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Optimization on physicomechanical and wear properties of wood waste filled poly(lactic acid) biocomposites using integrated entropy-simple additive weighting approach

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ABSTRACT

The present research work develops an evaluation method based on the hybrid entropy-simple additive weighting approach to select the best biocomposite material based on several potentially conflicting criteria. Poly (lactic acid) (PLA) biocomposites with varying proportions of wood waste (0, 2.5, 5, 7.5, and 10 by weight) was developed and evaluated for physical, mechanical, and sliding wear properties. The biocomposite containing 10 wt.% wood waste exhibited the lowest density (1.183 g/cm^3) and highest modulus properties (tensile modulus = 2.97 GPa; compressive modulus = 3.46 GPa; and flexural modulus = 4.03 GPa). The bare PLA exhibited the highest strength properties (tensile strength = 57.96 MPa; compressive strength = 105.67 MPa; impact strength = 15.25 kJ/m^2), whereas flexural strength (100.43 MPa) was the highest for 5 wt.% wood waste filled biocomposite. The wear of PLA decreased with 2.5 wt.% wood waste incorporated and increased with further addition of wood waste. The experimental results revealed a high compositional dependence with no discernible trend. As a result, prioritizing biocomposites' performance to choose the best from various biocomposite alternatives becomes tough. Therefore, a multi-criteria decision-making process based on a hybrid entropy-simple additive weighting approach was applied to find the optimal biocomposite by taking the experimental results as the selection criterion. The results show that the 2.5 wt.% wood waste added PLA biocomposite proved to be the best solution with optimal physical, mechanical, and wear properties. The validation with other decision-making models supports the robustness of the proposed approach in that the 2.5 wt.% wood waste added PLA biocomposite is the most dominating. This study contributes by providing preferences for the selection criteria and assessing the best alternative from the available PLA biocomposites.

1. Introduction

With the advent of technology, new materials for explicit purposes force researchers to focus on multiple mixtures of materials to protect the environment and overcome current technical difficulties (Mtshatsheni et al., 2019; Sanni et al., 2022; Fekete et al., 2021; Arita et al., 2022; Méité et al., 2022). One uncommon class is polymer biocomposite materials formed by the integration of a biopolymer matrix along with biodegradable filler, bringing about synergistic properties missing in both of the parent materials (Lendvai and Brenn, 2020; Pudełko et al., 2021; Viretto et al., 2021). The development of biocomposites using biodegradable resins with plant fibers and agro/industrial waste materials has received considerable attention due to its prudential and ecological benefits (Animpong et al., 2017; Mariana et al., 2021; Hazrati et al., 2021). In addition, much exploration on the improvement of biocomposites filled with agricultural or wood waste demonstrated that these items could be an effective mechanism for plastic removal and the use of land-filled or burned waste (Hazrati et al., 2021; Shanmugam et al., 2021; Das et al., 2022). Liminana et al. (2018) studied the effect of almond shell flour on the mechanical properties of poly(butylene

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succinate) (PBS) composites. The authors claimed that the tensile modulus increased, while elongation at break and tensile strength of the biocomposites decreased with the inclusion of 30 wt.% almond shell flour. Jittiwat and Namfon (2022) reported the influence of cassava pulp on the mechanical properties of PBS-based biocomposites. The study concluded that the hardness and Young's modulus increase while tensile strength, impact strength and elongation at break of the biocomposites decrease with increasing cassava pulp amount. Wood waste fibers also improved the mechanical and thermal performance of the poly (3-hydroxybutyrate)-based biocomposites (Panaitescu et al., 2020). Moreover, from in-room temperature to 125 °C, a relative increase of 25% to 90% in storage modulus was noticed for 10 wt.% wood waste fiber containing biocomposites. An improvement in tensile modulus from 140 MPa to 284 MPa and tensile strength from 19 MPa to 24 MPa was reported for 20 wt.% date palm fiber waste biomass added polycaprolactone biocomposites (Dhakal et al., 2018). A considerable enhancement in tensile modulus was claimed for wood waste (10, 20, and 30 wt.%) filled poly(lactic acid) (PLA) and polypropylene-based composites, however, at cost of tensile strength and toughness, especially at 20 wt.% wood content and above (Andrzejewski et al., 2019). Alkali treatment was reported to enhance the tensile properties (strength and modulus) of PLA biocomposites (Orue et al., 2020). A relative enhancement of 15% in tensile modulus was reported for biocomposites with treated waste filler compared to unfilled PLA. Moreover, compared to untreated waste-filled biocomposites, the strength value was nearly 40% higher for treated waste-filled biocomposites (Orue et al., 2020). The increased hemp hurd content (without and with glycidyl methacrylate grafting; 10, 20, and 30 wt.%) was reported to decrease the strength (tensile, impact and flexural) properties while tensile and flexural modulus increase with increasing hemp hurd concentration (Khan et al., 2018). Similar improvements in physical, mechanical, thermal, thermo-mechanical properties were reported for various biocomposites using agro-waste as filler material (Hejna et al., 2015; Kumar and Das, 2017; Barczewski et al., 2018; Boubekeur et al., 2020).

