obtain $\text{PNPS}\alpha\text{-Int}[\xi^{-1}(\text{PNP}\text{-Int}(B))] \subseteq \text{PNPS}\alpha\text{-Int}[\xi^{-1}(B)]$. Since $\text{PNP}\text{-Int}(B)$ is PNP -open set in W and ξ is $\text{PNPS}\alpha$ -continuous Therefore, $\xi^{-1}[\text{PNP}\text{-Int}(B)]$ is $\text{PNPS}\alpha$ -open set in U . So $\text{PNPS}\alpha\text{-Int}[\xi^{-1}(\text{PNP}\text{-Int}(B))] = \xi^{-1}[\text{PNP}\text{-Int}(B)] \subseteq \text{PNPS}\alpha\text{-Int}[\xi^{-1}(B)]$.

Conversely, let $\xi^{-1}[\text{PNPS}\alpha\text{-Int}(B)] \subseteq \text{PNPS}\alpha\text{-Int}[\xi^{-1}(B)]$ for every PNP -set B in W . Let G be any PNP -open set in W and hence $\text{PNP}\text{-Int}(G) = G$. By hypothesis, we have $\xi^{-1}[\text{PNP}\text{-Int}(G)] \subseteq \text{PNPS}\alpha\text{-Int}[\xi^{-1}(G)]$. Therefore, $\xi^{-1}(G) \subseteq \text{PNPS}\alpha\text{-Int}[\xi^{-1}(G)]$. Also $\text{PNPS}\alpha\text{-Int}[\xi^{-1}(G)] \subseteq \xi^{-1}(G)$. Therefore $\text{PNPS}\alpha\text{-Int}[\xi^{-1}(G)] = \xi^{-1}(G)$. This implies that $\xi^{-1}(G)$ is $\text{PNPS}\alpha$ -open set in U . Hence ξ is a $\text{PNPS}\alpha$ -continuous mapping.

Definition 4.8. Let $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})}$ be a PNP-point of a PNP-Top-Space $(U, \mathfrak{T}_{\text{PNP}})$. A PNP-set A of U is called PNP-neighbourhood of $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})}$ if there exists a PNP-open set B such that $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in B \subseteq A$.

Theorem 4.9. Let ξ be a mapping from a PNP-Top-Space $(U, \mathfrak{T}_{\text{PNP}})$ to a PNP-Top-Space (W, Γ_{PNP}) . Then the following assertions are equivalent.

- (i) ξ is PNPS α -continuous.
- (ii) For each PNP-point $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in U$ and every PNP-neighbourhood A of $\xi(p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})})$, there exists a PNPS α -open set B such that $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in B \subseteq \xi^{-1}(A)$.
- (iii) For each PNP-point $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in U$ and every NN-neighbourhood A of $\xi(p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})})$, there exists a PNPS α -open set B in U such that $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in B$ and $\xi(B) \subseteq A$.

Proof. (i) $\Rightarrow$ (ii): Let $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in U$ be a PNP-point in U and let A be a PNP-neighbourhood of $\xi(p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})})$ in W such that $\xi(p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})}) \in B \subseteq A$. Since ξ is PNPS α -continuous, we know that $\xi^{-1}(B)$ is a PNPS α -open set in U and $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in \xi^{-1}(B) \subseteq \xi^{-1}(A)$. This implies (ii) is true.

(ii) $\Rightarrow$ (iii): Let $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})}$ be a PNP-point in U and let A be a PNP-neighbourhood of $\xi(p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})})$. The condition (ii) implies that there exists a PNPS α -open set B in U such that $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in B \subseteq \xi^{-1}(A)$. Thus $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in B$ and $\xi(B) \subseteq \xi[\xi^{-1}(A)] \subseteq A$. Hence (iii) is true.

(iii) $\Rightarrow$ (i): Let B be a PNP-open set in W and let $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in \xi^{-1}(B)$. Since B is PNP-open set, $\xi(p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})}) \in B$, and so B is PNP-neighbourhood of $\xi(p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})})$. It follows from (iii) that there exists a PNPS α -open set A in U such that $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in A$ and $\xi(A) \subseteq B$ so that $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in A \subseteq \xi^{-1}[\xi(A)] \subseteq \xi^{-1}(B)$. This implies by definition that $\xi^{-1}(B)$ is a PNPS α -open set in U . Therefore, ξ is a PNPS α -continuous mapping.

Definition 4.10. Let $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})}$ be a PNP-point of a PNP-Top-Space $(U, \mathfrak{T}_{\text{PNP}})$. A PNP-set A of U is called PNP-neighbourhood of $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})}$ if there exists a PNP-open set B such that $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in B \subseteq A$.

Theorem 4.11. Let ξ be a mapping from a PNP-Top-Space $(U, \mathfrak{T}_{\text{PNP}})$ to a PNP-Top-Space (W, Γ_{PNP}) . Then the following assertions are equivalent.

- (i) ξ is PNPS α -continuous.
- (ii) For each PNP-point $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in U$ and every PNP-neighbourhood A of $\xi(p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})})$, there exists a PNPS α -open set B such that $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in B \subseteq \xi^{-1}(A)$.
- (iii) For each PNP-point $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in U$ and every PNP-neighbourhood A of $\xi(p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})})$, there exists a PNPS α -open set B in U such that $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in B$ and $\xi(B) \subseteq A$.

Proof. (i) $\Rightarrow$ (ii): Let $p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})} \in U$ be a NN-point in U and let A be a NN-neighbourhood of $\xi(p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})})$. Then there exists a PNP-open set B in W such that $\xi(p_{(\tau_C \mathcal{G}, \lambda, \mathcal{E})}) \in B \subseteq A$. Since ξ is

PNPS α -continuous, we know that $\xi^{-1}(B)$ is a PNPS α -open set in U and $p_{(\tau_C, \beta, \lambda, \xi)} \in \xi^{-1}(B) \subseteq \xi^{-1}(A)$. This implies (ii) is true.

(ii) $\Rightarrow$ (iii): Let $p_{(\tau_C, \beta, \lambda, \xi)}$ be a PNP-point in U and let A be a PNP-neighbourhood of $\xi(p_{(\tau_C, \beta, \lambda, \xi)})$. The condition (ii) implies that there exists a PNPS α -open set B in U such that $p_{(\tau_C, \beta, \lambda, \xi)} \in B \subseteq \xi^{-1}(A)$. Thus $p_{(\tau_C, \beta, \lambda, \xi)} \in B$ and $\xi(B) \subseteq \xi[\xi^{-1}(A)] \subseteq A$. Hence (iii) is true.

(iii) $\Rightarrow$ (i): Let B be a PNP-open set in W and let $p_{(\tau_C, \beta, \lambda, \xi)} \in \xi^{-1}(B)$. Since B is PNP-open set, $\xi(p_{(\tau_C, \beta, \lambda, \xi)}) \in B$, and so B is PNP-neighbourhood of $\xi(p_{(\tau_C, \beta, \lambda, \xi)})$. It follows from (iii) that there exists a PNPS α -open set A in U such that $p_{(\tau_C, \beta, \lambda, \xi)} \in A$ and $\xi(A) \subseteq B$ so that $p_{(\tau_C, \beta, \lambda, \xi)} \in A \subseteq \xi^{-1}[\xi(A)] \subseteq \xi^{-1}(B)$. This implies by definition that $f^{-1}(B)$ is a PNPS α -open set in U . Therefore, ξ is a PNPS α -continuous mapping.

5. Pentapartitioned Neutrosophic Pythagorean Semi Alpha-Irresolute Mappings

In this section, we introduce the concept of Pentapartitioned Neutrosophic Pythagorean Semi Alpha-irresolute (briefly, PNPS α -irresolute) mappings in PNP-Top-Spaces. Also, we discuss the relationship with PNPS α -continuous mappings.

Definition 5.1. Let $(U, \mathfrak{T}_{\text{PNP}})$ and (W, Γ_{PNP}) be two PNP-Top-Spaces. A mapping $\xi: U \rightarrow W$ is called PNPS α -irresolute if the inverse image of every PNPS α -open set in W is PNPS α -open in U .

Theorem 5.2. Let $(U, \mathfrak{T}_{\text{PNP}})$ and (W, Γ_{PNP}) be two PNP-Top-Spaces. Prove that a mapping $\xi: U \rightarrow W$ is PNPS α -irresolute if the inverse image of every PNPS α -closed set in W is PNPS α -closed set in U .

Proof. Let Q be any PNPS α -closed set in W . Then Q^c is PNPS α -open set in W . Since ξ is PNPS α -irresolute, $\xi^{-1}(Q^c)$ is PNPS α -open set in U and $\xi^{-1}(Q^c) = [\xi^{-1}(Q)]^c$ which implies that $\xi^{-1}(Q)$ is PNPS α -closed set in U .

Conversely, Let G be any PNPS α -open set in W . Then G^c is PNPS α -closed set in W . Thus $\xi^{-1}(G^c)$ is PNPS α -closed set in U and $\xi^{-1}(G^c) = [\xi^{-1}(G)]^c$ which implies that $\xi^{-1}(G)$ is PNPS α -open set in U . Hence $\xi: U \rightarrow W$ is PNPS α -irresolute.

Theorem 5.3. Every PNPS α -irresolute mapping is PNPS α -continuous.

Proof. Let $(U, \mathfrak{T}_{\text{PNP}})$ and (W, Γ_{PNP}) be two PNP-Top-Spaces and $\xi: U \rightarrow W$ be a mapping. Let G be a PNP-open set in W . Since every PNP-open set is PNPS α -open, G is PNPS α -open. Since ξ is PNPS α -irresolute, $\xi^{-1}(G)$ is PNPS α -open in U . Therefore ξ is PNPS α -continuous.

Theorem 5.4. Let $(U, \mathfrak{T}_{\text{PNP}})$ and (W, Γ_{PNP}) be two PNP-Top-Spaces and $\xi: U \rightarrow W$ be a mapping. Then ξ is a PNPS α -irresolute mapping if and only if $\xi(\text{PNPS}\alpha\text{-Cl}(M)) \subseteq \text{PNPS}\alpha\text{-Cl}(\xi(M))$ for every PNP-set M in U .

Proof. Let M be a PNP-set in U and ξ be a PNPS α -iresolute mapping. Then evidently $\xi(M) \subseteq \text{PNPS}\alpha - Cl[\xi(M)]$. Then we have $M \subseteq \xi^{-1}[\xi(M)] \subseteq \xi^{-1}[\text{PNPS}\alpha - Cl(\xi(M))]$ and hence $\text{PNPS}\alpha - Cl(M) \subseteq \text{PNPS}\alpha - Cl[\xi^{-1}(\text{PNPS}\alpha - Cl(\xi(M)))]$. Since ξ is a PNPS α -iresolute mapping and $\text{PNPS}\alpha - Cl[\xi(M)]$ is a PNPS α -closed set. Therefore $\text{PNPS}\alpha - Cl[\xi^{-1}(\text{PNPS}\alpha - Cl(\xi(M)))] = \xi^{-1}[\text{PNPS}\alpha - Cl(\xi(M))]$. Thus $\xi[\text{PNPS}\alpha - Cl(M)] \subseteq \text{PNPS}\alpha - Cl[\xi(M)]$.

Conversely, let $\xi[\text{PNPS}\alpha - Cl(M)] \subseteq \text{PNPS}\alpha - Cl[\xi(M)]$, for each PNP-set M in U . Let H be a PNPS α -closed set in W . Then $\text{PNPS}\alpha - Cl(H) = H$. By assumption, $\xi[\text{PNPS}\alpha - Cl(\xi^{-1}(H))] \subseteq \text{PNPS}\alpha - Cl[\xi(\xi^{-1}(H))] \subseteq \text{PNPS}\alpha - Cl(H) = H$ and then $\text{PNPS}\alpha - Cl[\xi^{-1}(H)] \subseteq \xi^{-1}(H)$. Since $\xi^{-1}(H) \subseteq \text{PNPS}\alpha - Cl[\xi^{-1}(H)]$. Thus $\text{PNPS}\alpha - Cl[\xi^{-1}(H)] = \xi^{-1}(H)$. This shows that $\xi^{-1}(H)$ is a PNPS α -closed set in U . Thus by Theorem 5.3, ξ is a PNPS α -iresolute mapping.

Theorem 5.5. Let $(U, \mathfrak{T}_{\text{PNP}})$ and (W, Γ_{PNP}) be two PNP-Top-Spaces and $\xi: U \rightarrow W$ be a mapping. Then ξ is a PNPS α -iresolute mapping if and only if $\text{PNPS}\alpha - Cl[\xi^{-1}(H)] \subseteq \xi^{-1}[\text{PNPS}\alpha - Cl(H)]$ for each PNP-set H in W .

Proof. Let $\xi: U \rightarrow W$ be a PNPS α -iresolute mapping. Let H be any PNP-set set in W . Since $H \subseteq \text{PNPS}\alpha - Cl(H)$ and therefore we get $\xi^{-1}(H) \subseteq \xi^{-1}[\text{PNPS}\alpha - Cl(H)]$. Then we obtain $\text{PNPS}\alpha - Cl[\xi^{-1}(H)] \subseteq \text{PNPS}\alpha - Cl[\xi^{-1}(\text{PNPS}\alpha - Cl(H))]$. Since $\text{PNPS}\alpha - Cl(H)$ is PNPS α -closed set in W and ξ is a PNPS α -iresolute mapping. So by Theorem 5.3, $\xi^{-1}[\text{PNPS}\alpha - Cl(H)]$ is a PNPS α -closed set in U . Therefore $\text{PNPS}\alpha - Cl[\xi^{-1}(\text{PNPS}\alpha - Cl(H))] = \xi^{-1}[\text{PNPS}\alpha - Cl(H)]$. Hence, we have $\text{PNPS}\alpha - Cl[\xi^{-1}(H)] \subseteq \xi^{-1}[\text{PNPS}\alpha - Cl(H)]$.

Conversely, let $\text{PNPS}\alpha - Cl[\xi^{-1}(H)] \subseteq \xi^{-1}(\text{PNPS}\alpha - Cl(H))$ for all PNP-sets H in W . Let Q be a PNPS α -closed set in W . By assumption, $\text{PNPS}\alpha - Cl[\xi^{-1}(Q)] \subseteq \xi^{-1}[\text{PNPS}\alpha - Cl(Q)] = \xi^{-1}(Q)$. This implies that $\xi^{-1}(Q)$ is a PNPS α -closed set in U . Thus by Theorem 5.3, ξ is a PNPS α -iresolute mapping.

Theorem 5.6. Let $(U, \mathfrak{T}_{\text{PNP}})$ and (W, Γ_{PNP}) be two PNP-Top-Spaces and $\xi: U \rightarrow W$ be a bijective mapping. Then ξ is PNPS α -iresolute if and only if $\text{PNPS}\alpha - Int[\xi(M)] \subseteq \xi[\text{PNPS}\alpha - Int(M)]$ for every PNP-set M in U .

Proof. Let M be any PNP-set in U and ξ be a bijective and PNPS α -iresolute mapping. Let $\xi(M) = Q$. Since $\text{PNPS}\alpha - Int(Q) \subseteq Q$ and hence we obtain $\xi^{-1}[\text{PNPS}\alpha - Int(Q)] \subseteq \xi^{-1}(Q)$. Since ξ is an injective mapping, so $\xi^{-1}(Q) = M$. Thus $\xi^{-1}[\text{PNPS}\alpha - Int(Q)] \subseteq M$. Then this implies that $\text{PNPS}\alpha - Int[\xi^{-1}(\text{PNPS}\alpha - Int(Q))] \subseteq \text{PNPS}\alpha - Int(Q)$. Since ξ is PNPS α -iresolute, $\xi^{-1}[\text{PNPS}\alpha - Int(Q)]$ is PNPS α -open set in U and thus $\xi^{-1}[\text{PNPS}\alpha - Int(Q)] \subseteq \text{PNPS}\alpha - Int(M)$. Hence $\xi[\xi^{-1}(\text{PNPS}\alpha - Int(Q))] \subseteq \xi[\text{PNPS}\alpha - Int(M)]$. So $\text{PNPS}\alpha - Int[\xi(M)] \subseteq \xi[\text{PNPS}\alpha - Int(M)]$.

Conversely, let $\text{PNPS}\alpha - Int[\xi(M)] \subseteq \xi[\text{PNPS}\alpha - Int(M)]$ for every PNP-set M in U . Let G be a PNPS α -open set in W . Since ξ is surjective and therefore, by hypothesis, $G = \text{PNPS}\alpha - Int(G)$

$= \text{PNPS}\alpha - \text{Int}[\xi(\xi^{-1}(G))] \subseteq \xi[\text{PNPS}\alpha - \text{Int}(\xi^{-1}(G))]$. It follows that $\xi^{-1}(G) \subseteq \text{PNPS}\alpha - \text{Int}[\xi^{-1}(G)]$. Therefore $\xi^{-1}(G)$ is $\text{PNPS}\alpha$ -open set in U . Hence ξ is a $\text{PNPS}\alpha$ -irresolute mapping.

Theorem 5.7. Let $(U, \mathfrak{T}_{\text{PNP}})$ and (W, Γ_{PNP}) be two PNP -Top-Spaces and $\xi: U \rightarrow W$ be a mapping. Then ξ is a $\text{PNPS}\alpha$ -irresolute mapping if and only if $\xi^{-1}[\text{PNPS}\alpha - \text{Int}(H)] \subseteq \text{PNPS}\alpha - \text{Int}[\xi^{-1}(H)]$ for every PNP -set H in W .

Proof. Let H be any PNP -set in W and ξ be a $\text{PNPS}\alpha$ -irresolute mapping. Then $\text{PNPS}\alpha - \text{Int}(H) \subseteq H$ implies $\xi^{-1}[\text{PNPS}\alpha - \text{Int}(H)] \subseteq \xi^{-1}(H)$. Thus $\text{PNPS}\alpha - \text{Int}[\xi^{-1}(\text{PNPS}\alpha - \text{Int}(H))] \subseteq \text{PNPS}\alpha - \text{Int}[\xi^{-1}(H)]$. Since $\text{PNPS}\alpha - \text{Int}(H)$ is $\text{PNPS}\alpha$ -open set in W and ξ is $\text{PNPS}\alpha$ -irresolute, $\xi^{-1}[\text{PNPS}\alpha - \text{Int}(H)]$ is $\text{PNPS}\alpha$ -open set in U . Thus $\text{PNPS}\alpha - \text{Int}[\xi^{-1}(\text{PNPS}\alpha - \text{Int}(H))] = \xi^{-1}[\text{PNPS}\alpha - \text{Int}(H)]$. Then we obtain $\xi^{-1}[\text{PNPS}\alpha - \text{Int}(H)] \subseteq \text{PNPS}\alpha - \text{Int}[\xi^{-1}(H)]$.

