The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2024

Volume 28, Pages 148-156

ICBASET 2024: International Conference on Basic Sciences, Engineering and Technology

Sustainable Ionic Liquids: A Practical Work about Improving the Mechanical Properties of Bamboo

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Abstract: Ionic liquids have superior properties compared with other solvents because they are environmentally friendly/green agents/renewable and are predicted to have the potential to improve the mechanical properties of bamboo. This study aims to examine the mechanical properties of bamboo with the application of ionic liquids and internal potential planning ESD learning at universities. This study used two kinds of ionic liquids: choline chloride-oxalic acid and choline chloride-$ZnCl_2$. Testing the mechanical properties of bamboo using ASTM D-638 for tensile tests and ASTM D-790 for flexural and compression tests. The results found that the tensile, bending, and compression strengths for bamboo without ionic liquid treatment for each test are 0.0290 kN/mm², 0.1458 MPa, and 0.0587 kN/mm², respectively. For bamboo with a choline chloride-oxalic acid coating, the tensile, bending, and compression strengths are 0.1037 kN/mm², 0.2370 MPa, and 0.0609 kN/mm² respectively. For bamboo with a choline chloride-$ZnCl_2$ coating, the tensile, bending, and compression strengths are 0.0737 kN/mm², 0.3191 MPa, and 0.0736 kN/mm² respectively. To understand the context-specific requirements for ESD integration in education, data was collected using open-ended questions. The results indicated the necessity to integrate ESD into chemistry education further, specifically emphasizing ionic liquids and their potential role in sustainable practices like bamboo processing. The use of ionic liquids in improving mechanical properties for ESD-loaded learning offers new insights into the potential of these compounds in understanding the mechanisms involved in the learning and knowledge process.

Keywords: Ionic liquid, Bamboo, Chemistry

Introduction

Bamboo, a sustainable material, is renowned as the fastest-growing plant globally and abundantly found in Indonesia (Mustafa et al., 2021). Bamboo can exhibit a daily growth rate of 60 cm or more and reach heights of up to 40 m This factor positions bamboo as the fastest-growing plant in the world (Laksono & Agustiningtyas, 2019). Bamboo finds applications in various fields, such as construction materials, textiles, and paper. In construction, bamboo is extensively utilized for its strong fibres, possessing compression strength twice that of concrete, while its tensile strength is nearly equivalent to steel (Yadav & Mathur, 2021). However, bamboo's durability is relatively low, leading to a relatively short lifespan (Mirdayanti & Rahmiza Muzana, 2023). Several factors can influence the mechanical properties of bamboo, including its age, height position, diameter, thickness of bamboo walls, load position (on nodes or internodes), radial position from the outer to inner part,

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

and bamboo moisture content. These mechanical properties are crucial in designing bamboo as a construction material, determining its strength, suitability for specific construction positions, and overall feasibility. Furthermore, the environment where bamboo grows also affects its mechanical properties (Afifah et al., 2023).

According to Afifah et al. (2023), ionic liquids can be utilized to address bamboo's weaknesses. Ionic liquids are salts with a melting point at room temperature and exceptional characteristics, including thermal stability, low viscosity, and negligible vapor pressure (Yokokawa et al., 2019). Based on Neyses et al. (2017), these ionic liquids serve as alternative solvents that can be recycled. They can be employed to preserve and enhance wood's anti-static properties and improve wood's strength by dissolving cellulose. These ionic liquids can act as crosslinking media through activation reactions, extract lignin from cellulose, be used as plasticizers to enhance density on the wood surface, exhibit positive effects as antifungal, antimicrobial, and UV degradation agents, and minimize water absorption in wood (Miyafuji & Fujiwara, 2013). One ionic liquid composed of choline chloride and lactic acid or oxalic acid is reported to be effective in removing lignin and hemicellulose from wood (Wang et al., 2023).

Ionic liquids (ILs) of choline chloride-$ZnCl_2$ and choline chloride-oxalic acid have shown potential in improving the mechanical properties of bamboo through their use as templates or solvents in various processes. These ILs have unique properties, such as low melting points, high boiling points, and good thermal and chemical stabilities, which make them suitable for promoting the preparation of new chemical nanostructures through mild reaction pathways (Preethi et al., 2017).