The reported researches highlight that each manufactured biocomposite has its performance rating for each characteristic. Hence, there is a demand to choose the biocomposite option with the highest level of satisfaction for each assessed property. This problem can be made possible using multi-criteria decision-making (MCDM) techniques. The MCDM techniques are systematic methods that reasonably decide the significance of the material properties (as a criterion) and recommend the most suitable candidate material (Aklilu et al., 2021; Moyo et al., 2021). Various MCDM methods, namely multiplicative exponent weighting (MEW), technique for order preference by similarity to ideal solution (TOPSIS), simple additive weighting (SAW) method, multiple objective optimizations on the basis of ratio analysis (MOORA), complex proportional assessment (COPRAS), preference selection index (PSI), multi-attributive border approximation area comparison (MABAC), and *vise kriterijumska optimizacija kompromisno resenje* (VIKOR) have been used successfully to solve many engineering and management related decision-making problems (Chauhan et al., 2018; Roozbahani et al., 2020; Singh, 2021a; Sonar and Kulkarni, 2021; Singh, 2021b). Among all, the SAW method is gaining popularity because of its ease of use and simple computational procedure (Kaliszewski and Podkopaev, 2016; Kumar et al., 2019). On the other hand, in many MCDM problems the entropy method is used to determine the importance or weight of the criterion (Kumar et al., 2021). Both the SAW and entropy methods are suitable for any MCDM problem and have been successfully applied in various fields of engineering and management (Fox et al., 2020; Khan et al., 2021).

In this study, wood waste filled PLA biocomposites were developed with a wood content of 0–10 wt.%. Further loading was avoided, since the literature reported an intensive drop in strength and toughness above this level. The prepared biocomposites were evaluated for physicomechanical (density, tensile strength, tensile modulus, compressive strength, compressive modulus, flexural strength, flexural modulus and impact strength) and sliding wear properties determined in a previous work (Singh et al., 2021). It was not easy to select the best biocomposite, as every biocomposite had its own performance for the evaluated property. Therefore, the hybrid entropy-SAW approach is proposed in this study to decide on the best biocomposite with the highest degree of fulfillment for all evaluated properties. The primary goal is to select the best biocomposite with the SAW method, which is strengthened by the entropy method for estimating the criterion weight.

2. Experimental design

2.1. Materials and biocomposite fabrication

The commercial extrusion grade PLA 2003D with a melt flow rate of 6 g/10 min (at 210 °C with a load of 2.16 kg) supplied by Nature Works (Minnetonka, USA) was used in this study as matrix material. This grade is characterized by high molecular weight (M_n = ~100 500 g/mol, M_w = ~183 000 g/mol), a melting temperature of 170 °C and density of 1.24 g/cm^3. Shisham (also known as *Dalbergia sissoo* and North Indian rosewood) wood waste was procured from a local timber store, Himachal Pradesh, India. The collected and microscopic images of the wood waste are presented in Figs. 1a and 1b, respectively. Prior to use, the wood waste particles were alkali-treated (2 wt.% NaOH solution). Biocomposites manufacturing was initiated by drying both the wood waste and PLA for 6 h at 80 °C in a dehumidifier (DEGA-2500, Italy). After that, the melt compounding of the PLA-based biocomposites containing 0, 2.5, 5, 7.5 and 10 wt.% wood waste (designated as PLA0, PLA1, PLA2, PLA3 and PLA4, respectively) was performed. Melt compounding was performed using a twin-screw extruder (LTE 20–44, Thailand) with 30 rpm screw speed and 155–185 °C temperature. After melt compounding, the mixture was granulated and injection molded into dumbbell specimens using an injection molding machine (Arburg Allrounder Advance 420C, Germany) with 40 cm^3/s of injection rate (Singh et al., 2021; Lendvai et al., 2021). The manufactured PLA biocomposites are presented in Fig. 1c.

2.2. Optimization methodology

In this work, the hybrid entropy-SAW methodology is used to select the optimal PLA biocomposite out of the prepared samples. The schematic algorithm of the methodology is depicted in Fig. 2. The proposed methodology contains three main parts:

Part 1: Alternatives, criteria and decision matrix
Part 2: Entropy method for criteria weight calculation
Part 3: SAW method for alternatives final ranking

Part 1: Alternatives, criteria and decision matrix

Here, the formulated biocomposite alternatives and performance criteria are selected and arranged in a decision matrix. For *m* alternatives, and *n* criterions, the decision matrix is constructed as:

$$\delta_{m\times m} = \begin{vmatrix} \delta_{11} & \delta_{12} & .. & \delta_{1n} \\ \delta_{21} & \delta_{22} & .. & \delta_{2n} \\ : & : & .. & : \\ \delta_{i1} & \delta_{i2} & \delta_{ij} & \delta_{in} \\ : & : & .. & : \\ \delta_{m1} & \delta_{m2} & .. & \delta_{mn} \end{vmatrix} \quad Alternatives; \mathrm{i}=1,2...\mathrm{m}; \mathrm{criteria}; \mathrm{j}=1,2...\mathrm{n} \tag{1}$$

Whereδ_{ij} represent results for ith alternative with respect to jth criterion.

Part 2: Entropy method for criteria weight calculation

The formulated decision matrix was evaluated for criterion weight by using the entropy method. Firstly, the projection value (Π_{ij}) was