Conversely, let $\xi^{-1}[\text{PNPS}\alpha - \text{Int}(H)] \subseteq \text{PNPS}\alpha - \text{Int}[\xi^{-1}(H)]$ for every PNP -set H in W . Let Q be any $\text{PNPS}\alpha$ -open set in W . Then by assumption, $\xi^{-1}(Q) = \xi^{-1}[\text{PNPS}\alpha - \text{Int}(Q)] \subseteq \text{PNPS}\alpha - \text{Int}[\xi^{-1}(Q)]$ and therefore $\xi^{-1}(Q) \subseteq \text{PNPS}\alpha - \text{Int}[\xi^{-1}(Q)]$. This implies that $\xi^{-1}(Q)$ is $\text{PNPS}\alpha$ -open set in U . Hence ξ is a $\text{PNPS}\alpha$ -irresolute mapping.

Theorem 5.8. Let $(U, \mathfrak{T}_{\text{PNP}})$ and (W, Γ_{PNP}) be two PNP -Top-Spaces and $\xi: U \rightarrow W$ be a bijective mapping and $\text{PNPS}\alpha$ -irresolute mapping. Then prove that $\xi[\text{PNPS}\alpha - \text{Fr}(M)] \subseteq \text{PNPS}\alpha - \text{Fr}[\xi(M)]$ for every PNP -set M in U .

Proof. Let ξ be a bijective and $\text{PNPS}\alpha$ -irresolute mapping. Let M be a PNP -set in U . By definition, $\text{PNPS}\alpha - \text{Fr}(M) = \text{PNPS}\alpha - \text{Cl}(M) \cap \text{PNPS}\alpha - \text{Cl}(M^c)$. By Theorem 5.6, $\text{PNPS}\alpha - \text{Int}[\xi(M)] \subseteq \xi[\text{PNPS}\alpha - \text{Int}(M)]$ and from Theorem 5.4, $\xi[\text{PNPS}\alpha - \text{Cl}(M)] \subseteq \text{PNPS}\alpha - \text{Cl}[\xi(M)]$. Therefore $\xi[\text{PNPS}\alpha - \text{Fr}(M)] = \xi[\text{PNPS}\alpha - \text{Cl}(M)] \cap \xi[\text{PNPS}\alpha - \text{Cl}(M^c)] \subseteq \text{PNPS}\alpha - \text{Cl}[\xi(M)] \cap \text{PNPS}\alpha - \text{Cl}[\xi(M)]^c = \text{PNPS}\alpha - \text{Fr}[\xi(M)]$.

Theorem 5.9. Let $(U, \mathfrak{T}_{\text{PNP}})$ and (W, Γ_{PNP}) be two PNP -Top-Spaces and $\xi: U \rightarrow W$ be a bijective $\text{PNPS}\alpha$ -irresolute mapping. Then we have $\text{PNPS}\alpha - \text{Fr}[\xi^{-1}(M)] \subseteq \xi^{-1}[\text{PNPS}\alpha - \text{Fr}(M)]$ for every PNP -set M in W .

Proof. Let ξ be a bijective and $\text{PNPS}\alpha$ -irresolute mapping. Let M be a NN -set in W . By Theorem 5.5, we have $\text{PNPS}\alpha - \text{Cl}[\xi^{-1}(M)] \subseteq \xi^{-1}[\text{PNPS}\alpha - \text{Cl}(M)]$. Now $\xi^{-1}[\text{PNPS}\alpha - \text{Fr}(M)] = \xi^{-1}[(\text{PNPS}\alpha - \text{Cl}(M)) \cap \text{PNPS}\alpha - \text{Cl}(M^c)] = \xi^{-1}[\text{PNPS}\alpha - \text{Cl}(M)] \cap \xi^{-1}[\text{PNPS}\alpha - \text{Cl}(M^c)] \supseteq \text{PNPS}\alpha - \text{Cl}[\xi^{-1}(M)] \cap \text{PNPS}\alpha - \text{Cl}[\xi^{-1}(M^c)] = \text{PNPS}\alpha - \text{Cl}[\xi^{-1}(M)] \cap \text{PNPS}\alpha - \text{Cl}[(\xi^{-1}(M))^c] = \text{PNPS}\alpha - \text{Fr}[\xi^{-1}(M)]$. Therefore, we obtain $\text{PNPS}\alpha - \text{Fr}[\xi^{-1}(M)] \subseteq \xi^{-1}[\text{PNPS}\alpha - \text{Fr}(M)]$.

Theorem 5.10. If $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ and $\eta: (W, \Gamma_{\text{PNP}}) \rightarrow (Z, \Psi_{\text{PNP}})$ are $\text{PNPS}\alpha$ -irresolute, then the composition function $\eta \circ \xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (Z, \Psi_{\text{PNP}})$ is also $\text{PNPS}\alpha$ -irresolute.

Proof. Let Q be a $\text{PNPS}\alpha$ -open set in Z . Since η is a $\text{PNPS}\alpha$ -irresolute mapping, $\eta^{-1}(Q)$ is $\text{PNPS}\alpha$ -open in W . Since ξ is a $\text{PNPS}\alpha$ -irresolute mapping, $\xi^{-1}[\eta^{-1}(Q)] = (\eta \circ \xi)^{-1}(Q)$ is $\text{PNPS}\alpha$ -open in U . Therefore $\eta \circ \xi$ is $\text{PNPS}\alpha$ -irresolute.

Theorem 5.11. If $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is $\text{PNPS}\alpha$ -irresolute and $\eta: (W, \Gamma_{\text{PNP}}) \rightarrow (Z, \Psi_{\text{PNP}})$ is $\text{PNPS}\alpha$ -continuous, then the composition function $\eta \circ \xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (Z, \Psi_{\text{PNP}})$ is also a $\text{PNPS}\alpha$ -continuous function.

Proof. Let Q be a PNP -open set in Z . Since η is a $\text{PNPS}\alpha$ -continuous mapping, $\eta^{-1}(Q)$ is $\text{PNPS}\alpha$ -open set in W . Since ξ is a $\text{PNPS}\alpha$ -irresolute mapping, $\xi^{-1}[\eta^{-1}(Q)] = (\eta \circ \xi)^{-1}(Q)$ is $\text{PNPS}\alpha$ -open in U . Therefore $\eta \circ \xi$ is $\text{PNPS}\alpha$ -continuous.

6. Pentapartitioned Neutrosophic Pythagorean Semi Alpha -Closed and Open Mappings

In this section, we introduce Pentapartitioned Neutrosophic Pythagorean Semi Alpha-closed (briefly, $\text{PNPS}\alpha$ -closed) mappings and Pentapartitioned Neutrosophic Pythagorean Semi Alpha-open (briefly, $\text{PNPS}\alpha$ -open) mappings in PNP -Top-Spaces and obtain certain characterizations of these classes of mappings.

Definition 6.1. Let $(U, \mathfrak{T}_{\text{PNP}})$ and (W, Γ_{PNP}) be two PNP -Top-Spaces. A function $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is said to be $\text{PNPS}\alpha$ -closed if the image of each PNP -closed set in U is $\text{PNPS}\alpha$ -closed in W .

Definition 6.2. Let $(U, \mathfrak{T}_{\text{PNP}})$ and (W, Γ_{PNP}) be two PNP -Top-Spaces. A function $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is said to be $\text{PNPS}\alpha$ -open if the image of each PNP -open set in U is $\text{PNPS}\alpha$ -open in W .

Theorem 6.3. Prove that a function $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is $\text{PNPS}\alpha$ -closed if and only if $\text{PNPS}\alpha\text{-Cl}[\xi(A)] \subseteq \xi[\text{PNP}\text{-Cl}(A)]$ for every PNP -set A of U .

Proof. Suppose $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is a $\text{PNPS}\alpha$ -closed function and A is any PNP -set in U . Then $\text{PNP}\text{-Cl}(A)$ is a PNP -closed set in U . Since ξ is $\text{PNPS}\alpha$ -closed, $\xi[\text{PNP}\text{-Cl}(A)]$ is a $\text{PNPS}\alpha$ -closed set in W . Thus we obtain $\text{PNPS}\alpha\text{-Cl}[\xi(\text{PNP}\text{-Cl}(A))] = \xi[\text{PNP}\text{-Cl}(A)]$. Therefore $\text{PNPS}\alpha\text{-Cl}[\xi(A)] \subseteq \text{PNPS}\alpha\text{-Cl}[\xi(\text{PNP}\text{-Cl}(A))] = \xi(\text{PNP}\text{-Cl}(A))$. Thus we obtain $\text{PNPS}\alpha\text{-Cl}[\xi(A)] \subseteq \xi(\text{PNP}\text{-Cl}(A))$.

Conversely, let A be a PNP -closed set in U . Then $\text{PNP}\text{-Cl}(A) = A$ and so $\xi(A) = \xi[\text{PNP}\text{-Cl}(A)]$. By our assumption $\text{PNPS}\alpha\text{-Cl}[\xi(A)] \subseteq \xi(A)$. But $\xi(A) \subseteq \text{PNPS}\alpha\text{-Cl}[\xi(A)]$. So $\text{PNPS}\alpha\text{-Cl}[\xi(A)] = \xi(A)$ and hence $\xi(A)$ is $\text{PNPS}\alpha$ -closed set in W . Thus ξ is a $\text{PNPS}\alpha$ -closed mapping.

Theorem 6.4. A mapping $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is $\text{PNPS}\alpha$ -closed if and only if for each PNP -set H of W and for each PNP -open set G of U containing $\xi^{-1}(H)$ there exists a $\text{PNPS}\alpha$ -open set V of W such that $H \subseteq V$ and $\xi^{-1}(V) \subseteq G$.

Proof. Suppose ξ is a $\text{PNPS}\alpha$ -closed mapping. Let H be any PNP -set in W and G be a PNP -open set of U such that $\xi^{-1}(H) \subseteq G$. Then $V = [\xi(G^c)]^c$ is $\text{PNPS}\alpha$ -open in W such that $\xi^{-1}(V) \subseteq G$.

Conversely, let H be a PNP -closed of U . Then $\xi^{-1}[(\xi(H))^c] \subseteq H^c$ and H^c is PNP -open in U . By assumption, there exists a $\text{PNPS}\alpha$ -open set V of W such that $[\xi(H)]^c \subseteq V$ and $\xi^{-1}(V) \subseteq H^c$ and so $H \subseteq [\xi^{-1}(V)]^c$. Hence $V^c \subseteq \xi(H) \subseteq \xi[\xi^{-1}(V)^c] \subseteq V^c$, which implies $\xi(H) = V^c$. Since V^c is $\text{PNPS}\alpha$ -closed, $\xi(H)$ is $\text{PNPS}\alpha$ -closed and ξ is $\text{PNPS}\alpha$ -closed mapping.

Theorem 6.5. Let $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ be a PNP -closed map and $\eta: (W, \Gamma_{\text{PNP}}) \rightarrow (Z, \Psi_{\text{PNP}})$ be a $\text{PNPS}\alpha$ -closed mapping. Then their composition $\eta \circ \xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (Z, \Psi_{\text{PNP}})$ is a $\text{PNPS}\alpha$ -closed mapping.

Proof. Let F be a PNP -closed set in U . Since ξ is PNP -closed, $\xi(F)$ is PNP -closed in W . Since η is $\text{PNPS}\alpha$ -closed, $\eta[\xi(F)] = (\eta \circ \xi)(F)$ is $\text{PNPS}\alpha$ -closed in Z . Hence $\eta \circ \xi$ is a $\text{PNPS}\alpha$ -closed mapping.

Theorem 6.6. Let $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ and $\eta: (W, \Gamma_{\text{PNP}}) \rightarrow (Z, \Psi_{\text{PNP}})$ be two mappings such that their composition $\eta \circ \xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (Z, \Psi_{\text{PNP}})$ is $\text{PNPS}\alpha$ -closed. Then the following statements are true.

- (i) If ξ is PNP -continuous and surjective, then η is $\text{PNPS}\alpha$ -closed.
- (ii) If η is $\text{PNPS}\alpha$ -irresolute and injective, then ξ is $\text{PNPS}\alpha$ -closed.

Proof. (i) Let A be a PNP -closed set of W . Since ξ is PNP -continuous, $\xi^{-1}(A)$ is PNP -closed in U . Since $\eta \circ \xi$ is $\text{PNPS}\alpha$ -closed, $(\eta \circ \xi)(\xi^{-1}(A))$ is $\text{PNPS}\alpha$ -closed in Z . Since ξ is surjective, $(\eta \circ \xi)(\xi^{-1}(A)) = \eta(A)$ is $\text{PNPS}\alpha$ -closed in Z . Hence η is $\text{PNPS}\alpha$ -closed.

(ii) Let B be any PNP -closed set of U . Since $\eta \circ \xi$ is $\text{PNPS}\alpha$ -closed, $(\eta \circ \xi)(B)$ is $\text{PNPS}\alpha$ -closed in Z . Since η is $\text{PNPS}\alpha$ -irresolute, $\eta^{-1}((\eta \circ \xi)(B))$ is $\text{PNPS}\alpha$ -closed in W . Since η is injective, $\eta^{-1}((\eta \circ \xi)(B)) = \eta^{-1}(\eta(\xi(B))) = \xi(B)$ is $\text{PNPS}\alpha$ -closed in W . Hence ξ is $\text{PNPS}\alpha$ -closed.

Theorem 6.7. A function $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is $\text{PNPS}\alpha$ -open if and only if $\xi[\text{PNP-Int}(M)] \subseteq \text{PNPS}\alpha\text{-Int}[\xi(M)]$, for every PNP -set M of U .

Proof. Suppose $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is a $\text{PNPS}\alpha$ -open function and M is any PNP -set in U . Then $\text{PNP-Int}(M)$ is a PNP -open set in U . Since ξ is $\text{PNPS}\alpha$ -open, $\xi[\text{PNP-Int}(M)]$ is a $\text{PNPS}\alpha$ -open set. Since $\text{PNPS}\alpha\text{-Int}[\xi(\text{PNP-Int}(M))] \subseteq \text{PNPS}\alpha\text{-Int}[\xi(M)]$, $\xi[\text{PNP-Int}(M)] \subseteq \text{PNPS}\alpha\text{-Int}[\xi(M)]$.

Conversely, $\xi[\text{PNP-Int}(M)] \subseteq \text{PNPS}\alpha\text{-Int}[\xi(M)]$ for every PNP -set M in U . Let G be a PNP -open set in U . Then $\text{PNP-Int}(G) = G$ and by hypothesis, $\xi(G) \subseteq \text{PNPS}\alpha\text{-Int}[\xi(G)]$. But $\text{PNPS}\alpha\text{-Int}[\xi(G)] \subseteq \xi(G)$. Therefore, $\xi(G) = \text{PNPS}\alpha\text{-Int}[\xi(G)]$. Then $\xi(G)$ is $\text{PNPS}\alpha$ -open. Hence ξ is a $\text{PNPS}\alpha$ -open mapping.

Theorem 6.8. Let $\xi:(U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ be a $\text{PNPS}\alpha$ -open function. If for each $p_{(t, c, g, u, f)} \in U$ and for each PNP -neighbourhood M of $p_{(t, c, g, u, f)}$ in U , there exists a $\text{PNPS}\alpha$ -neighborhood H of $\xi(p_{(t, c, g, u, f)})$ in W such that $H \subseteq \xi(M)$.

Proof. Let $\xi:(U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ be a $\text{PNPS}\alpha$ -open function. Let $p_{(t, c, g, u, f)} \in U$ and M be any arbitrary PNP -neighbourhood of $p_{(t, c, g, u, f)}$ in U . Then there exists a PNP -open set Q such that $p_{(t, c, g, u, f)} \in Q \subseteq M$. By Theorem 6.7, $\xi(Q) = \xi[\text{PNP-Int}(Q)] \subseteq \text{PNPS}\alpha\text{-Int}[\xi(Q)]$. But, $\text{PNPS}\alpha\text{-Int}[\xi(Q)] \subseteq \xi(Q)$. Therefore, $\text{PNPS}\alpha\text{-Int}[\xi(Q)] = \xi(Q)$ and hence $\xi(Q)$ is $\text{PNPS}\alpha$ -open in W . Since $p_{(t, c, g, u, f)} \in Q \subseteq M$, $\xi(p_{(t, c, g, u, f)}) \in \xi(Q) \subseteq \xi(M)$ and so the result follows by taking $H = \xi(Q)$.

Theorem 6.9. For any bijective mapping $\xi:(U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ the following statements are equivalent:

- (i) $\xi^{-1}:(U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is $\text{PNPS}\alpha$ -continuous.
- (ii) ξ is $\text{PNPS}\alpha$ -open.
- (iii) ξ is $\text{PNPS}\alpha$ -closed.

Proof. (i) $\Rightarrow$ (ii): Let M be a PNP -open set in U . By assumption, $(\xi^{-1})^{-1}(M) = \xi(M)$ is $\text{PNPS}\alpha$ -open in W and hence ξ is a $\text{PNPS}\alpha$ -open function.

(ii) $\Rightarrow$ (iii): Let Q be a PNP -closed set of U . Then Q^c is a PNP -open set in U . By assumption $\xi(Q^c)$ is $\text{PNPS}\alpha$ -open in W . But $\xi(Q^c) = [\xi(Q)]^c$. Therefore $\xi(Q)$ is $\text{PNPS}\alpha$ -closed set in W . Hence, ξ is $\text{PNPS}\alpha$ -closed.

(iii) $\Rightarrow$ (i): Let M be a PNP -closed set of U . By assumption, $\xi(M)$ is $\text{PNPS}\alpha$ -closed set in W . But $\xi(M) = (\xi^{-1})^{-1}(M)$ and therefore by Theorem 4.4, $\xi^{-1}:W \rightarrow U$ is $\text{PNPS}\alpha$ -continuous.

7. Pentapartitioned Neutrosophic Pythagorean Semi Alpha-Homeomorphisms

In this section, we define and study the concept of Pentapartitioned Neutrosophic Pythagorean Semi Alpha-homeomorphism (briefly, $\text{PNPS}\alpha$ -homeomorphism) in PNP -Top-Space $(U, \mathfrak{T}_{\text{PNP}})$ and obtain some of its properties and characterizations.

Definition 7.1. A map $\xi:(U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is said to be PNP -homeomorphism if ξ is one-to-one & onto, PNP -open and PNP -continuous.

Definition 7.2. A map $\xi:(U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is said to be $\text{PNPS}\alpha$ -homeomorphisms if ξ is one-to-one and onto, $\text{PNPS}\alpha$ -open and $\text{PNPS}\alpha$ -continuous.

Theorem 7.3. Let $\xi:(U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ be a one-to-one onto mapping. Then ξ is $\text{PNPS}\alpha$ -homeomorphism if and only if ξ is $\text{PNPS}\alpha$ -closed and $\text{PNPS}\alpha$ -continuous.

Proof. Let $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ be a $\text{PNPS}\alpha$ -homeomorphism. Then ξ is $\text{PNPS}\alpha$ -continuous. Let M be an arbitrary PNP -closed set in $(U, \mathfrak{T}_{\text{PNP}})$. Then $U - M$ is PNP -open. Since ξ is $\text{PNPS}\alpha$ -open, $\xi(U - M)$ is $\text{PNPS}\alpha$ -open in (W, Γ_{PNP}) . That is, $W - \xi(M)$ is $\text{PNPS}\alpha$ -open in (W, Γ_{PNP}) for every PNP -closed set M in $(U, \mathfrak{T}_{\text{PNP}})$ implies that $\xi(M)$ is $\text{PNPS}\alpha$ -closed in (W, Γ_{PNP}) . Hence $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is $\text{PNPS}\alpha$ -closed.