Additionally, ionic liquids have been found to have potent inhibitory effects on bamboo mildew (Liu et al., 2023). Using ILs as solvents can enhance the mechanical properties of bamboo by modifying its surface, structure, and morphology. For example, the sol-gel synthesis of mesoporous titania using choline chloride-zinc chloride IL as a green solvent has been shown to produce highly ordered titania particles with improved surface area and photocatalytic activity (Preethi et al., 2017). Similarly, using choline chloride-based ionic liquid analogs as solvents and plasticizers in producing agar films has demonstrated improved mechanical properties and water resistance (Sousa et al., 2014).

The potential of Ionic Liquids (ILs) in enhancing the mechanical properties of bamboo lies in their ability to act as green templates, offering advantages such as easy processability, less toxicity, and customizable mesoporous network structures in solids (Preethi et al., 2017). Incorporating ILs into the bamboo matrix makes it possible to create a more uniform and stable structure, which can improve mechanical properties such as tensile strength and elongation. In addition to their use as templates or solvents, ILs can also be employed in the treatment of bamboo, such as starch treatment with deep eutectic solvents, including choline chloride-based ILs, which can improve the surface area and porosity of bamboo (Zdanowicz, 2020).

Sustainable ionic liquid for the mechanical properties of bamboo is one of the approaches to support SDGs by utilizing sustainable materials. Given their progressively diminishing availability, sustainable materials can be regarded as substitutes for natural resources. These materials contribute to attaining Sustainable Development Goals (SDGs) owing to their intrinsic, easily renewable, and sustainable characteristics. They necessitate minimal energy consumption in their utilization and do not generate pollution or other emissions that could impact human health and comfort (Afifah et al., 2023).

However, more research is needed on sustainable ionic liquids as a context for ESD-loaded learning based on SDGs. This study explores the potential of ionic liquid contexts to improve the quality of bamboo's mechanical properties and internal potential planning for ESD learning at universities. By examining these aspects, the study aims to provide insights into the potential of ionic liquids in improving the mechanical properties of bamboo and promoting sustainable development in various fields, including construction, furniture, and packaging. The findings will also contribute to the further integration of ESD into chemistry education, specifically emphasizing ionic liquids and their potential role in sustainable practices like bamboo processing.

Methods

This experiment compares the mechanical properties of bamboo without ionic liquid coating and with ionic liquid coating, as well as determining the potential of sustainable ionic liquids as a context for ESD-Loaded Learning.

Materials

The bamboo used in the experiment is petung bamboo (*Dendrocalamus asper*), which is widely available in Indonesia. This study used two kinds of ionic liquids: choline chloride-oxalic acid and choline chloride-$ZnCl_2$. Testing the mechanical properties of bamboo using ASTM D-638 for tensile tests and ASTM D-790 for flexural and compression tests.

Experimental Procedures

Synthesis of Ionic Liquids

To make choline chloride and oxalic acid Ionic Liquid mixed in a molar ratio of 1:2, add them into a shlenk tube and stir on an electric stove with a magnetic stirrer inside at 80 ºC for 3 hours, as well as to make choline chloride and $ZnCl_2$ Ionic Liquid with a molar ratio of 1:1 at 80 ºC for 3 hours or until homogeneous.

Application of Ionic Liquids on Bamboo

Bamboo that has been formed according to the size for the tensile test (165 x 14 x 4) mm, bending test (125 x 20 x 4) mm, and compression test (10 x 10 x 25) mm is then coated with each type of ILs and allowed to stand for 7 days and aerated for 1 day.