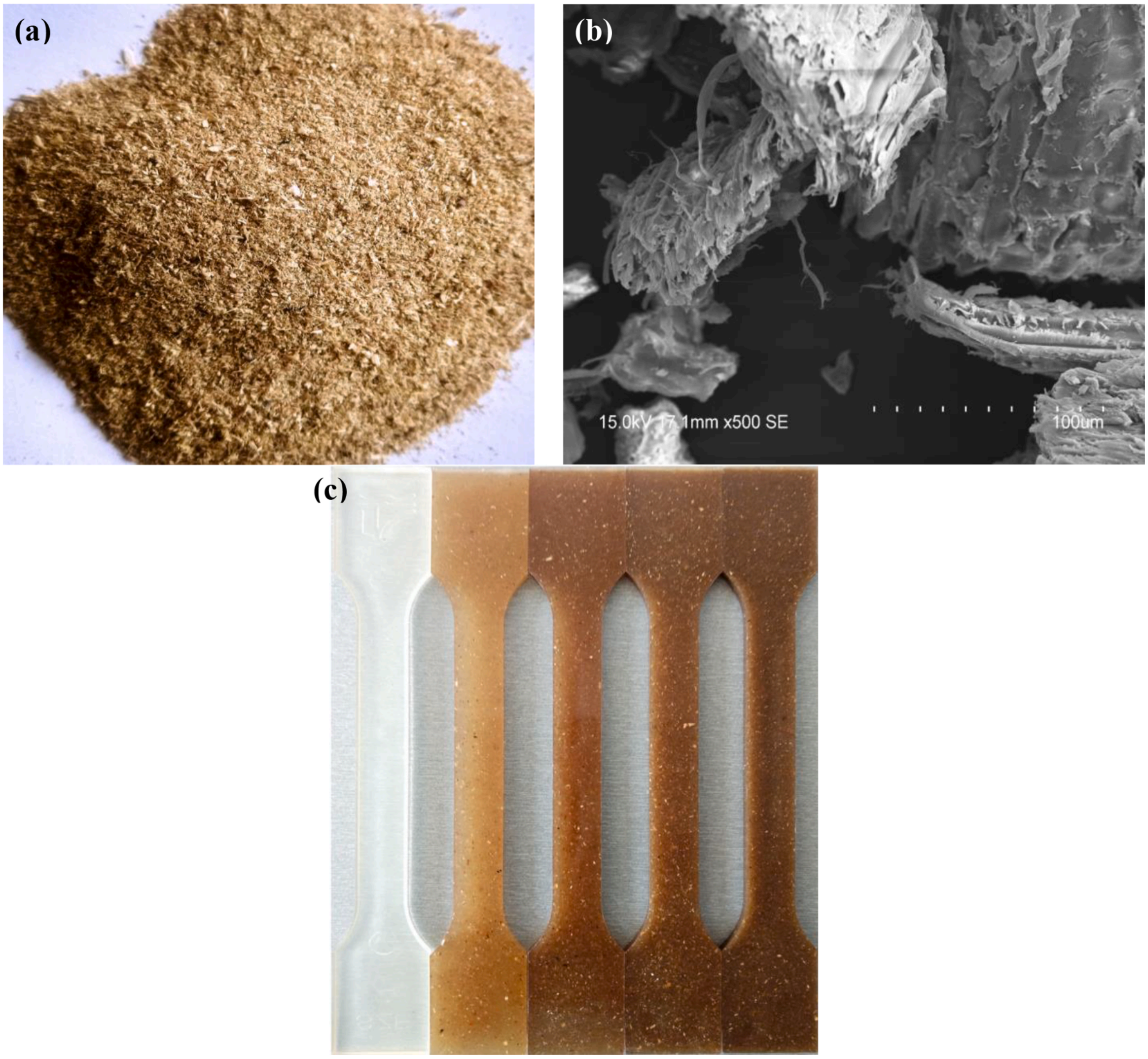

Fig. 1. (a-b) Shisham wood waste and (c) Fabricated biocomposites.

assigned for each alternative using the following equation.

$$\Pi_{ij} = \frac{\delta_{ij}}{\sum_{i=1}^{m} \delta_{ij}} \tag{2}$$

With the help of Π_{ij}, the entropy for each criterion was determined using the following equation.

$$\Sigma_j = -\lambda \sum_{j=1}^{n} \Pi_{ij} \ln\left(\Pi_{ij}\right) \tag{3}$$

The constant λ value was determined as, $\lambda = \frac{1}{\ln(m)}$

In the next step, dispersion value (ϕ_j) was assigned to each criterion using the following equation.

$$\phi_j = 1 - \Sigma_j \tag{4}$$

With the help of the dispersion value, the weight for each criterion was assigned using the following equation.

$$\omega_j = \frac{\phi_j}{\sum_{j=1}^{n} \phi_j} \tag{5}$$

Part 3: SAW optimization for ranking

The ranking of the biocomposites is obtained using the SAW technique. For ranking analysis, the values of the decision matrix were first normalized according to the beneficial (higher-the-better) and non-beneficial (lower-the-better) criterion. The normalization was performed using the following equations.

$\Delta_{ij} = \frac{\delta_{ij}}{\delta_j^{\max}}$, for higher-the-better criterion

$$\Delta_{ij} = \frac{\delta_j^{\min}}{\delta_{ij}}, \text{for lower} - \text{the} - \text{better criterion} \tag{6}$$

Where $\delta_j^{\max}$ and $\delta_j^{\min}$ are the maximum and minimum values of alternatives with corresponding criterion.

After normalization, the weighted normalized decision matrix is formulated using the following equation.

$$\varpi_{ij} = \sum_{j=1}^{n} \Delta_{ij}\omega_j \tag{7}$$

Finally the score index (θ_i) is determined to obtain the ranking order of the biocomposites as:

$$\theta_i = \sum_{j=1}^{n} \varpi_{ij} \tag{8}$$

The biocomposite alternative with highest value of θ_i is ranked first.