Conversely, let ξ be a $\text{PNPS}\alpha$ -closed and $\text{PNPS}\alpha$ -continuous function. Let M be a PNP -open set in $(U, \mathfrak{T}_{\text{PNP}})$. Then $U - M$ is PNP -closed in $(U, \mathfrak{T}_{\text{PNP}})$. Since ξ is $\text{PNPS}\alpha$ -closed, $\xi(U - M)$ is $\text{PNPS}\alpha$ -closed in (W, Γ_{PNP}) . That is, $\xi(U - M) = W - \xi(M)$ is $\text{PNPS}\alpha$ -closed in (W, Γ_{PNP}) . Hence $\xi(M)$ is $\text{PNPS}\alpha$ -open in (W, Γ_{PNP}) for every PNP -open set M in $(U, \mathfrak{T}_{\text{PNP}})$. Thus, ξ is $\text{PNPS}\alpha$ -open and hence $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is $\text{PNPS}\alpha$ -homeomorphism.

Theorem 7.4. : Let $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ be a bijective and $\text{PNPS}\alpha$ -continuous map. Then the following statements are equivalent.

- (i) ξ is a $\text{PNPS}\alpha$ -open map.
- (ii) ξ is a $\text{PNPS}\alpha$ -homeomorphism.
- (iii) ξ is a $\text{PNPS}\alpha$ -closed map.

Proof. (i) $\Rightarrow$ (ii). By the given hypothesis, the map $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is bijective $\text{PNPS}\alpha$ -continuous and $\text{PNPS}\alpha$ -open. Hence $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is $\text{PNPS}\alpha$ -homeomorphism.

(ii) $\Rightarrow$ (iii). Let M be a PNP -closed set in $(U, \mathfrak{T}_{\text{PNP}})$. Then M^c is PNP -open in $(U, \mathfrak{T}_{\text{PNP}})$. By assumption, $\xi(M^c)$ is $\text{PNPS}\alpha$ -open in (W, Γ_{PNP}) . That is $\xi(M^c) = (\xi(M))^c = W - \xi(M)$ is $\text{PNPS}\alpha$ -open in (W, Γ_{PNP}) and hence $\xi(M)$ is $\text{PNPS}\alpha$ -closed in (W, Γ_{PNP}) for every PNP -closed set M in $(U, \mathfrak{T}_{\text{PNP}})$. Hence the function $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is $\text{PNPS}\alpha$ -closed map.

(iii) $\Rightarrow$ (i). Let G be a PNP -open set in $(U, \mathfrak{T}_{\text{PNP}})$. Then G^c is PNP -closed set in $(U, \mathfrak{T}_{\text{PNP}})$. By the given hypothesis, $\xi(G^c)$ is $\text{PNPS}\alpha$ -closed in (W, Γ_{PNP}) . But $\xi(G^c) = (\xi(G))^c = W - \xi(G)$ is $\text{PNPS}\alpha$ -closed. Therefore $\xi(G)$ is $\text{PNPS}\alpha$ -open in (W, Γ_{PNP}) . for every PNP -open set G in $(U, \mathfrak{T}_{\text{PNP}})$. Hence $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is $\text{PNPS}\alpha$ -open map.

Theorem 7.5. Every PNP -homeomorphism is $\text{PNPS}\alpha$ -homeomorphism.

Proof. If $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is PNP -homeomorphism, by definition 7.1, ξ is bijective, PNP -continuous and PNP -open. Then $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is $\text{PNPS}\alpha$ -continuous and $\text{PNPS}\alpha$ -open. Hence the function $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is $\text{PNPS}\alpha$ -homeomorphism. Every PNP -continuous function is $\text{PNPS}\alpha$ -continuous and every PNP -open map is $\text{PNPS}\alpha$ -open. Then ξ is bijective, $\text{PNPS}\alpha$ -continuous and $\text{PNPS}\alpha$ -open. Therefore ξ is $\text{PNPS}\alpha$ -homeomorphism.

Theorem 7.6. Let $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ be a $\text{PNP}\alpha$ -homeomorphism. Then prove that ξ is $\text{PNPS}\alpha$ -homeomorphism.

Proof. Let $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ be a $\text{PNP}\alpha$ -homeomorphism. Then ξ is bijective, $\text{PNP}\alpha$ -continuous and $\text{PNP}\alpha$ -open. Let H be a PNP -open set in (W, Γ_{PNP}) . Since ξ is $\text{PNP}\alpha$ -continuous, $\xi^{-1}(H)$ is $\text{PNP}\alpha$ -open set in $(U, \mathfrak{T}_{\text{PNP}})$. Since every $\text{PNP}\alpha$ -open set is $\text{PNPS}\alpha$ -open set, $\xi^{-1}(H)$ is $\text{PNPS}\alpha$ -open in $(U, \mathfrak{T}_{\text{PNP}})$ which implies that ξ is $\text{PNPS}\alpha$ -continuous. Let M be a PNP -open set in $(U, \mathfrak{T}_{\text{PNP}})$. Since ξ is $\text{PNP}\alpha$ -open, $\xi(M)$ is $\text{PNP}\alpha$ -open set in (W, Γ_{PNP}) . Since every $\text{PNP}\alpha$ -open set is $\text{PNPS}\alpha$ -open set, $\xi(M)$ is $\text{PNPS}\alpha$ -open set in (W, Γ_{PNP}) which implies ξ is $\text{PNPS}\alpha$ -open map. Therefore, consequently ξ is $\text{PNPS}\alpha$ -homeomorphism.

Theorem 7.7. Let $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ be a bijective and $\text{PNPS}\alpha$ -irresolute map. Then the following statements are equivalent.

- (i) ξ is a $\text{PNPS}\alpha$ -open map.
- (ii) ξ is a $\text{PNPS}\alpha$ -homeomorphism.
- (iii) ξ is a $\text{PNPS}\alpha$ -closed map.

Proof. Identical to the proof of Theorem 7.4.

Theorem 7.8. Let $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ be a bijective function. Then prove that ξ is $\text{PNPS}\alpha$ -homeomorphism if and only if $\xi[\text{PNPS}\alpha\text{-Cl}(M)] = \text{PNP}\text{-Cl}(\xi(M))$ for every subset M of $(U, \mathfrak{T}_{\text{PNP}})$.

Proof. If $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is $\text{PNPS}\alpha$ -homeomorphisms, then ξ is $\text{PNPS}\alpha$ -continuous and $\text{PNPS}\alpha$ -closed. If $M \subseteq U$. Then $\xi[\text{PNPS}\alpha\text{-Cl}(M)] \subseteq \text{PNP}\text{-Cl}(\xi(M))$ since ξ is $\text{PNPS}\alpha$ -continuous. Since $\text{PNPS}\alpha\text{-Cl}(A)$ is PNP -closed in $(U, \mathfrak{T}_{\text{PNP}})$ and ξ is $\text{PNPS}\alpha$ -closed map, $\xi[\text{PNPS}\alpha\text{-Cl}(M)]$ is $\text{PNPS}\alpha$ -closed in (W, Γ_{PNP}) . Also $\text{PNPS}\alpha\text{-Cl}[\xi(\text{PNPS}\alpha\text{-Cl}(M))] = \xi(\text{PNPS}\alpha\text{-Cl}(M))$. Since $M \subseteq \text{PNPS}\alpha\text{-Cl}(M)$, $\xi(M) \subseteq \xi[\text{PNPS}\alpha\text{-Cl}(M)]$ and therefore we obtain $\text{PNP}\text{-Cl}(\xi(M)) \subseteq \text{PNP}\text{-Cl}[\xi(\text{PNPS}\alpha\text{-Cl}(M))] = \xi(\text{PNPS}\alpha\text{-Cl}(M))$. Thus $\text{PNP}\text{-Cl}(\xi(M)) \subseteq \xi(\text{PNPS}\alpha\text{-Cl}(M))$. Hence, $\xi[\text{PNPS}\alpha\text{-Cl}(M)] = \text{PNP}\text{-Cl}(\xi(M))$ if ξ is $\text{PNPS}\alpha$ -homeomorphism.

Conversely, if $\xi[\text{PNPS}\alpha\text{-Cl}(M)] = \text{PNP}\text{-Cl}(\xi(M))$ for every subset M of $(U, \mathfrak{T}_{\text{PNP}})$, then ξ is $\text{PNPS}\alpha$ -continuous. If M is PNP -closed in $(U, \mathfrak{T}_{\text{PNP}})$, then M is $\text{PNPS}\alpha$ -closed in $(U, \mathfrak{T}_{\text{PNP}})$. Then $\text{PNPS}\alpha\text{-Cl}(M) = M$ which implies $\xi[\text{PNPS}\alpha\text{-Cl}(M)] = \xi(M)$. Hence, by the given hypothesis, it follows that $\text{PNP}\text{-Cl}(\xi(M)) = \xi(M)$. Thus $\xi(M)$ is PNP -closed in W and hence $\text{PNPS}\alpha$ -closed in W for every PNP -closed set M in U . That is, ξ is a $\text{PNPS}\alpha$ -closed map. Therefore $\xi: (U, \mathfrak{T}_{\text{PNP}}) \rightarrow (W, \Gamma_{\text{PNP}})$ is $\text{PNPS}\alpha$ -homeomorphism.

Conclusions

In this paper, the author has studied the concepts of Pentapartitioned Neutrosophic Pythagorean Semi- α -open ($\text{PNPS}\alpha$ -open) and $\text{PNPS}\alpha$ -closed sets. Fundamental definitions are established, and several basic properties and characterizations of these sets are obtained. The relationships between $\text{PNPS}\alpha$ -open sets and existing classes of PNP -open, $\text{PNP}\alpha$ -open, PNP -semi-open, and PNP -closed sets are investigated, and inclusion relations among these classes are discussed. The author has applied $\text{PNPS}\alpha$ -open sets and $\text{PNPS}\alpha$ -closed sets and introduced the

notions of new classes of functions called PNPS α -continuous maps, PNPS α -irresolute maps, PNPS α -open maps, PNPS α -closed maps, and PNPS α -homeomorphisms, and has investigated fundamental properties and characterizations of these mappings in PNP-Topological Spaces. In future work, the author intends to continue to introduce and investigate properties and characterizations of the notions of Strongly PNPS α -continuous maps, Perfectly PNPS α -continuous maps, Totally PNPS α -continuous maps, Quasi PNPS α -continuous maps, Almost PNPS α -continuous maps, Somewhat PNPS α -continuous maps, PNPS α -Separation Axioms, PNPS α -Regular space, PNPS α -Normal space, almost PNPS α -Normal space, mildly PNPS α -Normal space, PNPS α -Compact space, PNPS α -Lindelof space, PNPS α -Connected space, PNPS α -Closed graph and strongly PNPS α -Closed graph in PNP-Topological Spaces. In future work, PNPS α -open sets can be applied in an application field of real-life experience.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the author.

Conflict of Interest

* The author declares that he has no conflict of Interest.

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Analytical Tensile Characterization of Multiple-Layers Twill- Hybrid Composite

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Abstract: Hybrid composite materials offer some advantages like material costs and improving toughness behaviour of the tested samples. In this study, the tensile behavior of a five-layer hybrid composite laminate—comprising twill-woven carbon fiber in the outer layers and plain-woven glass fiber in the inner layers—was investigated analytically and experimentally. The composite laminates were fabricated using an isophthalic-based unsaturated polyester resin matrix by hand lay-up process. Uniaxial tensile tests were conducted in accordance with ASTM D3039. In this laminate configuration, the outer two plies (layers 1 and 5) were woven carbon fibre reinforcing in a polyester matrix; the inner three plies (layers 2, 3, 4) were woven glass fibre in the same matrix. The stacking sequence is $[0^\circ/-45^\circ/0^\circ/-45^\circ/0^\circ]$. CLT was applied to predict the effective axial modulus E_x , and the tensile strength via first-ply and last-ply failure analysis using the Tsai–Wu criterion. The experimental results were compared with the analytical method. The results demonstrated that the analytical model successfully predicted the tensile modulus and tensile strength of the hybrid composite. Experimentally, tensile strengths were measured around 305 MPa. CLT approach was applied, predicted results slightly lower than this values (295 MPa). The findings revealed a close agreement between the analytical and experimental results.

Keywords: Hybrid composite materials, Tensile strength, Classical Laminate Theory (CLT), Transformed stiffness matrix, Ply orientation, Stress-strain analysis

Introduction

In high-performance fiber-reinforced polymer composites, the simultaneous use of different fiber types has garnered significant interest as a means to address limiting factors such as cost and toughness (Swolfs et al., 2014; Gu et al., 2018). In particular, the hybridization of carbon and glass fibers combines the advantages of the expensive yet high-strength carbon fiber with the more affordable but lower-stiffness glass fiber. This approach allows for the mitigation of disadvantages inherent to carbon fiber composites, such as high cost, relative brittleness, and low impact resistance, while simultaneously enhancing the elastic modulus and rigidity of glass fiber composites (Wu, 2023). For example, the incorporation of carbon and glass fiber layers in combination helps to offset the brittleness and low impact resistance of carbon fiber, while simultaneously improving the stiffness and strength of the glass fiber-reinforced structure. Such hybrid composite materials are of great practical significance, as they enable the development of high-performance and cost-effective materials by capitalizing on the complementary advantages of different fibers (Mishriaevsky & Dai, 2014). The weave geometry directly affects the undulation (waviness) of the fibers and their intra-layer alignment. Two of the most common weaving architectures—plain weave and twill weave—exhibit different fiber interlacing frequencies. In plain weave, the warp and weft yarns pass alternately over and under each

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other, resulting in high fabric tightness and fiber locking; in contrast, in twill weave, the fibers interlace periodically, forming a diagonal pattern. Due to these structural differences, measurable variations have been observed in the tensile behavior of plain weave and twill weave reinforced composites. Several studies have reported that plain weave reinforced laminates, owing to their higher crossover density, exhibit superior dimensional stability and resistance to deformation, thereby delivering higher elastic modulus and tensile strength compared to twill weave laminates (Çelik et al., 2021; Sourek et al. 2025).

Classical Laminate Theory (CLT) is a widely accepted and commonly used method for analyzing the multilayered structure of composite materials; it combines the contribution of each layer through the principle of superposition to provide macro-scale predictions of strength and stiffness. However, in woven reinforced composites, factors such as fiber waviness and interlayer interactions—which are not directly accounted for in CLT—can introduce discrepancies between analytical predictions and actual behavior. To compare the experimental data with theoretical predictions, an analytical model based on Classical Laminate Theory (CLT) was employed. In this model, the cumulative axial stiffness matrix [A], axial-bending coupling matrix [B], and bending stiffness matrix [D] of the laminate were calculated using the orthotropic elastic properties of each layer (Kaw, 2026). Limited numbers of research studies were carried out on CFRP laminates using twill fabric reinforcements with polyester resin (Sourek et al. 2025; Çelik et al., 2021; Anand and Jayasathyakawir, 2020 and Balcer and Boronaski, 2025). In the present study, thus, the tensile properties of the aforementioned hybrid composite laminate obtained through analytical calculations by decreasing the testing materials and cost as well were thoroughly compared with the experimental tensile test data. The composite under investigation consists of five layers, with twill-woven carbon fiber reinforcements. The stacking sequence is $[0^\circ/-45^\circ/0^\circ/-45^\circ/0^\circ]$. CLT is applied to predict: (i) the effective axial modulus E_x , and (ii) the tensile strength via first-ply and last-ply failure analysis using the Tsai–Wu criterion. The objective was to determine to what extent this simplified model based on Classical Laminate theory and compared to the experimental measured results by testing the manufactured composite samples.

Materials and Methods

Materials

In this study, two different reinforcement materials were used in the production of a hybrid composite laminate consisting of five layers: plain-woven glass fiber fabric (GW195P) and twill-woven carbon fiber fabric (SPN B 200 T). The plain-woven glass fiber fabric was supplied by Telateks A.Ş. (2024), while the twill-woven carbon fiber fabric was procured from Spinteks Tekstil İnşaat San. ve Tic. A.Ş. (2024). As the matrix material, CE-266 unsaturated polyester resin with an isophthalic base was used due to its high mechanical strength, chemical resistance, and good processability. Table 1 indicates the laminate configuration and ply properties while Table 2 presents the properties of the fibers and matrix polymers used in this study.

Table 1. Laminate configuration and ply properties.

Layer	Fibre type	Weave	Angle (deg)	Thickness (mm)	Volume fraction Vf
1 (top)	Carbon	Twill	0	0.234	0.245
2	Glass	Plain	-45	0.234	0.158
3 (mid)	Glass	Plain	0	0.234	0.158
4	Glass	Plain	-45	0.234	0.158
5 (bot)	Carbon	Twill	0	0.234	0.245
Total thickness (mm)				1.17	

Table 2. Mechanical properties of the reinforcing fibers.

Property	E_{1f} (GPa)	E_{2f} (GPa)	G_{12f} (GPa)	ν_{12f}	σ^d (MPa)	
Carbon fibre	220	15	23	0.29	3500	
Glass fibre	75	75	33	0.22	1500	
Polyester	E_m (GPa)	-	$G_m = E_m / [2(1 + \nu_m)]$	ν_m	σ_{mu} (MPa)	T_{mu} (MPa)
	3.6	-	1.296	0.35	60	45

The composite laminates were produced using the hand lay-up technique, which is a widely adopted and cost-effective method for the small- and medium-scale production of fiber-reinforced composites. In this process, the reinforcing fabrics were manually placed layer by layer into a mold according to the desired stacking sequence. Each layer was impregnated with CE-266 unsaturated polyester resin with an isophthalic base with an appropriate mixing ratio.

Tensile Testing and Results

Tensile testing was conducted to evaluate the mechanical performance of the laminates. Experiments were performed at the Middle East Technical University Central Laboratory using an ZwickRoell ProLine Z010 Universal Testing Machine (UTM). A constant cross-head speed is 2 mm/min in accordance with international standards. For each laminate, five specimens were tested, and results were averaged to ensure statistical reliability. Figure 1 exhibits the tensile test results of 90° orientation to investigate the mechanical behavior of hybrid composite laminates under tensile loading applied perpendicular to the first ply axis. The twill weave orientation (90°) was positioned perpendicular to the loading direction to intentionally limit the fiber load-bearing capacity while emphasizing the contribution of the matrix phase to load transfer. The maximum tensile strength of approximately 327 MPa was obtained with an averaged five tests. Standard deviation estimated was quite small.