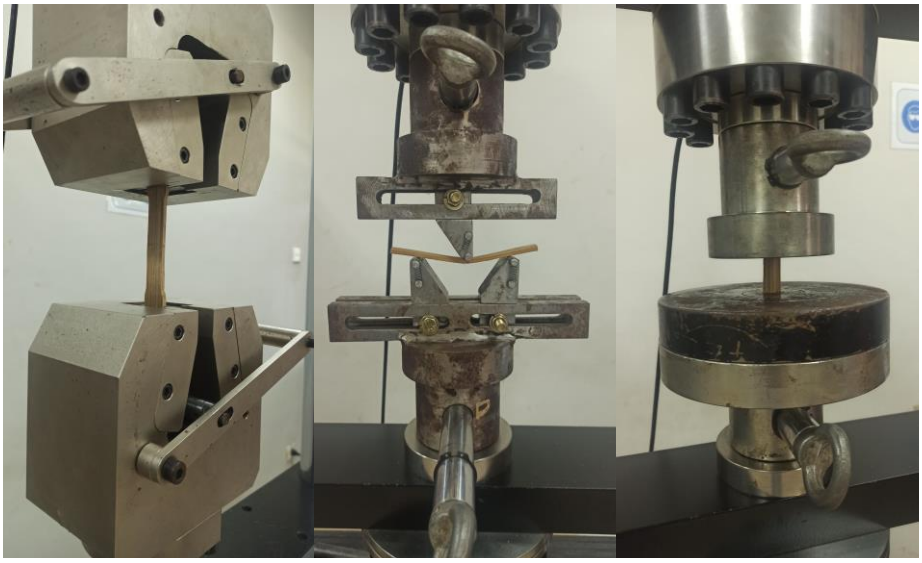
Testing the Mechanical Properties of Bamboo

The mechanical properties of bamboo were tested at the metallurgical laboratory of the University of Education Indonesia. Mechanical tests are carried out in the form of tensile, flexural, and compression tests.

Results and Discussion

Mechanical Properties of Bamboo with Ionic Liquids Coating

Petung bamboo (*Dendrocalamus asper*) is one of Indonesia's most widely available and fast-growing bamboo species (Suriani, 2020). Some of the favourable characteristics of petung bamboo include its wide adaptability, long annual growth period, and fast production speed. Therefore, petung bamboo was chosen as the experimental material for this study. This study used a practical work approach to investigate the improvement of mechanical properties in bamboo. This process involved treating the bamboo with an ionic liquid.



(a) (b) (c)

Figure (1a). Tensile Test; (1b) Flexural Test; and (1c) Compression Test

Ionic liquids of choline chloride-$ZnCl_2$ and choline chloride-oxalic acid are environmentally friendly and sustainable alternatives to conventional solvents used in wood processing (Tran et al., 2016). Choline chloride-$ZnCl_2$ and choline chloride-oxalic acid ionic liquids have gained attention for their potential to improve the mechanical properties of wood, including tensile, flexural, and compression strength. These ionic liquids are formed by mixing choline chloride with zinc chloride ($ZnCl_2$) or oxalic acid, resulting in a Ionic Liquid with unique properties. Based on Bušić et al. (2023), the formation of this ionic liquid is based on the concept of a deep eutectic solvent (DES), which is formed by mixing a hydrogen bond donor (HBD) with a hydrogen bond acceptor (HBA) in a specific molar ratio. Choline chloride acts as the HBA, while $ZnCl_2$ or oxalic acid is the HBD. Testing the mechanical properties of bamboo using ASTM D-638 for tensile tests and ASTM D-790 for flexural and compression tests. The instruments for each test can be seen in Figure 1. The results of the tensile test, bending test, and compression test on untreated bamboo, bamboo with Choline chloride-oxalic acid coating, and Choline chloride-$ZnCl_2$ coating are presented in Tables 1, 2, and 3 below, respectively.

Table 1. The result of tensile test

Sample	Maximum Stress (kN/mm^2)		
	Without Treatment	Choline chloride-Oxalic Acid	Choline chloride-$ZnCl_2$
1	0,0470	0,0930	0,0700
2	0,0240	0,1160	0,0770
3	0,0160	0,1020	0,0740
Mean	0,0290	**0,1037**	0,0737

The maximum stress result for bamboo had the highest average for coating with choline chloride-oxalic acid at 0.1037 kN/mm². This value represents the maximum strength that a bamboo sample can withstand before breaking under tension. Tensile tests measure the ability of a material to resist pulling. Maximum stress is an important property in engineering applications, as it helps determine the suitability of a material for various uses, such as in construction or manufacturing.