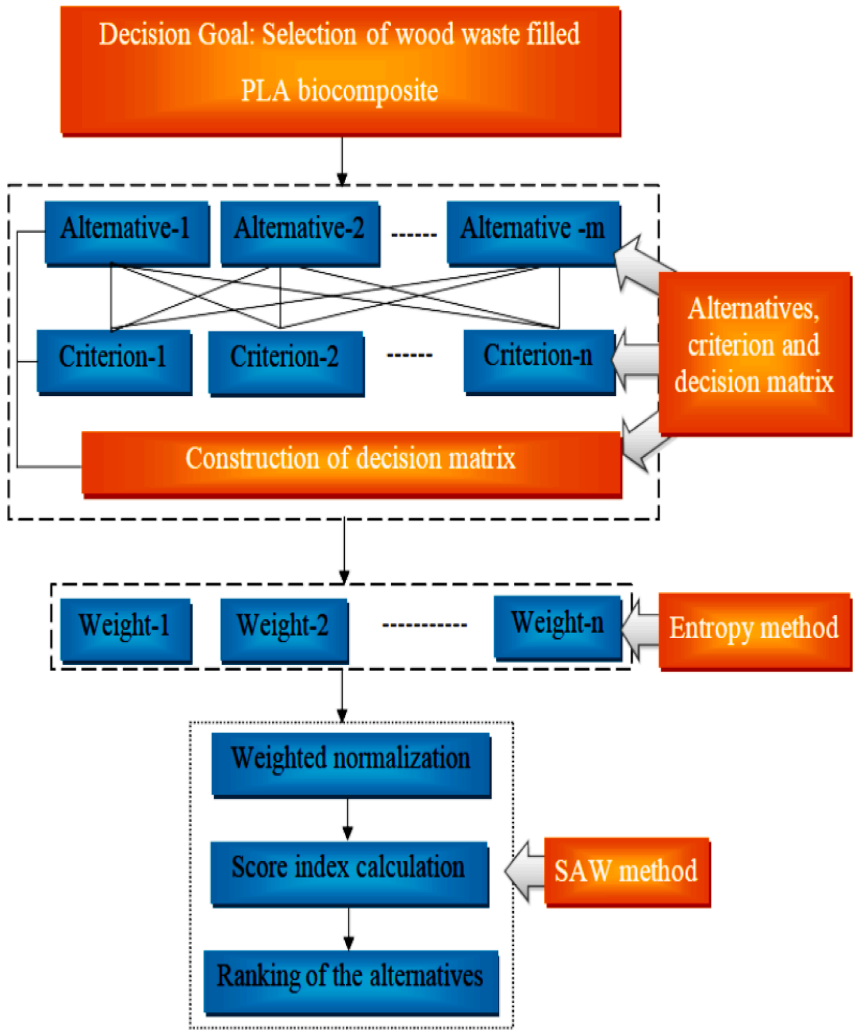

Fig. 2. Schematic algorithm adopted for biocomposite selection.

2.3. Measurements

The developed biocomposites were measured for various properties, including density, tensile strength and modulus, compression strength and modulus, flexural strength and modulus, impact strength, wear and selected as the criteria for ranking analysis as described in Table 1. The data represented in this work are given as mean values along with the corresponding standard deviations. Statistical differences in data were determined using ANOVA method and Tukey's HSD post hoc test. For all analyses, a significance level of $a < 0.05$ was applied.

3. Results and discussion

3.1. Criterion results

The results of manufactured PLA biocomposites with respect to the nine selected criteria described in Section 2.3 are listed in Table 2. The effects of wood waste loading on C1 (tensile strength) and C2 (tensile modulus) of the developed PLA biocomposites is illustrated in Fig. 3a. As the wood waste loading increased, a gradual decrease in the tensile strength of the biocomposites was observed, however, the decrement above 5 wt.% wood content was not significant according to the statistical analysis.

Mean ± standard deviation, different letters in the superscripts ([a, b, c, d, e]) indicate significant ($p > 0.05$) difference between the samples according to Tukey's HSD test.

For PLA0 (pure PLA), the tensile strength value was 57.96 MPa, which was the highest among the samples. The tensile strength of the PLA biocomposites decreased gradually with increased wood waste concentration and fluctuated between 50.9 to 53 MPa. The PLA4 biocomposite exhibited the lowest tensile strength of 50.90 MPa, almost 12% lower than pure PLA. Similar results, namely reduced tensile strength with increased natural fiber are well-described in the literature (Andrzejewski et al., 2019; Boubekeur et al., 2020). It was reported that the addition of wood waste particles weakens the interfacial adhesion of the PLA matrix with the wood particles (further confirmed in Fig. 5). The low interfacial adhesion between wood filler and the PLA matrix promotes microcrack formation in the interfacial region and thereby decreases the tensile strength (Das et al., 2022). Contrary to tensile strength, the tensile modulus (Fig. 3a) of the PLA biocomposites was significantly increased with an increase in wood waste loading, which is also supported by the Tukey's HSD post hoc test. The tensile modulus was the lowest for PLA0 (2.56 GPa), whereas a relative enhancement of 16% in tensile modulus (2.97 GPa) was recorded for the biocomposite having 10 wt.% wood waste content (PLA4). This increase in tensile modulus may be ascribed to the high stiffness of the wood waste filler compared to the PLA matrix. Moreover, it was reported in the literature that tensile strength is generally more sensitive to interfacial interaction than the tensile modulus (Chen et al., 2015). The increasing tensile modulus trends were in good agreement with the findings of various studies (Boubekeur et al., 2020). The high filler loading results in more rigid biocomposites since the lignocellulosic fillers are stiffer than the

Table 1
Selected criteria, their implication and description.