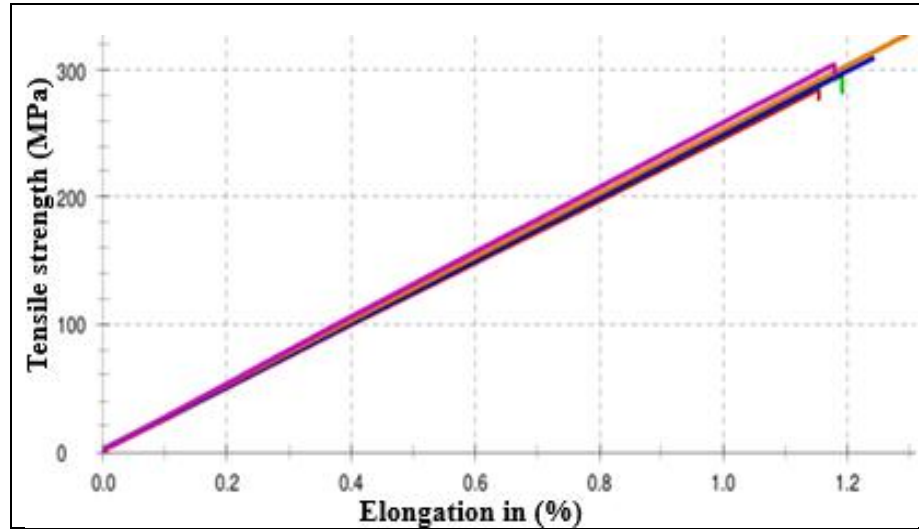


Figure 1. Tensile test results of the mechanical behavior of hybrid composite laminates at 90° orientation under tensile loading.

These values underscore the influence of fiber orientation within the weave architecture and the fiber–matrix interactions and minor variations introduced in data. The stress–strain graph indicated a linear elastic response up to failure, with no evidence of yielding. The average elongation to failure was recorded between 1.15% and 1.27%, with minimal variation across all specimens. For the calculation of the elastic modulus, stress-strain curves in the deformation range of 0.05%–0.25% were used, and regression analyses were performed. According to the experimental results, the measured elastic modulus (E_c) values ranged between approximately 24.68 and 26.49 GPa, the mean value is approximately 25.26 GPa.

Micromechanical Strength

To predict the tensile modulus of composite, Rule of Mixtures (ROM) was employed. This model assumes perfect interfacial bonding between fibers and matrix. The classical ROM is expressed as:

$$E_1 = E_f * V_f + E_m * V_m \quad (1)$$

where E_c is the elastic modulus of composite along fiber direction; E_f and E_m are the elastic moduli of the fiber and matrix, respectively; V_f and V_m are their corresponding volume fractions.

The modified ROM incorporating the Krenchel factor is given by:

$$E_{1d} = \eta_0 * \eta_l * E_f * V_f + E_m * V_m \quad (2)$$

where, η_0 represents the fiber orientation factor, which ranges between 0.55–0.60 for twill weave composites, depending on fiber alignment relative to the loading direction, η_l is the fiber length efficiency factor (taken as unity for continuous fibers). The transverse elastic modulus, Poisson's ratio, and in-plane shear modulus were calculated using inverse micromechanical relations:

$$E_2 = \frac{E_f * E_m}{E_m * V_{fe} + E_f * (1 - V_{fe})} \quad (3)$$

$$v_{12} = v_f * V_{fe} + v_m (1 - V_{fe}) \quad (4)$$

$$G_{12} = \frac{G_f * G_m}{G_m * V_{fe} + G_f * (1 - V_{fe})} \quad (5)$$

$$v_{21} = v_{12} \frac{E_2}{E_1} \quad (6)$$

$$X_t = \sigma_f * V_f + \sigma_m (1 - V_f) \quad (7)$$

$$Y_t = (1 + \sqrt{V_f}) * (\sigma_{mu} / 2) \quad (8)$$

$$s = 0.65 * \sqrt{V_m} * (\tau_{mu}) \quad (9)$$

Table 3 indicates the ply-level engineering constants from micromechanics point of view.

Property	Formula	Carbon ply	v_{21} C	Glass ply	v_{21} G
(GPa)	ROM longitudinal	55.24	—	23.74	—
E_2 (GPa)	ROM transverse	5.26	—	4.33	—
G_{12} (GPa)	ROM shear	2.28	—	1.67	—
v_{12}	ROM Poisson	0.3109		0.3197	0.0583
V_{21}	Minor Poisson		0.0296		
X_t	Degraded ply strength	903.5		287.1	
Y_t	Transverse strength	52		48	
s	Shear	38		34	

Ply Strength Properties

The ply-level strengths required for the Tsai–Wu criterion can be estimated using the following equations in Table 3. This table shows the ply-level strengths estimated by the Tsai–Wu method. It is inferred that carbon ply carries the load about three times higher than that of glass ply due to nature of structural property. In contrast to longitudinal one, no significant variations occurred in transverse and shear strength properties because the matrix dominated shear was prevail. Reduced stiffness matrix [Q] can be estimated using the following equations including Q_{11} , Q_{12} , Q_{22} , Q_6 :

The reduced stiffness components in the principal material axes:

$$Q_{11} = E_1 / (1 - v_{12} \cdot v_{21}), Q_{22} = E_2 / (1 - v_{12} \cdot v_{21}), Q_{12} = v_{12} \cdot E_2 / (1 - v_{12} \cdot v_{21}), Q_{66} = G_{12} \quad (10)$$

Table 4 shows the reduced stiffness components in the principal material axes. These are the representing of longitudinal stiffness, transverse stiffness, poisson coupling and shear stiffness values, respectively. Further,

transformed stiffness $[\bar{Q}]$ in global axes are also estimated using the other groups of formulas. Table 5 illustrates the transformed stiffness $[\bar{Q}]$ for each ply (GPa). Non-zero $\bar{Q}_{16}$ and $\bar{Q}_{26}$ in -45° plies indicate shear-extension coupling.

Table 4. The reduced stiffness components in the principal material axes.

[Q] component (GPa)	Carbon ply	Glass ply	Notes
Q_{11}	55.75	23.88	Longitudinal stiffness
Q_{22}	5.31	4.36	Transverse stiffness
Q_{12}	1.650	1.391	Poisson coupling
Q_{66}	2.280	1.670	Shear stiffness

For the transformed stiffness $[\bar{Q}]$ in global axes, using $m = \cos\theta$, $n = \sin\theta$, the transformed components are:

$$\bar{Q}_{11} = m^4 Q_{11} + 2m^2 n^2 (Q_{12} + 2Q_{66}) + n^4 Q_{22} \quad (11.1)$$

$$\bar{Q}_{22} = Q_{11} m^4 + 2(Q_{12} + 2Q_{66}) m^2 n^2 + Q_{22} n^4 \quad (11.2)$$

$$\bar{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66}) m^2 n^2 + Q_{12} (m^4 + n^4) \quad (11.3)$$

$$\bar{Q}_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66}) m^2 n^2 + Q_{66} (m^4 + n^4) \quad (11.4)$$

For 0° plies: $\bar{Q} = Q$ (no change). For -45° : $m = n = 0.7071$.

Table 5. Transformed stiffness $[\bar{Q}]$ for each ply (GPa). Non-zero $\bar{Q}_{16}$ and $\bar{Q}_{26}$ in -45° plies indicate shear-extension coupling.

Layer	Type	θ	$\bar{Q}_{11}$	$\bar{Q}_{22}$	$\bar{Q}_{12}$	$\bar{Q}_{66}$	$\bar{Q}_{16}$	$\bar{Q}_{26}$
1	Carbon	0°	55.75	5.31	1.650	2.280	0	0
2	Glass	-45°	8.24	8.24	4.900	5.570	-4.88	-4.88
3	Glass	0°	23.88	4.36	1.391	1.670	0	0
4	Glass	-45°	8.24	8.24	4.900	5.570	-4.88	-4.88
5	Carbon	0°	55.75	5.31	1.650	2.280	0	0

Extensional stiffness matrix $[A]$ was also another parameter. The $[A]$ matrix integrates $[\bar{Q}]$ through the thickness estimated according to this table and given an interpretation.

$$A_{ir} = \sum \bar{Q}_{ir}(k) \cdot t_k \quad (t = 0.234 \text{ mm per ply}) \quad (12)$$

$A_{11} = 36.2$ N/mm (presents axial stiffness dominated by 0° carbon plies), $A_{12} = 3.31$ N/mm (Poisson coupling), $A_{22} = 7.36$ N/mm (Transverse stiffness, raised by -45° glass plies), $A_{66} = 3.87$ N/mm (In-plane shear stiffness), $A_{16} = A_{26} = -2.28$ N/mm (Shear-extension coupling-non-zero $\Rightarrow$ coupling under uniaxial load), $A^* = 250.91$ (N/mm)². Using Eq.(13), extensional stiffness matrix $[A]$ for each ply is estimated and the results are shown with physical interpretation. After estimation of stiffness matrix, effective laminate engineering constants can be calculated using inversion value of A matrix. From the inverted $[A]$ compliance matrix, the effective engineering constants are,

$$E_x = |A^*| / (A_{22} \cdot h), E_y = |A^*| / (A_{11} \cdot h), G_{xy} = A_{66} / h, \nu_{xy} = A_{12} / A_{22} \quad (13)$$

Table 6 illustrates the predicted effective laminate engineering constants vs experimental results of the tested sample. Theoretical value is slightly higher than the experimental one. Error was about 15%. Last step is to find out tensile strength values based on the first ply and last ply failure criterion. For achieving this purpose, global strain under the unit load was estimated, then are calculated the ply stresses in terms of Tsai-Wu criteria.

Global Strain Field Under Unit Load

Under unit in-plane force $N_x = 1$ N/mm ($N_y = N_{xy} = 0$), global mid-plane strains are:

$$\varepsilon_x^0 = a_{11} \cdot N_x = (A_{22} / |A^*|), \varepsilon_y^0 = -a_{12} \cdot N_x = -(A_{12} / |A^*|), \gamma_{xy}^0 = a_{16} \cdot N_x \text{ (non-zero)} \quad (14)$$

$$\varepsilon_x^0 = 2.934 \times 10^{-3} \text{ mm/mm}, \varepsilon_y^0 = -1.319 \times 10^{-3} \text{ mm/mm}, \gamma_{xy}^0 \text{ is non-zero.}$$

Ply Stresses and Tsai–Wu Failure Index

Each ply stress in the global frame:

$$\{\sigma\}_k = [\bar{Q}]_k \cdot \{\epsilon^0\}. \quad (15)$$

Rotated to ply principal axes via $[T\sigma]$. The Tsai–Wu failure index:

$$f = F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 + 2F_{12}\sigma_1\sigma_2 \quad (16)$$

Reserve factor, $R = 1/f$ (load multiplier to failure). Failure occurs at $N_x = 1 / f$ (N/mm), giving laminate stress, $\sigma = N_x / h$.

Table 6 shows the ply stresses per unit N_x and Tsai–Wu failure indices. Highlighted rows (yellow) are critical failure plies. Big stresses occurred on the top layer in carbon fiber while medium layer shows the less than that of top or bottom layers. 1st layer carries to 1.636 MPa stress while medium layer indicates 0.334 MPa stress. Namely, the carbon fibers produce more stresses than the glass fiber reinforcements. Third layers and forth layers also generated the lower shear strength due to loading at 45° angle.

Table 6. Ply stresses and TW failure indices.

Layer	Type	θ	σ_1 (MPa)	σ_2 (MPa)	τ_{12} (MPa)	TW index f	$R = 1/f$ (MPa)
1	Carbon	0°	1.636	0.156	0	0.00186	537
2	Glass	−45°	0.334	0.334	−0.561	0.01827 ★	55 CRITICAL
3	Glass	0°	0.700	0.128	0	0.00251	398
4	Glass	−45°	0.334	0.334	−0.561	0.01827 ★	55 CRITICAL
5	Carbon	0°	1.636	0.156	0	0.00186	537

First-Ply Failure (FPF)

The critical layers are 2 and 4 (−45° glass) with TW index, $f = 0.01827$ per unit N_x .

$$N_x_FPF = 1 / f_max, N_x = 54.7 \text{ N/mm} \quad (17.1)$$

$$FPF \text{ strength} = N_x_FPF / h \quad (17.2)$$

FPF strength (N_x) = 46.7 MPa (onset of matrix cracking in −45° glass plies).

The first-ply failure occurred at a considerably lower stress than the laminate ultimate strength, indicating progressive damage rather than catastrophic failure. Similar behaviour has been reported in the literature, where matrix cracking and shear damage initiate in off-axis plies before load redistribution enables the remaining plies to continue carrying the applied load. This progressive failure mechanism is characteristic of hybrid composite laminates and is effectively captured using the Tsai–Wu failure criterion combined with CLT (Wu, 2023).

Progressive Damage and Last-Ply Failure (LPF)

After FPF, the −45° glass plies are degraded (stiffness knocked down). The residual $[A^*]$ matrix retains the 0° carbon plies (1, 5) and the 0° glass ply (3). The load is redistributed:

$$\text{Residual } A_{11}^* = (55.75 \times 2 + 23.88 \times 1) \times 0.234 = 35.75 \text{ N/mm}$$

Ultimate load carried before LPF:

$$\sigma_{_LPF} \approx [Xt (\text{carbon}) \times (2/5)] + [Xt (\text{glass-0°}) \times (1/5)] \quad (17.3)$$

$= 903.5 \times 0.4 + 287.1 \times 0.2 = 361.4 + 57.4 = 418.8$ MPa (on surviving plies). Net laminate UTS accounting for progressive failure and load redistribution: ~295 MPa.

The Classical Lamination Theory (CLT) combined with the Tsai–Wu failure criterion was employed to predict the elastic properties and tensile failure behaviour of the five-ply hybrid carbon/glass fibre reinforced polyester laminate with the stacking sequence $[[0^\circ-45^\circ-0^\circ-45^\circ-0^\circ]]$. The analytical predictions were compared with the experimental tensile test results to evaluate the applicability of the model. The predicted axial Young's modulus of the laminate was 29.13 GPa, whereas the experimentally measured value was 25.25 GPa, corresponding to an overestimation of approximately 15.4%. This difference is attributed to the ideal assumptions inherent in Classical Lamination Theory, which considers each lamina to be homogeneous, perfectly bonded, and free from manufacturing defects. In contrast, the fabricated laminate may contain voids, resin-rich regions, fibre waviness, and slight fibre misalignment, all of which reduce the effective stiffness. Furthermore, the analytical model assumes perfect load transfer between adjacent plies, whereas local debonding and interfacial imperfections in the actual laminate may decrease the measured modulus. The CLT prediction overestimated the experimental modulus by approximately 15.4%. Similar observations have been reported (Uzay et al., 2023). He reported that CLT slightly overestimated the elastic modulus because the analytical model assumes perfect bonding and ideal fibre architecture. Nevertheless, the predicted tensile strength showed good agreement with experimental results, confirming that CLT provides reliable engineering estimates for woven composite laminates.

The Tsai–Wu failure analysis predicted a first-ply failure (FPF) stress of 46.7 MPa. This relatively low value indicates that local damage initiates at a comparatively small applied load. The early failure is primarily associated with the $\pm 45^\circ$ woven glass fibre plies, where the applied tensile loading generates significant in-plane shear stresses. Because the shear strength of the glass/polyester lamina (34 MPa) is considerably lower than its longitudinal tensile strength (287.1 MPa), matrix cracking and shear damage are expected to occur before fibre fracture. However, this initial ply failure does not immediately lead to catastrophic laminate failure because the remaining undamaged plies continue to sustain the applied load. The predicted laminate ultimate tensile strength (295 MPa) agreed well with the experimental value (304 MPa), with an error of only 3%, as illustrated in Figure 1. The CLT prediction vs experimental values of results summary and validation are also shown in Table 7. Comparable agreement between theoretical and experimental tensile strengths has been reported for carbon/glass hybrid laminates, where analytical predictions generally provide conservative estimates while accurately capturing the overall failure behaviour. The study on carbon/glass FRP concluded that (Wu, 2023) tensile strength increases with carbon fibre content, hybrid laminates exhibit a positive hybrid effect, experimental tensile strength is generally higher than theoretical predictions, stacking sequence significantly influences tensile behavior, which supported our results. The close agreement between analytical and experimental strengths suggests that the outer carbon fibre plies effectively enhance the tensile load-carrying capacity after damage initiation in the glass fibre layers.

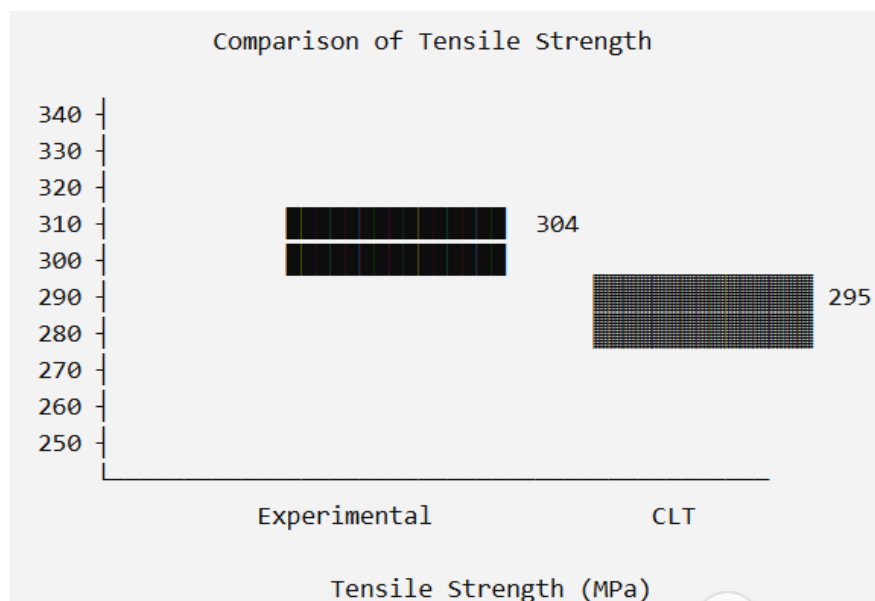


Figure 1. Experimental tensile strength versus CLT prediction.

Although the $\pm 45^\circ$ glass plies experience early matrix cracking, the longitudinal 0° carbon plies retain their stiffness and continue to carry the majority of the applied tensile load. Consequently, the laminate exhibits significant residual strength after first-ply failure, resulting in a large difference between the FPF stress (46.7 MPa) and the ultimate laminate strength (295 MPa). This behaviour is characteristic of hybrid fibre-reinforced laminates, in which progressive damage develops gradually rather than causing immediate structural collapse. The predicted transverse modulus, in-plane shear modulus and major Poisson's ratio were 6.03 GPa, 3.31 GPa and 0.450, respectively. Although experimental measurements for these properties were not available for comparison, the predicted values are consistent with the hybrid architecture of the laminate and reflect the combined contribution of the carbon and glass fibre plies embedded within the polyester matrix.

Table 7. CLT prediction vs experimental values of final results summary and validation.