Table 2. The result of flexural test

Sample	Stress in the outer fibres at midpoint (σ)		
	Without Treatment	Choline chloride-Oxalic Acid	Choline chloride-$ZnCl_2$
1	0,1440	0,2110	0,2636
2	0,1777	0,2448	0,4573
3	0,1157	0,2551	0,2366
Mean	0,1458	0,2370	**0,3191**

The highest stress result in the outer fibre at the midpoint in the bending test was shown for bamboo with choline chloride-$ZnCl_2$ coating at 0.3191 MPa. This value represents the maximum stress experienced by the outer fibres of the material during the test when subjected to bending force. The bending test is used to determine the ability of the material to resist bending, and the stress in the outer fibre at the midpoint is an important parameter in assessing the strength and stiffness of the material.

Tabel 3. The result of compression test

Sample	Compression Strength (kN/mm^2)		
	Without Treatment	Choline chloride-Oxalic Acid	Choline chloride-$ZnCl_2$
1	0,0609	0,0554	0,0757
2	0,0573	0,0726	0,0660
3	0,0579	0,0548	0,0790
Rata-rata	0,0587	0,0609	**0,0736**

The results of the compression strength are almost the same as the bending test, where the coating with choline chloride-$ZnCl_2$ has a better compression strength than the others. The compression strength obtained in the compression test was 0.0736 kN/mm². This value indicates the maximum force that the material can withstand before collapsing due to compression forces. The compression test measures the ability of the material to resist pressure, and the compression strength is an important parameter in assessing the strength and stability of the material.

Based on the mechanical properties testing outcomes, it has been established that the ILs coating on bamboo achieves superior performance compared to bamboo without coating. This observation aligns with the assertions of He et al. (2019) and Wang et al. (2023), who reported that chemical treatment of bamboo results in the cell walls becoming thinner and adhering to one another, thereby creating a honeycomb structure. This phenomenon can be attributed to the ability of ILs to remove lignin and hemicellulose, thereby softening the bamboo cell walls.

During pretreatment with ionic liquids, the H-bond between OH···Cl in ionic liquids is stronger than the OH···O bond in lignin in bamboo. A large amount of Cl- allows the ionic liquid to cleave the LCC (lignin-carbohydrate complex) in the biomass and some ether bonds in lignin (Li et al., 2023). In acidic ionic liquids such as choline chloride-oxalic acid, protons can catalyse the cleavage of ethers and esters present in the lignin-carbohydrate complex, leading to lignin extraction and depolymerisation (Scelsi et al., 2021). Ionic liquids can also interact with hydroxyl groups in cellulose, leading to swelling of cellulose fibres (Hong et al., 2016). The change in cellulose fibre structure can improve the mechanical properties of bamboo by increasing the bonding between fibres and reducing the likelihood of fibre breakage during stress application.

Higher tensile strength test results were shown for the ionic liquid type of choline chloride-oxalic acid. This is due to the nature of choline chloride-oxalic acid, a Brønsted acid ionic liquid that can be used as a reaction medium for the esterification of carboxylic acids with alcohols. The interaction between choline chloride-oxalic acid ionic liquid and bamboo cell wall components can cause swelling of the cellulose fibres, which can improve the tensile properties of bamboo by increasing the bond between fibres and reducing the likelihood of fibre breakage during stress application (Tran et al., 2016). As the fibres can withstand more stress before being damaged, the resulting tensile strength is higher. In addition, better dimensional stability can result in a more uniform stress distribution during the tensile test, resulting in a more accurate tensile strength measurement of the wood.

In contrast to the tensile strength, the results of the bending test and compression test, coating with choline chloride-$ZnCl_2$ showed higher results. Choline chloride-$ZnCl_2$ is a Lewis acid ionic liquid that can catalyze carbonyl protection at room temperature (Satlewal et al., 2018). Zinc chloride in Ionic Liquids can act as a catalyst to enhance the degradation of hemicellulose and cellulose in bamboo, leading to increased polymerisation of cellulose fibres, resulting in increased strength (Tran et al., 2016). In addition, the low acidity of zinc chloride solution at a specific temperature can decrease the hydroxy content of bamboo, improving dimensional stability and reducing hygroscopicity (Popescu et al., 2014).