Criterion and its implication	Testing description
C1: Tensile strength (MPa) Higher-the-better C2: Tensile modulus (GPa) Higher-the-better	The tensile (strength and modulus) properties were determined using a universal testing machine (Instron 5582, USA) according to EN ISO 527 standard with 100 mm clamping distance and 5 mm/min crosshead speed using dumbbell specimens with a cross-section of 4 × 10 mm. The test was repeated 5 times under identical conditions.
C3: Flexural strength (MPa) Higher-the-better C4: Flexural modulus (GPa) Higher-the-better	The flexural (strength and modulus) properties were determined using a universal testing machine (Instron 5582, USA) according to EN ISO 178 standard with 5 mm/min crosshead speed using prismatic specimens with a cross-section of 4 × 10 mm. The test was repeated 5 times under identical conditions.
C5: Compressive strength (MPa) Higher-the-better C6: Compressive modulus (GPa) Higher-the-better	The compression (strength and modulus) properties were determined using a universal testing machine (Instron 5582, USA) according to EN ISO 604 standard with 5 mm/min crosshead speed using prismatic specimens with a cross-section of 4 × 10 mm. The test was repeated 5 times under identical conditions.
C7: Impact strength (kJ/m^2) Higher-the-better	The impact strength of the unnotched specimens using impact testing machine (Ceast 6545, Italy) according to EN ISO 179 standard. The test was repeated 5 times under identical conditions.
C8: Density (g/cm^3) Lower-the-better	Standard water displacement method was used for density measurements.
C9: Wear (g) Lower-the-better	Wear was measured on a pin-on-disc machine (TR-411, DUCOM, India) using ASTM G-99 standard. Track diameter (50 mm), load (50 N), sliding velocity (3 m/s) and sliding distance (2.5 km) were fixed. The test was repeated 3 times under identical conditions.

polymer matrix, thus providing stiffness to the biocomposites (Chen et al., 2015; Boubekeur et al., 2020).

The influence of wood waste loading on C3 (flexural strength) and C4 (flexural modulus) parameters is presented in Fig. 3b. The results show that wood waste does not alter the flexural strength; there is no significant difference between any of the prepared samples. On the other hand, it obviously improves the flexural modulus of the PLA. For the manufactured biocomposites, the flexural strength fluctuates in the range of 99–101 MPa. The highest (100.43 MPa) and lowest (99.01 MPa) flexural strength were recorded for 7.5 wt.% and 10 wt.% wood waste containing, i.e. PLA3/PLA4 biocomposites. Compared to pure PLA (PLA0), the flexural strength was improved from 99.53 MPa to 100.43 MPa at 5 wt.% wood concentration. These results agree with the finding of a previous research where the addition of lignocellulosic fillers did not improve the flexural strength of polymer biocomposites (Das et al., 2016). With this slight increase in flexural strength, the same amount of wood waste causes a significant increase in the flexural modulus, namely a 17% relative enhancement in flexural modulus was observed for PLA4 biocomposites compared to PLA0. The literature reported similar results for increased flexural modulus with decreased flexural strength (Chen et al., 2015). It was also reported that the flexural modulus results were more dependent on experimental conditions such as support span and environmental conditions (Chen et al., 2015). The increased flexural modulus was ascribed to the efficient stress transfer between the PLA matrix and the wood waste particles. The observed ascending trend of flexural modulus with increased filler loading agrees with the literature (Chen et al., 2015; Das et al., 2016).

Fig. 4a depicts the effect of wood waste loading on C5 (compressive strength) and C6 (compressive modulus) results of PLA biocomposites. The compressive strength of PLA decreased while the compressive modulus increased with wood waste content. The highest compressive strength of 105.67 MPa was recorded for PLA0, whereas it reduced by ~4–6% and fluctuated between 99.44 MPa to 100.86 MPa for wood waste-filled biocomposites. Apparently, there was no significant difference between the compressive strength of wood waste containing samples, regardless of the filler content according to the statistical analysis. This slight decrease in compressive strength with the inclusion of wood

Table 2
Experimental data of the alternatives.

Alter-natives	C1	C2	C3	C4	C5	C6	C7	C8	C9
PLA0	57.96 ± 0.27^{a}	2.56 ± 0.04^{a}	99.53 ± 0.21^{a}	3.43 ± 0.02^{a}	105.67 ± 1.06^{a}	2.71 ± 0.11^{a}	15.25 ± 1.66^{a}	1.240 ± 0.032	0.1652 ± 0.004^{a}
PLA1	53.01 ± 0.62^{b}	2.66 ± 0.04^{b}	100.20 ± 0.67^{a}	3.51 ± 0.01^{b}	99.44 ± 2.42^{b}	2.94 ± 0.06^{a}	$12.31 \pm 2.25^{a,b}$	1.225 ± 0.030	0.1176 ± 0.003^{b}
PLA2	$51.87 \pm 0.54^{b,c}$	2.78 ± 0.04^{c}	100.43 ± 0.59^{a}	3.74 ± 0.03^{c}	100.86 ± 2.44^{b}	3.36 ± 0.09^{b}	10.44 ± 0.52^{b}	1.211 ± 0.022	0.1646 ± 0.005^{a}
PLA3	$51.52 \pm 1.31^{b,c}$	2.94 ± 0.04^{d}	99.96 ± 1.08^{a}	3.90 ± 0.04^{d}	100.68 ± 1.72^{b}	3.43 ± 0.08^{b}	9.38 ± 1.79^{b}	1.198 ± 0.020	0.2017 ± 0.005^{c}
PLA4	50.90 ± 0.41^{c}	2.97 ± 0.04^{d}	99.01 ± 0.66^{a}	4.03 ± 0.02^{e}	99.98 ± 2.07^{b}	3.46 ± 0.27^{b}	9.63 ± 1.80^{b}	1.183 ± 0.028	0.2618 ± 0.006^{d}