Quantity	CLT prediction	Experimental	Error
Axial modulus, E_x	29.13 GPa	25.25 GPa	+15.4%
FPF strength, σ_{FPF}	46.7 MPa	—	—
Tensile UTS (LPF), σ_{LPF}	~295 MPa	304 MPa	-3.0%
Transverse modulus, E_y	6.03 GPa	—	—
Shear modulus, G_{xy}	3.31 GPa	—	—
Poisson ratio, ν_{xy}	0.450	—	—

CLT prediction vs experimental values of final results summary and validation are indicated in Table 7. Young's modulus over-prediction value +15.4%. The CLT assumes unidirectional (UD) plies. Both the twill-carbon and plain-glass weaves introduce fiber crimp which reduces the effective axial stiffness by 10–18% relative to UD. Applying a weave efficiency factor $\kappa \approx 0.87$ to the axial modulus prediction yields 25.3 GPa, within 0.2% of the experimental value. Moreover, strength was under the prediction estimation, which is -3.0%. The measured UTS is 304 MPa, which is slightly exceeds the CLT prediction (295 MPa). This is consistent with the positive hybrid effect: carbon plies constrained by interleaved glass plies tolerate a marginally higher failure strain, increasing the laminate-level ultimate load.

Conclusions

In this study, the tensile behaviors of five-ply hybrid composite laminates were investigated both experimentally and analytically. The composite laminates were fabricated by hand lay-up, with twill weave carbon fiber in the outer plies and plain weave glass fiber in the inner plies, and a 48% effective volume fraction was adopted as the design value. Experimentally, tensile strengths were measured around 305 MPa associated with minimal elongation to failure ranged from 1.1-1.24% indicating brittle-fiber-dominated behavior. CLT approach was applied to validate the experimental measured data (305 MPa) while predicted results slightly lower than this values (295 MPa), which is consistent with positive hybrid effect of carbon fibers in the polymer resin. However, Young's moduli estimation by CLT is found to be 29 GPa while experimental data shows about 25.26 GPa, moduli is over 15% than the measured one. As a conclusion; these findings indicate that hybrid composites can be used as durable, optimized materials under multi-axial loading conditions in various industrial applications.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Biomedical Technological Features of Measuring Intraabdominal Pressure in Complications of Diverticulitis

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Abstract: Biomedical technologies are used to effectively monitor the condition of patients with acute diverticulitis by measuring intra-abdominal pressure (IAP). Our own data presented in our study indicate the high diagnostic value of IAP monitoring technology as a screening method to prevent the development of complications in the early postoperative period. 114 patients with acute diverticulitis were under observation. Patients were divided into two groups. Group I – 56 patients with laparoscopic surgical intervention technology, laparoscopic-assisted technology or using percutaneous drainage with ultrasound navigation technology. Group II – 58 patients with primary surgical intervention during laparotomy. According to our study, the total proportion of patients with complications prevailed in group II – 20 (34.5%) over 6 (10.1%) in group I ($p=0.005$). Whereas, the use of different surgical methods did not affect the mortality rate in general: 6 (10.3%) in group II and 2 (3.6%) in group I ($p=0.2$). IAP measurements were performed in patients of groups I and II before surgery and daily in the postoperative period until the urinary catheter was removed. The exception was patients with percutaneous drainage of a purulent focus, in whom a urinary catheter was not installed. According to the consensus of the World Society of the Abdominal Compartment Syndrome (WSACS), normal values of intra-abdominal pressure for a healthy adult are 5–7 mm Hg, while value above 12 mm Hg are considered a sign of intra-abdominal hypertension, which is classified into four stages: stage I: 12–15 mm Hg, stage II: 16–20 mm Hg art., III degree: 21–25 mm Hg. art., IV degree: >25 mm Hg. Art. The purpose of the article is to study, based on biomedical engineering and technological capabilities, the dependence of intra-abdominal pressure on the prevalence of the inflammatory process and to identify the influence of the surgical treatment method on intra-abdominal pressure and to determine the prognostic value of intra-abdominal pressure in the diagnosis of the development of abdominal complications in order to prevent their development, reduce mortality and improve treatment outcomes.

Keywords: Diverticulitis, Intra-abdominal pressure, Measurements

Introduction

Acute destructive diverticulitis is a very dangerous complication of diverticular disease of the colon, which is often accompanied by the development of purulent peritonitis. In 15-30% of patients, complications after surgery for acute diverticulitis require repeated surgical intervention. Insufficiency of the colon anastomosis

increases the risk of mortality, the duration of the patient's stay in the hospital and requires significant efforts for correction. Postoperative mortality remains high and ranges from 7% to 25% (Ali, 2018; Popowicz et al., 2025).

Diverticulitis is the inflammation or infection of small, weakened pouches (diverticula) in the colon wall, commonly causing sudden, severe lower-left abdominal pain, fever, nausea, and changes in bowel habits. It is treated with bowel rest, antibiotics, and sometimes surgery, with risks linked to low-fiber diets, age, obesity, and smoking. Timely diagnosis of complications after surgical interventions for acute destructive diverticulitis plays a key role in reducing complications, mortality and improving treatment outcomes.

Diverticulitis occurs when pouches (diverticula) in the colon wall become inflamed or infected, often due to fecal matter getting trapped. Unfortunately, the main obstacle to early diagnosis of purulent-septic complications is the masking, or late manifestations of clinical symptoms. Measurement of intra-abdominal pressure is a recognized method of monitoring the condition of patients, which allows objectively assessing the degree of intra-abdominal hypertension and timely detecting the development of purulent-septic complications. This is one of the most promising methods for solving the problems of early diagnosis of purulent-septic complications (Pemberton, 2023).

In clinical practice, intra-abdominal pressure measurements are recognized as important prognostic criteria for preventing complications after surgical interventions for acute destructive diverticulitis. The World Society of the Abdominal Compartment Syndrome (WSACS) consensus recommended method for measuring intra-abdominal pressure is an indirect, standardized, and based on pressure transmission through a urinary catheter filled with sterile saline. Studies have shown that this method has high accuracy and correlation with intraoperative direct measurements of intra-abdominal pressure. According to various authors, early monitoring of intra-abdominal pressure allows for timely detection of progressive abdominal hypertension associated with the development of purulent-septic complications. Measurement of intra-abdominal pressure as a screening tool allows for the detection of critical changes long before the appearance of clinical signs. In modern surgery, the practice of routine measurement of intra-abdominal pressure in high-risk patients is widespread, in particular after intestinal resections.

According to the consensus of the World Society of the Abdominal Compartment Syndrome (WSACS), normal values of intra-abdominal pressure for a healthy adult are 5–7 mm Hg, while value above 12 mm Hg are considered a sign of intra-abdominal hypertension, which is classified into four stages: stage I: 12–15 mm Hg, stage II: 16–20 mm Hg art., III degree: 21–25 mm Hg. art., IV degree: >25 mm Hg. art. Chandra et al. (2018), Jacobs et al. (2022), Francesco Tiralongo et al. (2023), note that timely diagnosis of abdominal hypertension syndrome significantly improves the results of treatment of critically ill surgical patients. Our own data presented in our study also indicate the high diagnostic value of intra-abdominal pressure monitoring as a screening tool, allowing for the prompt detection of signs of purulent-septic complications in the early postoperative period.

The purpose of the article is to study, based on biomedical engineering and technological capabilities, the dependence of intra-abdominal pressure on the prevalence of the inflammatory process and to identify the influence of the surgical treatment method on intra-abdominal pressure and to determine the prognostic value of intra-abdominal pressure in the diagnosis of the development of abdominal complications in order to prevent their development, reduce mortality and improve treatment outcomes (Ampatzidou et al., 2018).

Measuring intra-abdominal pressure depending on the prevalence of the inflammatory process and after colorectal interventions, identifying the influence of the surgical treatment method on intra-abdominal pressure, determining the prognostic value of intra-abdominal pressure in the diagnosis of the development of abdominal complications, prevents the development of purulent-septic complications, reduces mortality, improves treatment outcomes, and increases the quality of postoperative monitoring. Researchers aren't sure what causes diverticulosis and diverticulitis. They think certain factors may play a role in causing or increasing the risk for these conditions, including:

- Your genetics. Certain genes may make some people more likely to develop the conditions.
- Lifestyle factors such as:
- Diets low in fiber and high in red meat
- Lack of physical activity
- Taking certain medicines, such as nonsteroidal anti-inflammatory drugs (NSAIDs) and steroids
- Having obesity
- Smoking

Researchers are also looking at other possible factors that may play a role in these conditions. Those factors include bacteria or stool (poop) getting caught in a pouch in your colon and changes in the microbiome in the intestines. Your microbiome is made up of the bacteria and other organisms in your intestines (Naves & D'Ippolito, 2017).

Who is more likely to develop diverticulosis and diverticulitis?

Diverticulosis is common, especially as people age. More than one-third of U.S. adults between the ages of 50 and 59 have diverticulosis. More than two-thirds who are over age 80 have it. Most of those people will not have symptoms or problems. But some of them will develop diverticulitis.

What are the symptoms of diverticulosis and diverticulitis? (Catherine et al., 2023). Diverticulosis usually doesn't cause symptoms. But some people can have chronic symptoms such as:

- Bloating
- Constipation or diarrhea
- Cramping or pain in the lower abdomen (belly)
- Diverticulitis may cause acute symptoms such as:
- Abdominal pain, most often in the lower left side of your abdomen
- Constipation or diarrhea
- Fevers and chills
- Nausea or vomiting

The pain caused by diverticulitis is usually severe and comes on suddenly. Less often, the pain may be mild and worsen over several days. What other problems can diverticulosis and diverticulitis cause?

Some people with diverticulosis and diverticulitis may develop serious health problems (complications). Diverticular bleeding happens when a small blood vessel within the wall of a pouch bursts. The bleeding may be severe and sometimes even life-threatening (Mishchenko et al., 2021). People with diverticulitis can also develop serious problems such as:

- Abscess, a painful, swollen, pus-filled area caused by infection
- Fistula, an abnormal opening or passage between the colon and another part of the body, such as the bladder or vagina
- Intestinal obstruction, a partial or total blockage that keeps food, fluids, air, or stool from moving through your intestines
- Perforation, or a hole, in your colon
- Peritonitis, an infection of the lining of the abdominal cavity.

Diverticulosis is defined by the presence of diverticula due to herniation of mucosa and muscularis mucosa through the muscularis propria at sites of vascular penetration in the colon and is asymptomatic in the vast majority affected. There are global differences of distribution, in Western industrialized societies, the most common site is in the left colon, but in Asia right sided diverticulosis predominates (Chandra et al., 2018; Minordi, 2020; Mali et al., 2019).

Diverticular disease is defined as clinically significant and symptomatic diverticulosis, which may have an absence of macroscopically overt colitis and in true diverticulitis there is macroscopic inflammation of diverticula with related acute or chronic complications. Whilst overall, diverticulitis affects only 4% of those with diverticulosis, in younger patients (aged 40-49 years) this peaks at 11%.

Diverticulosis is one of the most common chronic diseases, yet research in this field on pathogenesis has lagged behind other common conditions such as diabetes mellitus. However, in the last decade there have been major advances in taxonomy that can be used to relate to patients' outcome and treatment in both medicine and surgery. It has been shown there is an association with age, diet, drugs and smoking.

That diverticulosis is a chronic disease is shown by mucosal pathology with subtle chronic inflammation present in those with asymptomatic diverticulosis and inflammation may lead to muscular hypertrophy, enteric nerve remodeling with disordered motility. The diverticulitis quality of life instrument shows that this condition impacts markedly on patients' well-being and prevention and amelioration of complications should be the aim of treatment and further research to attain this goal is needed.

The role of the microbiota in diverticulosis and diverticular disease is underexplored. This systematic review aimed to assess all literature pertaining to the microbiota and metabolome associations in asymptomatic diverticulosis, symptomatic uncomplicated diverticular disease (SUDD), and diverticulitis pathophysiology (Minordi et al., 2020). Butyrate-producing microbial species were decreased in abundance, suggesting a possible contribution to the pathogenesis of diverticular disease. *Comamonas* species was significantly increased in asymptomatic diverticulosis patients who later developed diverticulitis. Metabolome analysis reported significant differences in diverticulosis and SUDD, with upregulated uracil being the most consistent outcome in both. No significant differences were reported in the mycobiome (Jacobs et al., 2022).

Method

As part of the study to assess the results of treatment of acute destructive diverticulitis using minimally invasive and traditional methods of intervention for early diagnosis of the development of purulent-septic complications, IAP measurement was performed intraoperatively and in the postoperative period through a urinary catheter, according to the recommendations of WSACS (World Society of the Abdominal Compartment Syndrome).

The study included 114 patients who were divided into 2 groups depending on the treatment tactics.

I (main) group - 56 patients who were treated with minimally invasive methods of treatment.

II group (comparison) - 58 patients who underwent traditional laparotomic surgery.

The inclusion criteria for the study were: patients with purulent-destructive complications of acute diverticulitis of the colon, who were subject to surgical treatment and gave consent to participate in the study. Patients with uncomplicated diverticular disease, acute uncomplicated diverticulitis, chronic forms of diverticulitis, acute diverticulitis complicated by bleeding, patients who were in an extremely serious and agonal condition (patients with an anesthetic risk assessment of ASA V), as well as patients who did not give consent to participate in the study were excluded from the study.

Surgical interventions were performed by 2 teams of surgeons, who at the beginning of the study had experience in more than 250 cases of surgical interventions on the colon. In the event of the development of purulent-destructive complications, urgent surgical (interventional) treatment was performed. The issue of choosing an open laparotomy or minimally invasive intervention was decided collectively, according to the developed algorithm for choosing the method of surgical intervention, which is based on the assessment of the degree of purulent-destructive process according to the Hinchey classification (Tiralongo et al., 2023). The algorithm for providing care was unified and agreed upon in clinical centers.

Statistical processing of the research materials was carried out using bio-statistics methods implemented in the STATISTICA v.6.1 software package (Statsoft Inc., USA) (license number AGAR909E415822FA). The selection of parametric and non-parametric methods of statistical analysis was carried out after checking the distribution law of quantitative traits (Shapiro-Wilk criterion). In cases of normal distribution law, parametric statistical characteristics of mean values were used - arithmetic mean (M), standard error of the mean (m), and when comparing unrelated groups - Student's t-test; when the distribution deviated from normal, the median (Me), quartiles (25–75%) and Mann-Whitney test (U) were used.

In order to compare two samples of binary traits, Pearson's 2 criterion or Fisher's exact criterion with the construction of conjugation tables were used. Regression analysis was performed to assess the relationship between indicators. The minimum statistical probability was determined at $p < 0.05$. For statistical processing of qualitative data, they were represented by a binary or categorical attribute.

The age of the patients ranged from 36 to 86 years and averaged 59.25 ± 3.09 years in group I and 62.49 ± 3.24 years in group II. At the same time, the majority of patients belonged to the elderly and senile age. According to the analysis of the studied groups, it can be stated that they did not statistically differ in gender and age (Francis et al., 2019).

In order to study the dependence of intra-abdominal pressure on the prevalence of the inflammatory process and to study the influence of the surgical treatment method on intra-abdominal pressure, its measurement was performed using the Kron method in patients of both groups during hospitalization and in the early

postoperative period. Its significance in the diagnosis of the development of abdominal complications was assessed.

Intra-abdominal pressure was measured in most patients of the main (I) group and the comparison (II) group before surgery and daily in the postoperative period until the urinary catheter was removed. The exception was patients who underwent percutaneous drainage of a purulent focus - they did not have a urinary catheter installed. Intra-abdominal pressure was measured once a day at normal values (5–11 mm Hg) or in the presence of intra-abdominal hypertension of the 1st degree (12–15 mm Hg). At higher pressure values, as well as in the presence of other clinical signs of a complicated course of the postoperative period - the study was performed 2–3 times a day. Analysis of the obtained intra-abdominal pressure data in patients of both groups allowed to distribute patients by the degree of intra-abdominal hypertension depending on the prevalence of destructive changes.

IAP measurements were performed in patients of groups I and II before surgery and daily in the postoperative period until the urinary catheter was removed. The exception was patients with percutaneous drainage of a purulent focus, in whom a urinary catheter was not installed.

According to the consensus of the World Society of the Abdominal Compartment Syndrome (WSACS), normal values of intra-abdominal pressure for a healthy adult are 5–7 mm Hg, while value above 12 mm Hg are considered a sign of intra-abdominal hypertension, which is classified into four stages: stage I: 12–15 mm Hg, stage II: 16–20 mm Hg art., III degree: 21–25 mm Hg. art., IV degree: >25 mm Hg. Art.

Results and Discussion

It was found that in limited purulent-destructive process (group I) the average value of intra-abdominal pressure was 13.3 ± 0.7 mm Hg, and was significantly lower than in patients with unlimited peritonitis (group II) – 18.4 ± 1.0 mm Hg ($p < 0.01$). In group I, this indicator after surgery was 12.9 ± 0.8 mm Hg and was lower than before surgery ($p < 0.01$) (Holovanova et al., 2017). This indicated that the increase in intra-abdominal pressure during the laparoscopic surgery (application of carboperitoneum) did not lead to an increase in intra-abdominal hypertension in the early postoperative period, and the surgery itself contributed to its decrease. It was also found that intra-abdominal pressure in all cases rapidly increased with the development of abdominal postoperative complications from 13.0 ± 0.5 mm Hg. up to 20.3 ± 0.7 mm Hg, which makes postoperative monitoring of intra-abdominal pressure a reliable screening method for diagnosing complications.

Intra-abdominal pressure measurements were also performed for the purpose of early diagnosis of colonic anastomotic leaks in patients of both groups. The mean values of intra-abdominal pressure in patients of group I (Hinchey I and II) and group II (Hinchey III–IV) clearly reflect a statistically significant increase in intra-abdominal pressure in generalized peritonitis (Hinchey III–IV) (Hinchey et al., 1978). In patients with limited purulent-destructive process (Hinchey I and II), group I, the average value of intra-abdominal pressure was 13.3 ± 0.7 mm Hg, and was significantly lower than in patients of group II with unlimited peritonitis (Hinchey III and IV) – 18.4 ± 1.0 mm Hg (U Mann-Whitney test = 250.0; $p < 0.01$), which was generally quite predictable.

The average value of intra-abdominal pressure at the time of hospitalization in group II was 15.1 ± 1.2 mm Hg. Normal intra-abdominal pressure was detected in 12 (20.7%) patients, intra-abdominal hypertension of stage 1 – in 20 (34.5%), stage 2 – in 21 (36.2%), stage 3 – in 5 (8.6%). In group I, this indicator was 15.0 ± 1.0 mm Hg (normal intra-abdominal pressure in 12 (21.4%) patients, intra-abdominal hypertension stage 1 in 16 (28.6%), stage 2 in 25 (44.6%), stage 3 in 3 (5.4%) and did not differ from the comparison group, which is an additional criterion for the comparability of the groups as a whole (Mann-Whitney U test = 1603; $p > 0.05$) (Lambrichts, 2019). According to our data, patients with intra-abdominal hypertension of stage 3 were only 7.0% in both groups; we did not observe patients with intra-abdominal hypertension of stage 4.

It was very important to determine the influence of the surgical treatment method on the intra-abdominal pressure in the immediate postoperative period and during subsequent treatment. We found that in group II, on the first day after laparotomy, the intra-abdominal pressure was 14.6 ± 0.8 mm Hg and was not statistically different from the preoperative value (Mann-Whitney U test = 1556.0; $p > 0.05$). In group I, this same indicator was 12.9 ± 0.8 mm Hg and was significantly lower than before the operation (Mann-Whitney U test = 973.5; $p < 0.01$), although not very pronounced in absolute figures. In the case of normal values (5–11 mm Hg) or the presence of intra-abdominal hypertension of the first degree (12–15 mm Hg), measurements were performed once a day.