Choosing between choline chloride-$ZnCl_2$ and choline chloride-oxalic acid to improve bamboo's mechanical properties depends on the wood product's specific requirements and the desired properties. Choline chloride-$ZnCl_2$ may be more suitable for applications requiring improved dimensional stability and reduced hygroscopicity. In contrast, choline chloride-oxalic acid may be more effective for applications requiring swelling of cellulose fibres to improve inter-fibre bonding.

Sustainable Ionic Liquids as a Context for ESD-Loaded Learning

The superior properties of ionic liquids align with several Sustainable Development Goals (SDGs) (United Nations, 2015). Ionic liquids (ILs) are environmentally sustainable materials that align with several Sustainable Development Goals (SDGs) due to their unique properties and potential applications. Ionic liquids (ILs) exhibit low volatility and high thermal and electrochemical stability, making them suitable for various applications, including energy storage and conversion devices, such as fuel cells, lithium-ion batteries, supercapacitors, and solar cells (Choudhary et al., 2024). They can also be employed in biomass transformations and electrocatalysis, contributing to reducing environmental impact and developing sustainable sensors (Andonegi et al., 2023). Moreover, ILs can produce advanced functional materials, such as electroactive polymer composites and proton exchange membranes, which enhance energy storage and conversion efficiency (Bailey et al., 2023). Additionally, ILs can be engineered to be nontoxic and biodegradable, aligning with the SDG of sustainable chemistry and reducing environmental pollution (Beil et al., 2021). Overall, the use of ILs in various applications can contribute to the achievement of several SDGs, including No Poverty, Quality Education, Industry, Innovation and Infrastructure, Sustainable Cities and Communities, Climate Action, and Life on Land. Therefore, integrating the concept of ionic liquids in Education for Sustainable Development (ESD) can provide valuable insights into sustainable materials development and contribute to the achievement of the aforementioned SDGs.

Based on in-depth responses through open-ended questions, 91% of students aware of ionic liquids stated that they had heard about them in introductory chemistry, organic chemistry, physical chemistry, and inorganic chemistry courses. Students study various chemical concepts and theories in these courses, including ionic liquids. However, more than merely being acquainted with ionic liquids from coursework is required. Students must also have a profound understanding of ionic liquids, including their properties, characteristics, and applications in various fields. Therefore, students must develop the ability to seek information and comprehend chemical concepts thoroughly to apply this knowledge in the future. Furthermore, students mostly agree that Ionic liquids can be an environmentally friendly alternative in various industrial applications; ionic liquids have great potential in sustainable chemistry lecture applications, and learning about ionic liquids is relevant to current environmental issues. The result can be seen in Figure 2.