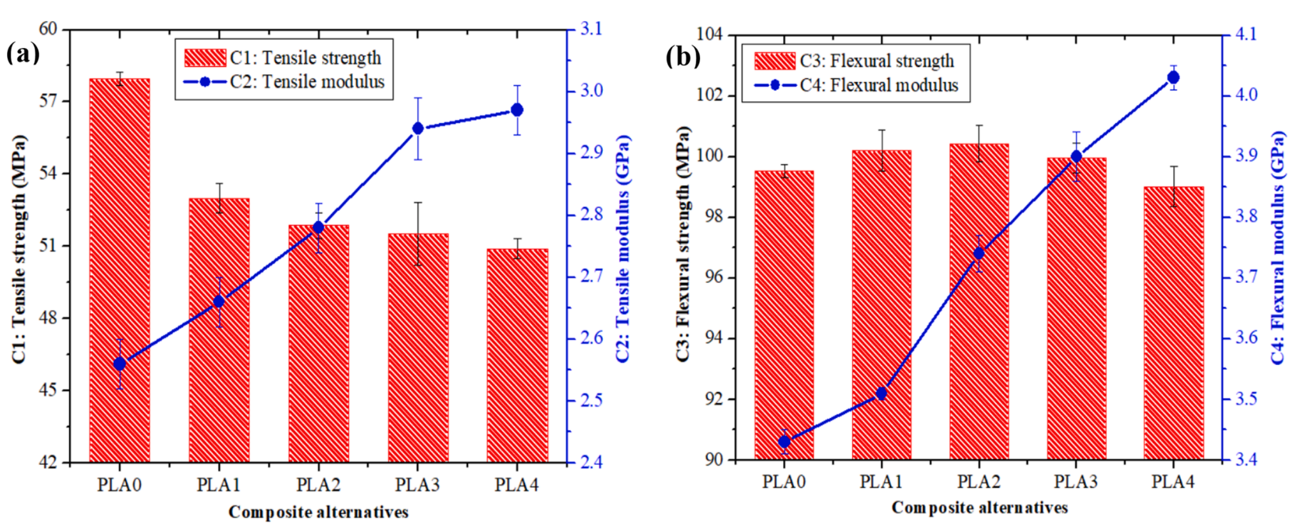

Fig. 3. Variation of (a) C1: tensile strength; C2: tensile modulus and (b) C3: flexural strength; C4: flexural modulus.

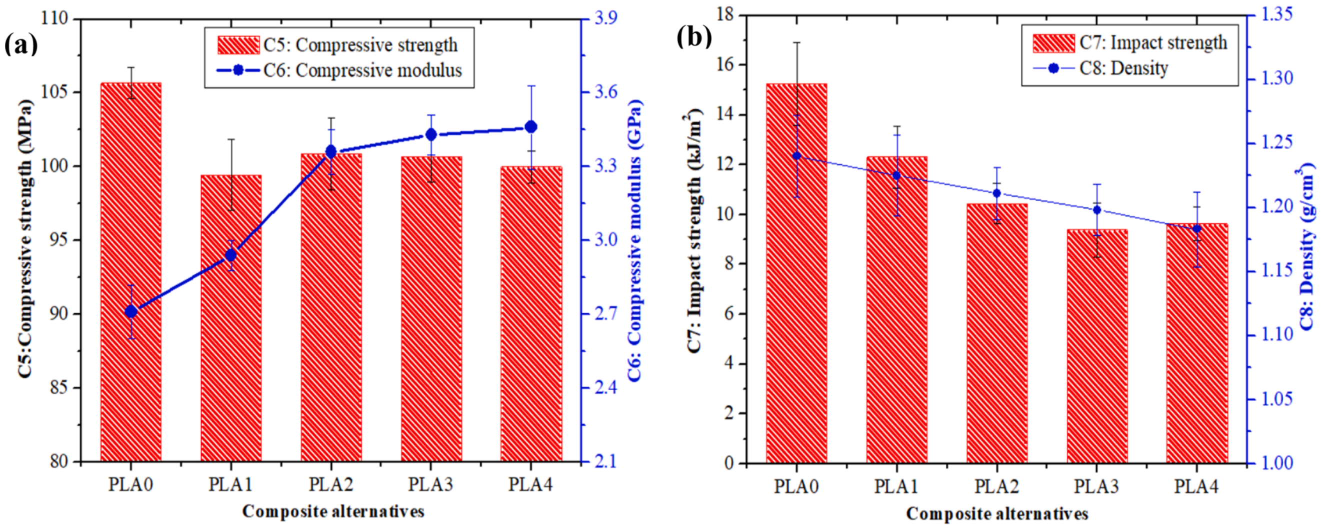

Fig. 4. Variation of (a) C5: compressive strength; C6: compressive modulus and (b) C7: impact strength; C8: density.

waste particles was ascribed to the decreased interfacial adhesion of the wood particles and the PLA matrix (Andrzejewski et al., 2019; Das et al., 2022). The compressive modulus of PLA0 sample was lowest (2.71 GPa) and increased relatively by ~28% at 10 wt.% wood waste content (PLA4) composite, which was the highest (3.46 GPa). This enhancement in compressive modulus was ascribed to the higher stiffness of the wood waste particles compared to the PLA matrix.