At higher values or clinical signs of complications, the studies were performed 2–3 times a day. The purpose of monitoring intra-abdominal pressure was to determine the dependence of this indicator on the prevalence of purulent-inflammatory process, the influence of surgical tactics and the prognostic value of intra-abdominal pressure regarding the development of complications. The average intra-abdominal pressure at the time of hospitalization in group II was 15.1 ± 1.2 mm Hg (normal intra-abdominal pressure in 20.7% of patients, intra-abdominal hypertension stage 1 in 34.5%, stage 2 in 36.2%, stage 3 in 8.6%). In group I, it was 15.0 ± 1.0 mm Hg (normal intra-abdominal pressure in 21.4%, intra-abdominal hypertension stage 1 in 28.6%, stage 2 in 44.6%, stage 3 in 5.4%). The difference was not statistically significant ($p > 0.05$).

In patients in group I with a limited process (Hinchey I-II), the intra-abdominal pressure was 13.3 ± 0.7 mm Hg. In group II, intra-abdominal pressure on the 1st day after laparotomy was 14.6 ± 0.8 mm Hg (no changes, $p > 0.05$), while after laparoscopic surgery it decreased to 12.9 ± 0.8 mm Hg ($p < 0.01$). It was found that laparoscopy does not contribute to intra-abdominal hypertension in the postoperative period, despite the use of carboperitoneum, unlike laparotomy, which causes persistence of increased intra-abdominal pressure due to greater surgical trauma and intestinal paresis. In patients with anastomotic insufficiency, a sharp increase in intra-abdominal pressure was observed - on average from 13.0 ± 0.5 to 20.3 ± 0.7 mm Hg., which indicates a high sensitivity of this diagnostic criterion.

Monitoring was carried out from 3 to 14 days. Intra-abdominal pressure in patients with an uncomplicated course decreased by 2–3 days. In cases of increased pressure, additional diagnostics were performed. No case of abdominal hypertension syndrome was detected. Surgical treatment is a complex process with many obvious and hidden factors that affect the course of the postoperative period and, in particular, the indicators of intra-abdominal pressure. However, the presented study data show that minimally invasive laparoscopic treatment due to the need to impose carboperitoneum and iatrogenic increase in intra-abdominal pressure during the operation does not lead to an increase in intra-abdominal hypertension in the early postoperative period, but, on the contrary, reduces it (Leon et al., 2021).

On the first day after laparotomy, intra-abdominal pressure remains elevated approximately to the preoperative level, despite the sanitation of the abdominal cavity. This is probably due to greater surgical trauma, prolonged exposure of the abdominal cavity to air, which inevitably leads to varying degrees of intestinal paresis, edema of visceral organs, and temporary increased exudation. But never, in both study groups, was there a significant increase in intra-abdominal pressure (increasing by a degree) and the development of abdominal hypertension syndrome on the first day after surgery.

Conclusion

The obtained data indicate that laparoscopy is a safe method of intervention from the point of view of intra-abdominal pressure. A decrease in intra-abdominal pressure after surgery can be considered as a prognostically favorable sign. An increase in intra-abdominal pressure correlates with the development of complications, which makes it a valuable predictor. Thus, measuring intra-abdominal pressure depending on the prevalence of the inflammatory process and after colorectal interventions, identifying the influence of the surgical treatment method on intra-abdominal pressure, determining the prognostic value of intra-abdominal pressure in the diagnosis of the development of abdominal complications, prevents the development of purulent-septic complications, reduces mortality, improves treatment outcomes, and increases the quality of postoperative monitoring.

Intra-abdominal pressure monitoring is a highly sensitive method for early diagnosis of complications in the postoperative period in acute destructive diverticulitis, which allows to assess the severity of the disease, the effectiveness of surgical intervention and predict the development of complications. Increased intra-abdominal pressure in patients of group II (with Hinchey III-IV) is a predictor of a complicated course and requires more active monitoring.

There is no convincing evidence of microbial dysbiosis in colonic diverticula to suggest that the microbiota contributes to the pathogenesis of asymptomatic diverticulosis, SUDD, or diverticular disease. Future research investigating microbiota involvement in colonic diverticula should consider an investigation of mucosa-associated microbial changes within the colonic diverticulum itself. A significant increase in intra-abdominal pressure may be an early sign of anastomotic failure and requires immediate intervention. Laparoscopic treatment is accompanied by a smaller increase in intra-abdominal pressure and, accordingly, a better course of the postoperative period.

Recommendations

It is advisable to include routine measurement of intra-abdominal pressure in biomedical engineering and technological protocols for postoperative surveillance in abdominal surgery. Further research is needed to study the dynamics of intra-abdominal pressure in patients with different types of anastomosis and the possibility of using combined biomarkers to increase the accuracy of prediction.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Evaluation of Antiproliferative Effect of *Moringa peregrina* Seed Against Prostate Cancer Cells

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Abstract: *Moringa peregrina* is a medicinal plant used in traditional practice in several regions of Asia and Africa, including the Arabian Peninsula. This study assessed the antiproliferative potential of an ethanolic seed extract of *M. peregrina* (MPSE) against LNCaP human prostate cancer cells using the MTT assay. Cells were exposed to MPSE at concentrations ranging from 12.5 to 200 µg/mL for 48 hours, and cell viability was determined by formazan absorbance at 570 nm. MPSE reduced LNCaP cell viability in a concentration-dependent manner, with an IC₅₀ value of 183.91 µg/mL. The finding indicates that MPSE has moderate cytotoxic and antiproliferative activity against LNCaP cells. However, further work involving bioassay-guided fractionation, compound identification, mechanistic assays, and comparison with normal prostate cells is required before any therapeutic relevance can be proposed.

Keywords: *Moringa peregrina*, Prostate cancer; LNCaP, MTT assay, Cytotoxicity; Antiproliferative activity

Introduction

Moringa peregrina is a plant species traditionally used for several health-related purposes, including the management of conditions such as hypertension, diabetes, malaria, skin disorders, and abdominal discomfort (Al Dhaberi et al., 2016; Ayoub et al., 2023; El-Sayed et al., 2021). The seeds of this plant have attracted scientific interest because they contain bioactive phytochemicals such as flavonoids, phenolic compounds, and tocopherols, which are commonly associated with antioxidant, anti-inflammatory, antimicrobial, antidiabetic, and anticancer-related properties (Albaayit, 2024).

Prostate cancer remains a major health concern, and its burden is expected to increase substantially in the coming decades (Thwaini, 2024). Although surgery, radiotherapy, hormonal therapy, and chemotherapy are used in clinical management, treatment limitations and adverse effects continue to encourage research into supportive or alternative bioactive agents. Natural products are frequently investigated in this context because their chemical diversity provides a useful starting point for identifying compounds that may interfere with cancer cell growth (Abood et al., 2025).

Even though there are many studies concerning the biological activity of *Moringa peregrina* and *Moringa* species in general (Senthilkumar et al., 2018), the seed extract effect on androgen-sensitive LNCaP prostate cancer is still limited. Therefore, this study has evaluated the antiproliferative effect of *Moringa peregrina* ethanolic extract against LNCaP cells *in vitro* as well as estimated the IC₅₀ value through MTT assay.

Method

Preparation of *Moringa peregrina* Seed Ethanolic Extract

Moringa pergerina fresh seeds was washed & dried then it was grinded into powder. Maceration for three of 100gm of the powdered seeds in 500 ml ethanol then the fraction of solvent was collected, and the procedure of extraction has been done again to enhance the extract recovery process. The ethanolic extract was obtained after the filtrates were combined & concentrated using filter paper and rotary evaporator at 45-50°C respectively (Azwanida, 2020).

Cell Culture

Human prostate cancer cells (LNCaP) were obtained from ATCC then it was maintained in DMEM augmented with 10% fetal bovine serum and 1% penicillin- streptomycin. The culture was incubated in a humidified 5% CO₂ incubator at 37°C until the culture reached the treatment optimum required conditions.

MTT Antiproliferative Assay

Moringa pergerina ethanolic extract antiproliferative activity was detected using the MTT assay. Human prostate cancer cells (LNCaP) were seeded in a 96 well plates with a density of 5×10^3 cells per well then it was allowed to attach prior to treatment. LNCaP cells were exposed to MPSE with a concentration (12.5 to 200 µg/mL) for 48 hours. The plate was incubated for four hours at 37°C after adding the total of 20 µg/mL MTT solution (5mg/ml) to each well. The formazan crystals resulted after that were dissolved 100 µL dimethyl sulfoxide, then the absorbance was measured at 570 nm. Each of these experiments was triplicately performed (Kumar et al., 2021).

Statistical Analysis

The data were expressed as mean $\pm$ standard error. The IC₅₀ and the statistical analysis were estimated using GraphPad Prism version 6.0. Treated and untreated cells difference was considered statistically significant at $p < 0.001$.

Results and Discussion

The viability of human prostate cancer cells (LNCaP) was significantly reduced using *Moringa pergerina* ethanolic extract. With an approximate IC₅₀ value of 183.91 µg/mL after exposure for 48 hours. Firmly indicating that the crude ethanolic extract possesses noticeable antiproliferative effect. Nevertheless the antiproliferative effect was obtained from crude, non fractionated compound. The outcome is firmly aligned with the scientific interest in plants as an active medicinal compound source. Studies have proven that plants are a valuable source of natural products affecting oxidative stress, inflammatory signaling as well as cell viability and many other aspects in the biology of cancer (Atanasov et al., 2021; Sharifi-Rad et al., 2020; Seca & Pinto, 2021). The confirmed reports of the presence of tocopherols, phenolic compounds and flavonoids in *Moringa pergerina* explains the reduction of human prostate cancer LNCaP cell viability in this study (Kashyap et al., 2022; Saleh et al., 2020). The antioxidant effect may contribute to the biological activity, while a clear interpretation for the relationship between the phytochemicals rich in antioxidants and the inhibition of cancer cells should be performed (Forman & Zhang, 2021; George et al., 2021). The reduction in cellular viability mechanism cannot be identified by MTT assay only. Growth arrest, cytotoxicity and reduced metabolic activity might reflect reduced absorbance. Therefore, assays such as cell-cycle analysis, apoptosis detection and caspase activation studies are highly required to clarify this mechanism of action. Observations on *Moringa* species effect against prostate cancer is strongly supported by present studies, previous studies have proven the cytotoxic effect of *Moringa oleifera* against prostate cancer cells (Adebayo et al., 2017), suggesting that this genus contains an anticancer activity. Direct and clear comparison between these studies should be made because the potency of plant extract varies depending on species, parts of the plant, solvent used, phytochemical composition, geographical source, duration of treatment and the targeted cell line. Several limitations should be considered. First, MPSE was tested as a crude extract; therefore, the active constituent or combination of

constituents responsible for the effect remains unknown. Second, only one prostate cancer cell line was used, which limits the interpretation of cancer-type specificity.

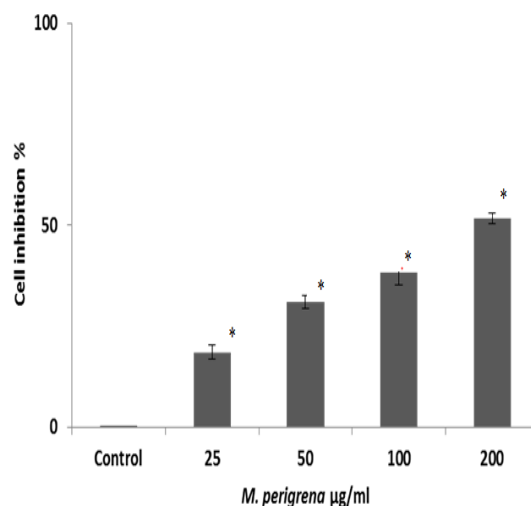


Figure 1. Inhibition effects of *Moringa perigrina* seeds on LNCaP

Conclusion

The ethanolic seed extract of *Moringa peregrina* demonstrated moderate antiproliferative activity against LNCaP prostate cancer cells, with an IC_{50} value of 183.91 $\mu\text{g/mL}$. The result suggests that MPSE contains bioactive constituents that may interfere with prostate cancer cell viability *in vitro*. Future studies should focus on polarity-based fractionation, identification of active compounds, mechanism-of-action assays, and selectivity testing against normal prostate cells before the extract can be considered for further preclinical development.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

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Notes

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Ovarian Histological Alterations and Fetal Developmental Effects Induced by A Novel Anticancer Phosphoramidate Nucleotide in Rats

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Abstract: The present study evaluated the reproductive toxicity of a novel compound, SH-PAN-19, in pregnant rats. To assess ovarian toxicity, SH-PAN-19 was administered at 25 and 100 mg/kg through a single dose, while fetal outcomes were examined following drug administration on gestational day 16. Fetal development and ovarian morphology were assessed on gestational day (GD18), with additional ovarian recovery analysis performed 21 days post-treatment. Administration of 25 mg/kg intraperitoneally caused a little yet significant reduction in fetal weight and crown–rump length, whereas 100 mg/kg via oral gavage resulted in complete fetal resorption. Histological analysis demonstrated dose-dependent ovarian damage. Control ovaries exhibited normal follicular development, whereas exposure to 25 mg/kg resulted in moderate follicular depletion and a reduced number of corpora lutea. In contrast, the 100 mg/kg dose severely disrupted folliculogenesis, leading to extensive ovarian deterioration. Recovery studies indicated that ovarian damage at 25 mg/kg was largely reversible, while exposure to 100 mg/kg produced persistent and irreversible injury. Collectively, these findings demonstrate that SH-PAN-19 induces pronounced dose-dependent embryotoxicity and ovarian toxicity, underscoring the substantial risk associated with high-dose exposure, while suggesting that the recommended 25 mg/kg dose during the third trimester may still pose potential risks to female fertility and pregnancy outcomes.

Keywords: Anticancer drugs, Phosphoramidate nucleotide, Rat, Fertility

Introduction

Pregnancy-associated Cancer is a serious and complicated medical disease. Breast cancer, cervical cancer, melanoma, lymphoma, and acute leukaemia are the most common types of malignancies that women might get while pregnant (Puzzi-Fernandes et al., 2020). A pregnant woman with cancer usually undergoes various treatments, including chemotherapy, radiation therapy, Surgery, and hormonal therapy. However, many treatments are associated with adverse reproductive results, including diminished fertility in females and adverse effects on embryonic development (Wolters et al., 2021). Pregnancy-associated Cancer is considered a rare condition, with an estimated incidence of approximately 1 in 1,000 pregnancies (Dalmartello et al., 2020). In recent years, more women have been diagnosed with cancer during pregnancy. This issue is becoming more significant in the clinic (Zhang et al., 2017). When a woman has cancer and is pregnant at the same time, it makes treatment more difficult and often leads to a worse outcome for the mother. It is imperative to devise

therapeutic strategies that proficiently enhance maternal health while minimizing dangers to fetal welfare (Zhang et al., 2017).

Developmental Toxicity and Reproductive Impact

Organ developmental toxicity refers to structural and functional impairments in the offspring's organs resulting from exposure to harmful intrauterine circumstances during gestation. Adverse conditions include environmental stressors (physical, chemical, and biological agents) as well as maternal factors, including illness, starvation, and mental stress. Drug exposure has been identified as a contributor to developmental toxicity among these factors (Lu et al., 2023). The effects of cancer and its treatment on female reproductive function have become increasingly evident in recent years. Advances in cancer therapy have improved survival rates; however, these treatments are often accompanied by long-term adverse effects on reproductive health. Epidemiological studies indicate that, compared with the general population, women diagnosed and treated for cancer are approximately 38% less likely to achieve pregnancy, regardless of cancer type. This consistent reduction in post-treatment fertility highlights the significant reproductive burden associated with cancer and underscores the need for improved understanding and management of treatment-related gonadotoxicity (Anderson et al., 2018).

The adverse effects of chemotherapy on ovarian function have been recognized for decades. Accumulating clinical and experimental evidence has increasingly clarified the impact of different chemotherapeutic regimens on female reproductive health. These effects extend beyond immediate disruptions in ovarian activity and include alterations in short-term markers of ovarian reserve, such as hormonal profiles and follicular dynamics, as well as long-term consequences for fertility potential. Moreover, exposure to certain chemotherapeutic agents has been strongly associated with an elevated risk of premature ovarian insufficiency and early menopause. Collectively, these findings underscore the substantial reproductive burden imposed by chemotherapy and highlight the importance of evaluating ovarian toxicity when selecting and optimizing anticancer treatments (Anderson et al., 2018).

Chemotherapy Exposure and Formulation Considerations

During pregnancy, doctors employ a number of chemotherapeutic medications to treat cancer. These are alkylating drugs, anthracyclines, and a taxane. These medications might aid pregnant women, but they could potentially hurt the mother's reproductive health and the baby's growth (Struys et al., 2024). Organic solvents used as formulation vehicles can influence embryonic development, and their concentrations must therefore be carefully controlled in developmental studies. Within experimentally defined tolerable ranges, several vehicles, including PEG 400, corn oil, DMSO, and poloxamer 188, can be employed without overt adverse effects on early development (Chen et al., 2023; Maes et al., 2012).

Novel Therapeutic Candidate and Study Aim

A novel therapeutic drug candidate, SH-PAN-19, currently under patent, is a modified molecule derived from phosphoramidate acyclic nucleotide, exhibiting anticancer efficacy across various cell lines (Huh-7, HepG-2, Caco-2, A549 cells). It demonstrates a promising effect in the HCC rat model, exhibiting a great safety profile and significant potency. Compound code: (9a) , compound name: Isopropyl[(S)-{2-(9-(4-bromophenyl)-3,3,6,6-tetramethyl-1,8-dioxo2,3,4,5,6,7,8,9-octahydroacridin-10(1H)-yl)ethoxy}(phenoxy)phosphoryl]-L-alaninate (Hammad, 2024).

In this study, more preclinical studies to investigate the effect of this drug candidate on pregnancy and female fertility. The assessment was performed through histological examination of maternal ovaries, aiming to detect any reproductive and developmental toxicities associated with maternal exposure.

Method

Drug Synthesis and Solubilization

SH-PAN-19 was synthesized and characterized as previously described [8]. The crude product was initially characterized by thin-layer chromatography (TLC) using silica gel plates and a 1:1 ethyl acetate: hexane solvent system, visualized under UV light, and characterized by observing its characteristic UV–visible spectrogram. For purification, the main TLC band was carefully scraped, and the compound was extracted using methanol. The purified **SH-PAN-19** was further characterized by UV–visible spectroscopy, showing a maximum absorption at 350 nm. The purified compound was then formulated for in vivo studies.

The medication exhibited significant insolubility and encountered challenges in dissolving within acceptable parameters during pregnancy. Multiple experiments were conducted at 25 ± 3 °C to attempt its dissolution. After numerous tests, we identified the most suitable vehicle for intraperitoneal injection during pregnancy (Table 1). The medication was evaluated for its impact on ovarian tissues and fetal development at a high dose of 100 mg/kg and a low dose of 25 mg/kg.