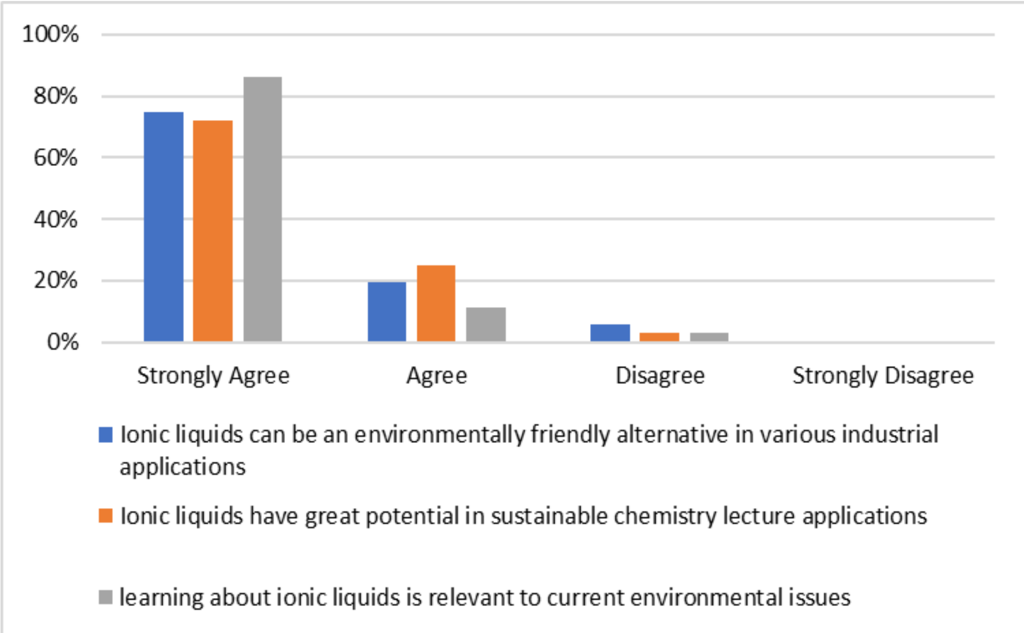


Figure 2. Context of ionic liquids

Ionic liquids (ILs) have gained attention as an environmentally friendly alternative in various industrial applications due to their unique properties and potential in sustainable chemistry (Khoo et al., 2021). As a student, it is essential to understand the significance of ionic liquids in the context of current environmental issues and their relevance to sustainability.

Learning about ionic liquids is relevant to current environmental issues and their potential applications in sustainable chemistry. By exploring green synthesis routes and understanding the environmental impact of these materials, students can contribute to developing more sustainable technologies and practices in various industries.

Chemistry education plays a vital role in promoting sustainable development by integrating sustainability and green chemistry principles into the curriculum. This integration can help students understand the environmental impact of chemical processes and products, encouraging them to develop more sustainable practices. By incorporating sustainability into chemistry education, students can learn how to design and evaluate chemical processes and products in a safe, efficient, and environmentally friendly way. This can help prepare the next generation of chemists to address global challenges such as resource depletion, pollution, and climate change. Moreover, promoting sustainability in chemistry education can contribute to raising awareness of the Sustainable Development Goals (SDGs) outlined by the United Nations (Burmeister & Eilks, 2013; Sjostrom et al., 2015; Wissinger et al., 2021; Zuin et al., 2021).

The use of ionic liquids in improving mechanical properties for ESD-charged learning offers new insights into the potential of these compounds in understanding the mechanisms involved in the learning and knowledge process. This research offers the opportunity to use ionic liquids to observe the mechanisms involved in ESD-charged learning systems, which may assist in developing new methods to optimise learning and knowledge processes. Therefore, incorporating the context of ionic liquids in improving mechanical properties for ESD-charged learning is essential in exploring new possibilities to enhance the learning process.

Conclusion

Choline chloride-$ZnCl_2$ and choline chloride-oxalic acid ionic have the potential to improve the mechanical properties of wood, including tensile, flexural, and compression strength. The results found that the tensile, bending, and compression strengths for bamboo without ionic liquid treatment for each test are 0.0290 kN/mm², 0.1458 MPa, and 0.0587 kN/mm², respectively. For bamboo with a choline chloride-oxalic acid coating, the tensile, bending, and compression strengths are 0.1037 kN/mm², 0.2370 MPa, and 0.0609 kN/mm² respectively. For bamboo with a choline chloride-$ZnCl_2$ coating, the tensile, bending, and compression strengths are 0.0737 kN/mm², 0.3191 MPa, and 0.0736 kN/mm² respectively. The use of ionic liquids in improving mechanical properties for ESD-loaded learning also offers new insights into the potential of these compounds in understanding the mechanisms involved in the learning and knowledge process.

Recommendations

A suggestion that the researcher can make in relation to the findings of this study is for future research to develop integrated ionic liquids and their potential role in sustainable practices such as bamboo processing into chemistry education. Therefore, it is recommended to explore the potential of ionic liquids in various scientific and technological domains, including energy conversion and storage 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.

Acknowledgements

* This article was presented as an oral presentation at the International Conference on Basic Sciences, Engineering and Technology (www.icbaset.net) held in Alanya/Turkey on May 02-05, 2024.

* The researchers would like to sincerely thank the Education Fund Management Institute (LPDP/Indonesia Endowment Fund for Education) under the Ministry of Finance of the Republic of Indonesia for sponsoring their master's degree and supporting this paper and publication. Additionally, the researchers would like to thank the Department of Chemistry Education at the Indonesia University of Education for supporting this paper.

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To cite this article:

Fadhilah, A., Hernani, H., Mudzakir, A., & Lestari, N.A. (2024). Sustainable ionic liquids: A practical work about improving the mechanical properties of bamboo. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 28,* 148-156.