Fig. 4b depicts the effect of wood waste loading on PLA biocomposites' C7 (impact strength). The impact strength was found to be the highest (15.25 kJ/m^2) for PLA0 sample and it gradually decreased with the increasing wood waste amount and it was the smallest (9.38 kJ/m^2) for 7.5 wt.% wood waste containing (i.e. PLA3) biocomposite. A relative decrease of 38% reduction of impact strength for PLA3/PLA4 biocomposites (≥7.5 wt.% wood waste) was observed in comparison to

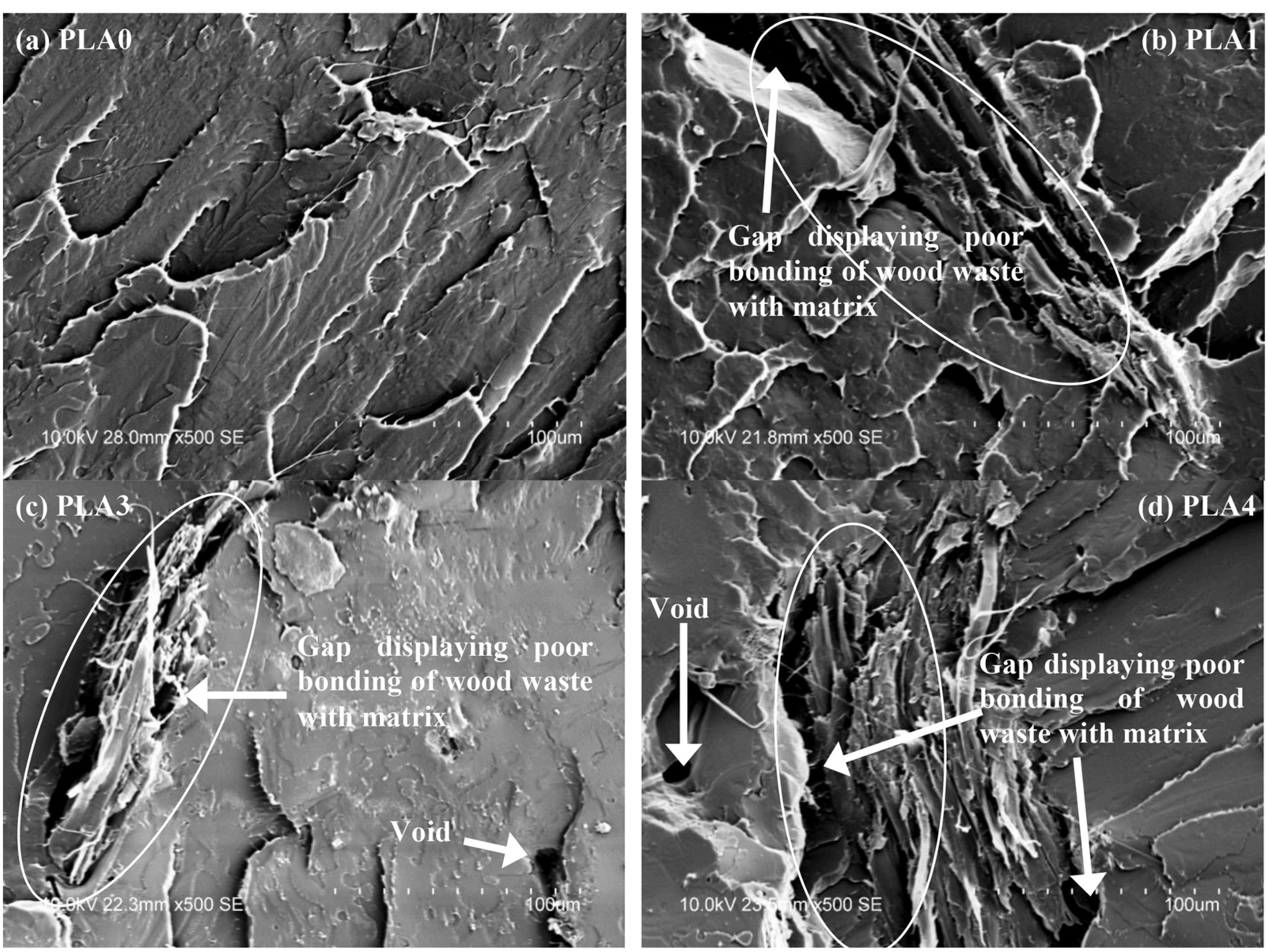

Fig. 5. Fracture surface morphology of PLA biocomposites.

bare PLA (PLA0). It has to be noted, however, that there was no significant difference in the impact strength of all the wood waste containing samples according to the Tukey's HSD test. Similar results, i.e. reduction in impact strength with natural fiber/particles were reported in the literature (Khan et al., 2018; Andrzejewski et al., 2019). The authors claimed that the added wood waste particles decreased the bonding capability of the PLA matrix. The reduced interfacial adhesion results in the formation of voids. The voids quickly propagate in the form of cracks and result in the reduction of impact strength (Barczewski et al., 2018; Das et al., 2022). The fractured surfaces of the samples were investigated to determine the possible failure mechanism and this is depicted in Fig. 5. The fractured surface of PLA0 (Fig. 5a) appears to be clean and smooth, with no voids or pores being present. Conversely, different topographical aspects were found for the wood waste added PLA biocomposites (Fig. 5b-d).