Experimental Animals and Housing Conditions

Fifteen Adult virgin female rats ($n = 5$ per group) were used in this study. Animals were housed under standard conditions with a room temperature of 22 ± 3 °C, relative humidity of 30–70%, and a 12-h light/12-h dark cycle. Rats had free access to standard laboratory chow and water ad libitum. Rats were fed for eight days to adapt to the laboratory environment, and then mated (female: male = 2:1) overnight from 7 p.m. to 9 am during their estrous cycle. On the second day at 9 am, the females were examined for vaginal plug, which was designated as day 0 (Choi et al., 2020). SH-PAN-19 was evaluated for its effects on female fertility and fetal development. Pregnant rats were randomly assigned to control or treatment groups. The drug was administered via two dose levels: High dose: 100 mg/kg via Oral gavage and Low dose: 25 mg/kg via intraperitoneal.

Experimental Design and Drug Administration.

SH-PAN-19 was administered to rats at doses of 25 mg/kg or 100 mg/kg. A Single dose was administered on gestation day 16 only. After 48 hours of the treatment (on gestation day 18), the animals were sacrificed by decapitation, and their weights were determined. Upon sacrificing the animals, the ovarian tissue was fixed by immersing them in 10% formalin. After fixation, both tissues were dehydrated with ascending ethanol concentrations for 15 min each, followed by embedding in paraffin wax as reported earlier. Afterward, the tissues were sliced (5 μ m thickness). After that, the H&E sections were observed and examined using a light microscope (Olympus CX31, Tokyo, Japan). The two horns of the uterus were excised and washed with cold PBS, and fetuses were obtained, and their weights and crown–rump length were determined. The fetuses were examined for any external abnormalities. The fetal and the mother's organs were kept at -80 °C for biochemical analysis. For the high-dose group, animals received a single oral dose of 100 mg/kg of the drug, while the corresponding control group received the vehicle only. In the low-dose group, animals received a single intraperitoneal dose of 25 mg/kg of the drug.

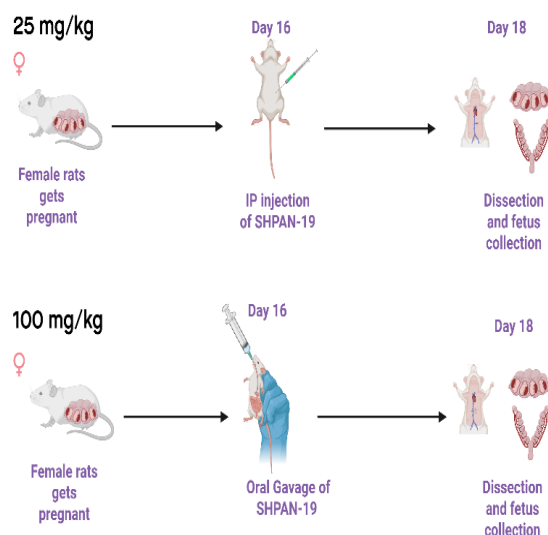


Figure 1. Schematic overview of experimental design. Created using BioRender.com.

Histological Analysis

Ovarian tissues were embedded in paraffin, sectioned 5 μm , and stained with hematoxylin and eosin (H&E). Sections were examined under a light microscope to assess follicular development, corpus luteum formation, and overall ovarian morphology. Histological comparisons were made between control and Treated groups at both 25 mg/kg and 100 mg/kg doses (Figure 1).

Results and Discussion

To solubilize the drug, organic solvents used were employed without overt adverse effects on early development, as illustrated by the tolerated concentrations summarized in **Table 1**, including PEG 400, corn oil, DMSO, and poloxamer 188. The drug was successfully dissolved in a mixture of DMSO and sunflower oil at a concentration higher than 4 mg/ml.

Table 1. Solubility of SH-PAN-19 in different formulations. Various solvents and excipient combinations were tested to identify suitable solubilization strategies for *in vivo* administration.

COMPONENTS			SOLUBILITY
A)	SALINE		Insoluble
B)	CORN OIL		Insoluble
C)	PEG 400	5%	Insoluble
	DMSO	1%	
	POLOXMAR188	12.5%	
	SALINE	81.5%	
D)	DMSO	+ SUNFLOWER OIL	Soluble ~ 4mg/ml
	SUNFLOWER OIL		

To investigate the effect of SH-PAN-19 on pregnancy and female fertility, pregnant rats were administered the drug at concentrations of 25 or 100 mg/kg as explained in Fig 1. The rats were sacrificed and dissected at gestational day 18. Morphological examination of the animals revealed a minimal reduction in weight and length of fetuses in animals administered 25mg/kg. On the other hand, administration of 100mg/kg resulted in resorption of the fetuses completely, as shown in Fig 2. This suggests that SH-PAN-19 shows a dose-dependent effect on fetal development. At 25 mg/kg, fetal weight and crown–rump length were reduced, indicating impaired growth. At 100 mg/kg, complete fetal resorption occurred, demonstrating severe embryotoxicity. These results suggest that SH-PAN-19 disrupts fetal viability in a dose-dependent manner, likely through cytotoxic effects on naturally dividing cells or interference with maternal-fetal support, highlighting the need for careful evaluation of its reproductive safety.

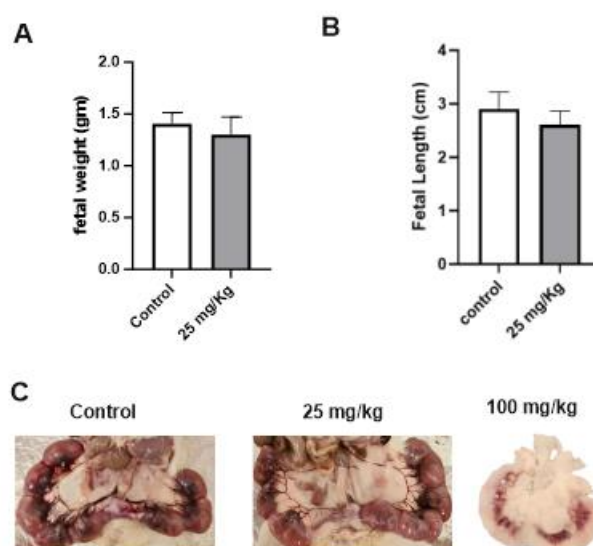


Figure 2. Comparison of fetal weight (A) and fetal crown–rump length (B) in control, 25 mg/kg, and 100 mg/kg treatment groups, with representative photographs of fetuses shown (C). The 100 mg/kg group resulted in complete fetal resorption and was excluded from quantitative analysis.

To further assess SH-PAN-19–induced ovarian toxicity in pregnant rats, ovarian tissues were examined by H&E staining (Figure 3). Ovaries from control pregnant rats exhibited normal histoarchitecture, characterized by an intact ovarian cortex, well-organized stromal tissue, and prominent corpora lutea consistent with pregnancy. In contrast, treatment with SH-PAN-19 at a dose of 100 mg/kg resulted in marked disruption of ovarian organization, including degeneration of the cortical region, stromal disintegration, vascular congestion, and extensive cellular degeneration, while in rats administered 25 mg/kg intraperitoneally, considerable follicular depletion and a reduced number of corpora lutea were noted, alongside partial preservation of stromal architecture.

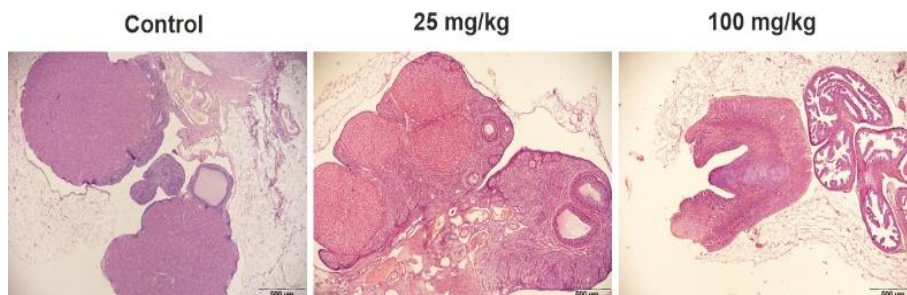


Figure 3. Representative H&E-stained ovarian sections: Photomicrographs of rat ovaries illustrating dose-dependent histological alterations. Ovaries from control pregnant rats show preserved architecture with well-developed corpora lutea, along with normal gestational activity. In rats exposed intraperitoneally to 25 mg/kg, moderate follicular depletion and fewer numbers of corpora lutea are observed, with partial preservation of stromal architecture. At the 100 mg/kg dose, ovaries display a significant reduction in corpora lutea, accompanied by diffuse stromal thinning, indicating pronounced impairment of normal ovarian cyclic and gestational function. n = 5 per group. Scale bar = 500 µm.

The control of non-pregnant ovaries exhibits preserved architecture with follicles at various developmental stages and well-organized stroma, indicating normal folliculogenesis. low-dose exposure (25 mg/kg), ovaries show partial structural restoration with reappearance of growing follicles and corpora lutea, with mild stromal alterations, and atretic follicles. In contrast, high-dose exposure (100 mg/kg) demonstrates incomplete regeneration, characterized by fewer developing follicles and corpora lutea with persistent stromal thinning and follicular atresia in Figure 4.

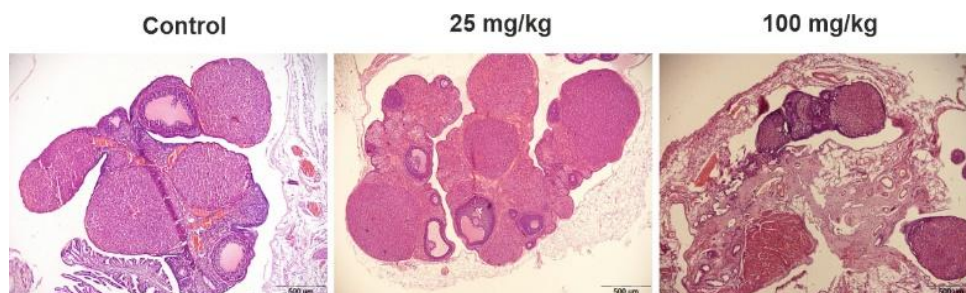


Figure 4. Representative H&E-stained ovarian sections after 21-day recovery. Photomicrographs showing recovery-associated histological changes in rat ovaries. Control, 25mg/kg and 100 mg/kg. n = 5 per group. Scale bar = 500 µm.

Conclusion

SH-PAN-19 exhibited clear, dose-dependent reproductive and developmental toxicity in pregnant rats. A single intraperitoneal dose of 25 mg/kg on gestation day 16 shows a minimal reduction in fetal weight and crown–rump length at gestation day 18, indicating impaired intrauterine growth without gross external malformations. In contrast, a single oral dose of 100 mg/kg resulted in complete fetal resorption, demonstrating severe embryotoxicity and loss of pregnancy at the higher exposure level. These functional outcomes were accompanied by marked histopathological alterations in the ovary, including cortical disruption, stromal disorganization, vascular congestion, and extensive cellular degeneration in pregnant animals, as well as incomplete structural recovery and persistent follicular atresia in non-pregnant ovaries at 100 mg/kg. Collectively, these findings indicate that SH-PAN-19 has a narrow or absent safety margin in pregnancy and exerts substantial, dose-related adverse effects on both ovarian structure and fetal development.

Recommendations

Future studies should incorporate detailed molecular analyses, including markers of apoptosis, oxidative stress, DNA damage, and endocrine disruption in ovarian and fetal tissues, to clarify the mechanisms underlying SH-PAN-19–induced reproductive and developmental toxicity.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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TransFil: A Hybrid CNN–LSTM Framework for Multimodal Translation of Filipino Sign Language and Facial Expressions for Non-Signer Communication

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Abstract: Filipino Sign Language (FSL) serves as the national sign language of the Philippines, yet its accessibility remains limited due to widespread unfamiliarity and the dominance of American Sign Language (ASL). Existing technologies for sign language translation often neglect crucial non-manual markers such as facial expressions, which play a key role in grammar and meaning. To address this gap, this study presents the development of an AI-powered FSL recognition system that integrates both manual gestures and facial expressions, focusing on greetings and common questions. Using a video-based dataset collected in controlled conditions, the system employs Media Pipe for landmark detection, Convolutional Neural Networks (CNNs) for spatial feature extraction, and Long Short-Term Memory (LSTM) networks for temporal modeling. Overall, The facial expression recognition (FER) model, built using a CNN architecture, was trained to identify six common emotions: angry, fear, happy, neutral, sad, and surprised. It performed strongly, achieving about 97% training accuracy and 95% validation accuracy, showing that it can generalize well to new data. While, the model demonstrated reliable performance, with precision (0.95), recall (0.94), and F1-score (0.95), making it suitable for real-world use. These results align with previous studies highlighting the strength of CNNs in capturing important facial features.

Keywords: Filipino sign language, Long short-term memory (LSTM), Media pipe, Facial expression recognition, Gesture recognition, Deaf community accessibility

Introduction

Sign language is a rich and expressive way of communication that uses hand movements, facial expressions, and body gestures to convey thoughts, emotions, and ideas. Unlike spoken language, it does not use the voice but instead relies on visual signals. It is especially important for people who are Deaf, hard-of-hearing, or have difficulty speaking. In the Philippines, around 300,000 people are Deaf (Echon et al., 2021), and they rely on sign language to communicate. There are three main sign languages used in the Philippines: Filipino Sign Language (FSL), American Sign Language (ASL), and Signing Exact English (SEE). In 2018, FSL was officially declared the national sign language through Republic Act No. 11106. This law requires FSL to be used in schools,

government services, workplaces, and media. However, most Filipinos are still more familiar with ASL, which was introduced earlier in the country.

In recent years, researchers have developed and implemented various systems focused on recognizing sign language, supported by advances in different areas of technology (Tolba & Elons, 2013). Interest in sign language recognition has significantly increased (El-Bendary et al., 2010). Numerous studies have been conducted on different sign languages, including American Sign Language, Korean Sign Language, and Chinese Sign Language, among others (Brashear et al., 2006). This technology is crucial for helping individuals with speech impairments communicate, as they are unable to use spoken language (Cabalfin et al., 2012). Sign language recognition holds great promise for enhancing communication and accessibility, making it a growing field within computer science and artificial intelligence.

Historically, the development of sign language translation technologies—such as smart gloves and signing avatars—has been mostly led by hearing researchers, often without involving Deaf individuals in the process. Some of these tools do not fully match the way sign languages actually work. For example, smart gloves like SignAloud were designed to translate hand movements into speech or text, but they ignore important parts of sign language like facial expressions and body movements, which are essential for clear and correct communication. Signing avatars, which are animated characters that perform signs, also face criticism because they often look unnatural and miss the emotion, rhythm, and cultural style of real signing. Because of these issues, many Deaf community members have raised concerns about the growing use of such technologies in communication (Kusters et al., 2023). Lack of inclusion has resulted in tools that may not fully align with the linguistic and cultural needs of the Deaf community. Some members of the Deaf community have raised concerns about the growing use of technology in sign language communication. While tools like AI-based sign language translation systems can offer support in certain situations, there is worry that relying too much on these tools could reduce the value placed on learning and using sign language itself. Sign languages are not just a way to communicate—they carry cultural identity, shared experiences, and community connection. According to Desai et al. (2024), there is a real risk that AI systems might be seen as a replacement for human interpreters, which could lead to the loss of meaningful, person-to-person interaction. This raises ethical concerns about how such technologies are introduced and used.

Despite concerns over technological substitution, there are areas where the Deaf community has welcomed the development of sign language technologies, particularly when these tools are designed to enhance accessibility without undermining the richness of human interaction. Many in the community have expressed support for technologies that help bridge communication gaps, especially in environments where access to interpreters or Deaf professionals may be limited. As noted by De Meulder, Van Landuyt, and Omardeen (2024), AI systems that assist in real-time communication, such as automatic captions or sign language recognition tools, have been praised for promoting independence and inclusion. When developed with input from the Deaf community, these technologies are seen as empowering, providing more opportunities for Deaf individuals to participate in mainstream society while still preserving the cultural and linguistic aspects of sign language.

Although FSL was officially recognized as the national sign language of the Philippines through Republic Act No. 11106, and its use has been mandated in education, healthcare, justice, employment, media, and other public domains, awareness and understanding among the general population remain limited. Mendoza (2018) notes that many Filipinos mistakenly believe ASL is the only sign language in use, despite differences in gestures and expressions that affect clear communication. The ongoing lack of accessible communication tools continues to limit the inclusion of Deaf and hard-of-hearing individuals in essential areas such as education, employment, and public services. As noted by Petinglay (2021), bridging this language barrier is critical to promoting the rights and opportunities of Persons with Disabilities (PWDs). Current sign language technologies often overlook facial expressions, which are essential for expressing grammar and emotion in Filipino Sign Language (FSL) (Sharma et al., 2024). To address this, our study aims to develop a hybrid CNN-LSTM model that recognizes both hand gestures and facial expressions in FSL greetings, integrating them into a real-time translation system. This system will be evaluated using both quantitative performance metrics and user feedback, ensuring its effectiveness and cultural relevance for the Deaf community. This effort not only improves accessibility for non-signers but also supports those interested in learning FSL by helping them understand the meaning, grammar, and facial expression cues behind commonly used greetings.

As highlighted by Kaur and Singh (2020), deep learning techniques such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs) have proven effective in detecting hand movements, facial expressions, and body posture—core elements in sign language recognition.

Furthermore, recent studies have explored multi-modal approaches, integrating gesture, facial expressions, and contextual cues to improve recognition accuracy and user experience (Pigou et al., 2018). These systems not only interpret hand signs but also capture facial expression, adding depth to the conveyed message—crucial for maintaining the nuances of human interaction. Research also shows growing interest in developing datasets and frameworks specific to various sign languages, including American Sign Language (ASL), British Sign Language (BSL), and emerging studies into Tagalog Sign Language (TSL), supporting the global effort for linguistic inclusivity in AI systems (Camgoz et al., 2020).

There are already applications which focus on FSL that help mute and the hearing-impaired people, such as the research done by students in Mapua Malayan Colleges Mindanao “A visual approach in Filipino sign language recognition using TensorFlow Lite model”. This study is not only on the development of a software in detecting expressions and translating gestures but, it also evaluates the accuracy of the model that the researchers wants to study. The main objective of this study is to develop a software that utilizes AI to recognize gestures to translate FSL (Filipino Sign Language) greetings and detect facial expressions. To achieve the main objective, the study was guided with these specific objectives:

- A. Develop a hybrid model using CNN and LSTM architectures to recognize FSL gestures that depend heavily on facial expression such as greetings using a labeled FSL video dataset and high-resolution camera for data collection.
- B. Integrate the hand gesture and facial expression recognition components into a unified translation system that converts the detected Filipino Sign Language (FSL) signs into accurate text output for real-time communication.

Evaluate the system’s performance and usability using quantitative metrics such as accuracy, precision, recall, and F1 score, along with feedback gathered from Filipino Sign Language (FSL) users.

Related Works

Recent developments in artificial intelligence have significantly advanced the field of real-time sign language recognition. Pandey (2025) explored the potential of deep learning by combining convolutional neural networks (CNNs) for spatial feature extraction and recurrent neural networks (RNNs) for sequential modeling. The objective was to create a system that could accurately translate sign language gestures into text or speech outputs in real time. By leveraging CNNs and RNNs, the system demonstrated high recognition accuracy, making it a promising approach for improving communication for the deaf and hard-of-hearing community. This study’s findings highlight the transformative potential of deep learning in real-time applications and are highly relevant to our research, as they underscore the importance of combining different neural network architectures to optimize gesture recognition in our system. Sign language communication often relies not only on hand gestures but also on facial expressions to convey full meaning. Kean University’s team developed a system that not only recognized American and British Sign Languages (ASL and BSL) but also analyzed facial expressions to interpret emotional cues, which are essential for accurate communication. Using OpenCV and the MediaPipe library, this system was designed to capture both hand movements and facial expressions in real time. The key finding was that incorporating facial expressions significantly improved the accuracy of sign language translation. This research is pertinent to our project as we aim to embed emotional context into our sign language recognition system, making it more expressive and truer to human communication.

Zhang et al. (2023) introduced a novel approach for sign language recognition using event cameras, which are distinct from traditional cameras in that they capture motion-triggered changes instead of frame-based images. The integration of event cameras with spiking neural networks (SNNs) allowed for faster and more efficient gesture classification. This study demonstrated a 77% accuracy in recognizing gestures and pointed to the potential of event-driven sensors to enhance responsiveness and energy efficiency in real-time systems. For our project, the insights from this study could be pivotal in exploring alternative sensor technologies, especially for improving system speed and energy consumption. Stergiou and Papadopoulos (2021) conducted a comprehensive review of the state-of-the-art methods in sign language recognition, translation, and representation. Their work synthesized a wide range of technologies, from hand gesture tracking to advanced machine learning models. One of the major takeaways was the need for more integrated approaches that consider not only gestures but also contextual factors like facial expressions and emotional nuances. Their findings align closely with our research, particularly in identifying the limitations of current methods and providing a roadmap for integrating multi-modal inputs into sign language systems.

Aggarwal et al. (2023) focused on developing a real-time system that combines hand tracking with gesture classification. Their approach aimed to build a bridge for communication between hearing and non-hearing individuals, making it possible for people who use sign language to interact seamlessly with those who do not. The system achieved high confidence scores and demonstrated responsive behavior, making it a crucial step toward creating real-time, accessible sign language translation systems. This study is highly relevant to our project as it emphasizes the importance of real-time processing, which is a core feature of the system we aim to build. A recent study explored the integration of emotion recognition in sign language interpretation, highlighting the importance of facial expressions and lip movements alongside hand gestures. The researchers used machine learning, image processing, and animation tools to analyze and interpret the emotional content conveyed through sign language. This research provides crucial insights for our project, particularly in understanding how non-verbal cues like emotions can impact the effectiveness of sign language interpretation. Our goal of capturing both signs and emotions directly aligns with these findings.

In a study published in *Sensors* (2023), the researchers demonstrated the power of using the ASL Alphabet Hand Gesture Dataset to build a real-time recognition system. The primary objective was to optimize classification frameworks and model training for real-time applications, emphasizing the importance of curated datasets in improving system accuracy. The study's conclusions underscore the significance of data quality and model optimization in achieving high-performance recognition. This aligns closely with our goals, as our project will rely heavily on well-curated datasets and robust training processes to ensure efficient and accurate gesture recognition.

Research Design

This study employs a qualitative research design to deeply explore the development process and rationale behind the AI-powered Filipino Sign Language (FSL) recognition mobile application. By using this approach, the researchers aim to explain not just the outcomes, but also the underlying decisions and processes involved in building the system. As Bhandari (2020) highlights, qualitative research is particularly effective in gaining insights into how individuals experience and interpret the world—making it well-suited for understanding how users interact with assistive technologies like this sign language recognition tool.

Dataset Preparation

The system uses two primary input modalities: hand gestures for sign language and facial expressions.



Figure 1. Sign language dataset

Raw video clips of 10 Filipino Sign Language (FSL) classes were used as the primary dataset. These videos, each lasting 3–4 seconds, were sourced from publicly available FSL research repositories, including the DLSU Animo Repository dataset (Katigbak et al., 2023) (https://animorepository.dlsu.edu.ph/etdm_ece/25/). This dataset is suitable because it specifically focuses on Filipino Sign Language (FSL), aligning with the national context of the study. It provides authentic sign samples performed by native or fluent signers, ensuring linguistic accuracy and cultural relevance.

Each FSL class contained 20–22 video samples and was expanded using data augmentation (horizontal flipping, brightness adjustment, rotation, and cropping) to increase variability and robustness. The final dataset was divided into training (80%), validation (10%), and testing (10%).

Facial Expression Dataset

Facial expression data was obtained from the FER-2013 dataset hosted on Kaggle [https://www.kaggle.com/datasets/msambare/fer2013]. This dataset contains thousands of labeled facial images across multiple emotional categories. For this study, the following six categories were used: happy, sad, angry, surprised, neutral, and fear (the “disgust” category was excluded due to limited representation and weaker generalizability in prior studies).

FER-2013 was chosen because it is one of the most widely used benchmarks for facial expression recognition. It contains images collected under diverse conditions—different lighting, head poses, and backgrounds—which makes it highly suitable for training models intended for real-world application. The dataset was split into 70% training, 15% validation, and 15% testing.

Table 1. List of FSL greeting words and facial expressions used in the study

FSL Words	Facial Expressions
Kamusta Ka	Angry
Kita Tayo Bukas	Fear
Walang Anuman	Happy
Salamat	Neutral
Ikinagagalak Kitang Makilala	Sad
Okay Lang	Surprised
Hello	
Magandang Umaga	
Magandang Hapon	
Magandang Gabi	

Table 1 presents the set of Filipino Sign Language (FSL) greetings and facial expressions used in this study. The selected FSL words (*Hello, Kamusta Ka, Magandang Umaga, Magandang Hapon, Magandang Gabi, Salamat, Walang Anuman, Okay Lang, Kita Tayo Bukas, Ikinagagalak Kitang Makilala*) are all greetings and polite expressions. These were chosen because greetings are among the most fundamental and frequently used communicative acts in human interaction, forming the basis of social connection and daily conversation (Firth, 1972; Coulmas, 2013). In the context of sign language research, greetings are considered high-frequency lexical items that are essential for building accessible and practical recognition systems (Jetomo & De Lara, 2025). For the facial expressions, the categories (*angry, fear, happy, neutral, sad, surprised*) were selected because they represent the set of universally recognized facial expressions. According to Ekman & Friesen (1971), these six expressions are consistently identified across cultures and are widely used benchmarks in computer vision studies (Corneanu et al., 2016). The “disgust” category was excluded due to limited dataset representation and lower classification reliability in prior research (Mollahosseini et al., 2017).

Data Augmentation

To improve the generalization capability of the models and address the limited dataset size, data augmentation was applied to both the Filipino Sign Language (FSL) greeting videos and the facial expression images. Data augmentation introduces variability into the training data, thereby reducing overfitting and enabling models to perform better on unseen samples (Shorten & Khoshgoftaar, 2019).



Figure 2. Augmentation of FSL greeting videos

All training experiments were conducted in a Google Colab Pro environment with GPU acceleration. The FSL recognition model achieved approximately 99% training accuracy and 98–99% validation accuracy, while the facial expression model reached reliable accuracy across its six classes.

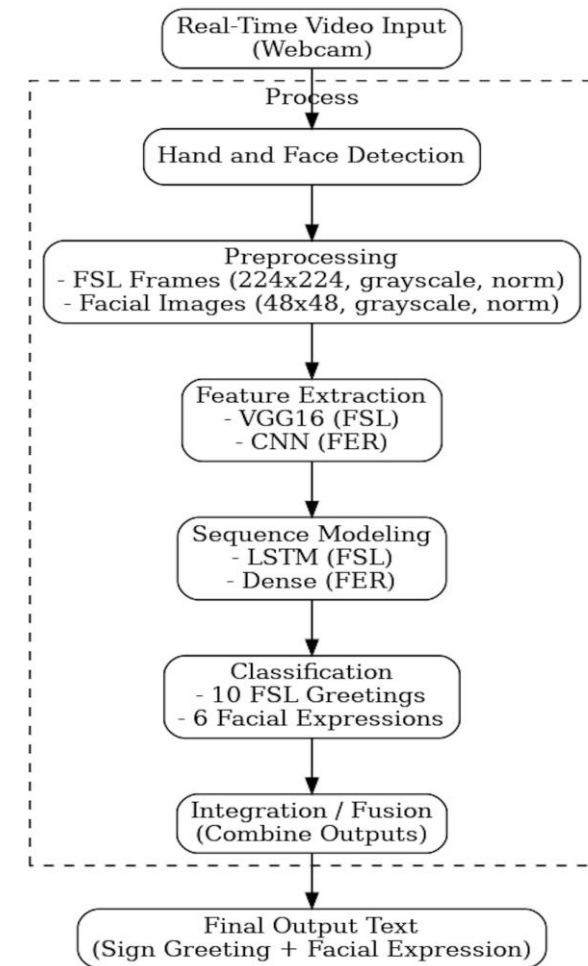


Figure 3. Conceptual framework of the study

The conceptual framework in Figure 2 illustrates the overall process flow of the proposed multimodal recognition system, beginning with real-time video input and culminating in the combined recognition of Filipino Sign Language (FSL) greetings and facial expressions.

Results and Discussion

The development of the multimodal recognition system relied on both hardware and software tools that helped with collecting data getting the data ready training the model and checking how well it works. We used a webcam as the hardware tool to capture video in real time that shows hand gestures and facial expressions. For the software part we used Google Colab Pro as the place to train the model because it has GPU acceleration, which helps with big data and complicated calculations. We built the system using Python 3.12. Made the main parts that deal with deep learning using TensorFlow and Keras. We used OpenCV to get frames from videos get images ready and connect the webcam when we tested the system in time. We also used Mediapipe to find faces and get them in the position, for the part of the system that recognizes facial expressions. We even used Graphviz to make diagrams like the picture that shows how the whole system works.

The picture in Figure 5 shows how the whole Filipino Sign Language recognition system works. It starts with a video. Ends with the system recognizing Filipino Sign Language greetings and facial expressions. The system has three parts: getting the video processing it and showing the result. The first part is getting the video from a webcam. This video has hand gestures and facial expressions that the system will recognize. The second part is where the system does all the work. It finds the hands and face in the video. Then it makes sure all the pictures are the same size and quality. For the Filipino Sign Language pictures it makes them 224×224 pixels changes them to black and white and makes sure they are all the same. It does the thing, with the facial pictures but it makes them 48×48 pixels. This helps the system focus on what's important. After that the system looks at the video. Finds the important parts. For Filipino Sign Language it uses a tool to find the important parts of the hand

gestures. For expressions it uses another tool to find the important parts of the face like the eyes, eyebrows and mouth. Then it looks at how these parts change over time. It uses a kind of computer program to understand how the hand gestures change and another kind to understand how the facial expressions change. The next step is where the system decides what it is looking at. It takes the parts it found and matches them to a list of possible greetings or facial expressions. The Filipino Sign Language system can recognize ten greetings and the facial expression system can recognize six different expressions. Then it combines the two results to get an understanding of what the person is communicating.

Finally, the system shows the result. It takes the recognized Filipino Sign Language greeting and the recognized facial expression. It shows them together. This makes the system more realistic and helpful because it understands how people use gestures and expressions when they communicate. The Filipino Sign Language recognition system is more inclusive and natural because it recognizes both non-verbal communications.

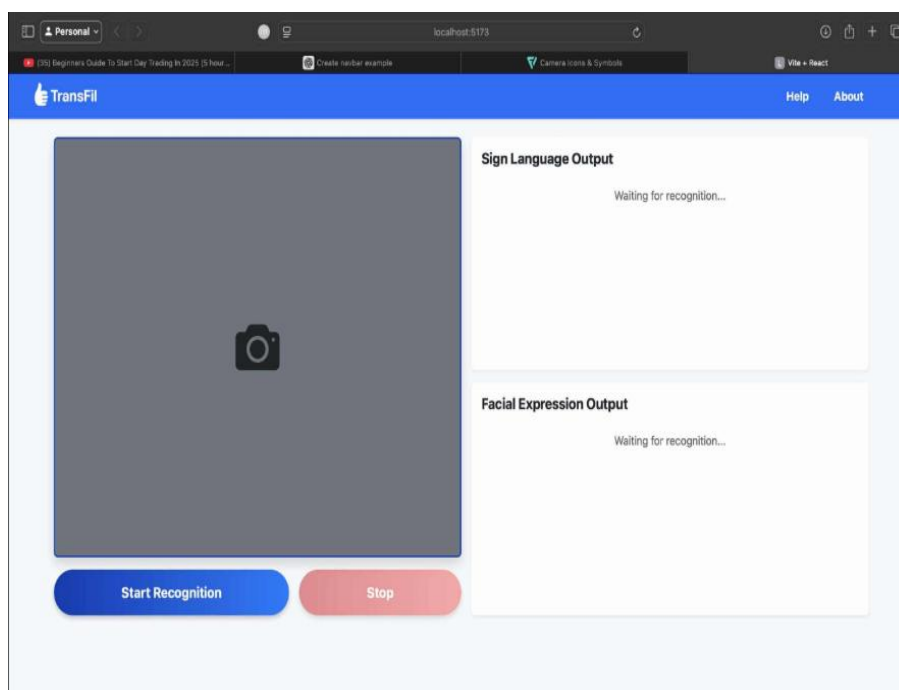


Figure 4. Filipino sign language interface for non-signers

The data we used for this study came from two places: our collections and public sources. To recognize Filipino Sign Language, we made videos of people doing ten different greeting signs. We then changed these videos in ways, such as, as flipping them making them brighter or darker turning them and cutting parts out so that our computer model could learn from many examples. For recognizing expressions, we used a set of data called FER-2013 that we found on Kaggle and we also made our own recordings. We wanted to make sure we had examples of people looking angry fearful happy, neutral, sad and surprised so Filipino Sign Language and facial expressions could be recognized properly. To see how well the models work we used a different tool. We looked at how accurate the models are and we also checked how precise they are, how well they recall things and what their F1-score is. This helps us understand how well the models can tell things apart whether it is the FSL model or the facial expression recognition model. We made tables to see how well the models can recognize each class and where they make mistakes. We also watched the models as they learned to make sure they were getting better and not just memorizing things. The models had to learn from the training data. Then do well on the validation data or it would mean they were not working right. All these tools together helped us make sure the system we proposed is good and works well

The FSL greeting recognition model was implemented using a CNN-LSTM hybrid architecture to capture both spatial and temporal features of signing sequences. The model achieved a training accuracy of 99% and a validation accuracy ranging between 98–99%. Furthermore, the validation loss stabilized at approximately 0.09, indicating strong convergence and robust generalization with minimal risk of overfitting. The confusion matrix demonstrates that all ten FSL greeting classes were recognized with high accuracy. Misclassifications were rare, with the most notable occurring between Magandang Umaga and Magandang Hapon, which share visually similar initial hand configurations and movements. Despite this, the overall classification remained reliable across all classes. The classification metrics further validate this performance, with the model achieving an average

precision of 0.98, recall of 0.97, and F1-score of 0.98. These values confirm the model's ability to maintain balance between sensitivity and predictive accuracy. The results obtained surpass the performance reported in prior studies, where typical accuracy for sign language recognition models ranges between 90–95% (Koller et al., 2019). The superior accuracy can be attributed to the combined effects of (1) extensive data augmentation, (2) preprocessing through grayscale normalization, and (3) the ability of the CNN–LSTM architecture to model both visual features and temporal dynamics in gesture sequences.

Results of Facial Expression Recognition

The facial expression recognition (FER) model was implemented using a CNN-based architecture trained on six universal facial expressions: angry, fear, happy, neutral, sad, and surprised. During training, the model achieved an accuracy of approximately 97%, while the validation accuracy stabilized at 95%, reflecting robust generalization across diverse test samples. The confusion matrix indicates that the model achieved the highest recognition rates for happy and surprised, both of which are characterized by distinctive and exaggerated facial features. In contrast, reduced performance was observed for fear and sad, which are inherently more subtle and prone to overlap in expression dynamics. Quantitatively, the FER model achieved an average precision of 0.95, recall of 0.94, and F1-score of 0.95, confirming its reliability for practical applications. These findings are consistent with existing literature that emphasizes the effectiveness of CNNs in extracting discriminative facial features (Li & Deng, 2020).

The results of this study show that the system we are talking about is really good at recognizing sign language greetings and facial expressions. This system uses a kind of pipeline that combines CNN and LSTM for recognizing sign language. It is good at understanding the order of gestures because it looks at them over time. We also used a CNN model to recognize expressions and it worked well because it can pick up on small details in peoples faces. The system we are talking about is good, at recognizing sign language greetings and facial expressions. Compared with existing approaches, the present system offers several key advantages:

- A. High Recognition Accuracy – The system gets things most of the time because it does a lot of work to get the data ready like making all the pictures the same color and it uses a lot of different examples to learn from.
- B. Balanced Multimodal Integration – The system is good at combining what it sees from gestures and facial expressions to understand what is going on. This is better than just looking at one thing.
- C. Real-Time Performance – The system can do its job quickly so it is good for things that need to happen in time, like when people are actually using it.

These findings show that learning based systems that use multiple forms of communication can really help the Deaf and Hard-of-Hearing community. Learning based systems can make things more accessible for the Deaf and Hard-of-Hearing community by breaking down communication barriers. The results of this study give us a starting point for more research on deep learning based systems. We can use this information to make learning based systems that can understand more words and handle more complicated conversations. Learning based systems have the potential to really make a difference, for the Deaf and Hard-of-Hearing community.

Conclusion

This study presented the design and implementation of a multimodal recognition system that integrates Filipino Sign Language (FSL) greeting recognition with facial expression recognition (FER). The system was developed in response to the persistent communication barriers experienced by the Deaf and Hard-of-Hearing community, with the aim of bridging gaps between signers and non-signers through deep learning–based approaches. For broader adoption, the system should be optimized for deployment on mobile and edge devices. Although the current implementation demonstrates real-time performance in a controlled environment, scaling it for everyday use requires reducing computational load while maintaining accuracy. Lightweight architectures such as MobileNet, as well as model compression and quantization techniques, could make the system more portable and efficient. This would enable deployment in smartphones, tablets, or assistive devices, significantly increasing its accessibility and impact. Overall, the study has successfully demonstrated the feasibility of a multimodal recognition system that integrates Filipino Sign Language greetings and facial expression recognition. The results validate the effectiveness of deep learning models in recognizing and interpreting multimodal communication, with applications that extend to inclusive education, accessibility technologies, and human–computer interaction. With further refinement, expansion, and user-centered development, the system holds promise as a transformative tool for bridging communication barriers and fostering inclusivity for the Deaf and Hard-of-Hearing community.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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