The topology of the PLA-based biocomposites appeared to have some voids/pores. Besides, a gap appeared in the interface region of the PLA matrix and the added filler. The fracture surfaces exhibit voids/pores and gaps between the interface of the PLA matrix and added wood waste particles, which is assumed to be the main culprit for strength deterioration. Similar reports for decreased mechanical strength with increased wood waste in PLA biocomposites were reported. It was reported that the inclusion of wood waste resulted in a gap formed between reinforcement and the PLA matrix. This gap characterizing the poor adhesion between wood waste and the PLA matrix resulted in a decrement in strength properties (Khan et al., 2018; Andrzejewski et al., 2019).

Fig. 4b depicts the effect of wood waste loading on the C8 (density) of the biocomposites. The density of PLA was found to decrease with increasing wood waste content and remained in the range of 1.183–1.240 g/cm^3. This decrease in density can be related to the wood waste particles being lighter than the PLA resin (Singh et al., 2021). Fig. 6 depicts the effect of wood waste loading on the C9 (wear) of the biocomposites.

For PLA0, the wear was 0.1652 g. By adding 2.5 wt.% wood waste the wear decreased relatively by ~29% and remained lowest for PLA1 biocomposite. It is assumed, that the uniform distribution of the wood waste particles with low loading (~2.5 wt.%) in the PLA matrix may have improved wear resistance. The uniform dispersion protected the matrix from failure and resulted in lower wear as found experimentally. With further addition of wood waste ≥5 wt.%, the wear increases by 40% for PLA2, by 72% for PLA3 and by 122% for PLA4 biocomposites. The highest wear of 0.2618 g was recorded for 10 wt.% wood waste containing, i.e. PLA4 biocomposites. With increased wood waste loading, the number of wood waste particles on the biocomposite

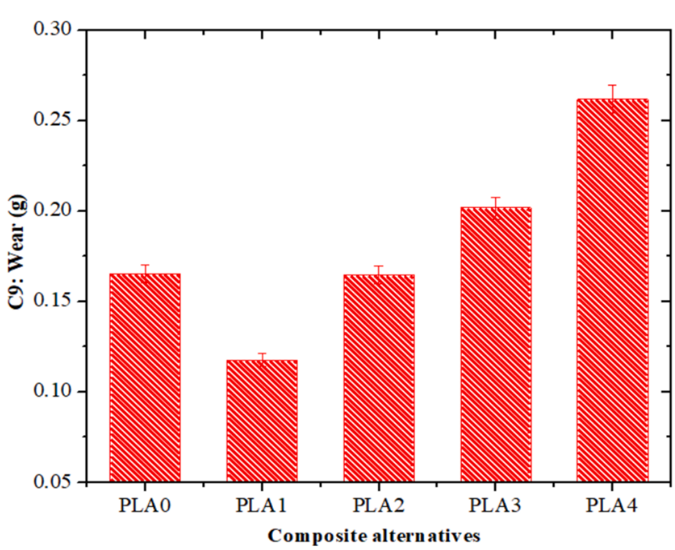

Fig. 6. Variation of C9: wear of PLA biocomposites.

surface increased. As the normal load increases, more heat is generated, resulting in the enhancement of contact temperature. With this increased temperature, the bonding of wood waste and the matrix weakens; material removal becomes easier and wear increases as a consequence (Bajpai et al., 2013).

The biocomposite alternatives can be arranged in a performance order with respect to each criterion recognized in the Section 2.2 as:

C1: PLA0 > PLA1 > PLA2 > PLA3 > PLA4
C2: PLA4 > PLA3 > PLA2 > PLA1 > PLA0
C3: PLA2 > PLA1 > PLA3 > PLA0 > PLA4
C4: PLA4 > PLA3 > PLA2 > PLA1 > PLA0
C5: PLA0 > PLA2 > PLA3 > PLA4 > PLA1
C6: PLA4 > PLA3 > PLA2 > PLA1 > PLA0
C7: PLA0 > PLA1 > PLA2 > PLA4 > PLA3
C8: PLA4 > PLA3 > PLA2 > PLA1 > PLA0
C9: PLA1 > PLA2 > PLA0 > PLA3 > PLA4

The results demonstrate that none of the evaluated composite alternatives attains the selected criteria' highest performance. More specifically, the bare PLA alternative, i.e., PLA0, presented the most significant value of tensile strength (57.96 MPa), compressive strength (105.67 MPa) and impact strength (15.25 kJ/m^2), but it exhibits the lowest performance for tensile modulus (2.56 GPa), flexural modulus (3.43 GPa) and compression modulus (2.71 GPa). The biocomposite PLA1 displays the highest wear resistance (0.1176 g), but compressive strength (99.44 MPa) remains the lowest. The biocomposite PLA4 shows the most considerable value for tensile modulus (2.97 GPa), flexural modulus (4.03 GPa), and compression modulus (3.46 GPa) with the lowest density (1.183 g/cm^3). However, the tensile strength (50.90 MPa), flexural strength (99.01 MPa), and wear resistance (0.2618 g) of PLA4 is the lowest. Moreover, the biocomposite PLA2 shows the highest flexural strength (100.43 MPa), and second-highest wear resistance (0.1646 g) and compressive strength (100.86 MPa). By considering all the criteria simultaneously, evidently no biocomposite exhibits the overall highest performance. Therefore, to pick the best biocomposite alternative by considering all criteria simultaneously, a hybrid entropy-SAW methodology is used.

3.2. Ranking analysis

For selecting the optimal biocomposite, the results obtained from the various characterizations have been optimized using the entropy-SAW approach. First of all, criterion weight was computed using the entropy method. For this, the experimental values of biocomposite alternatives concerning the selected criteria were arranged in the form of a decision matrix. Each entity in the decision matrix $\delta_{m\times n}$ (Eq. (1)) is signified by elementδ_{ij} (*for* $i = 1, 2, 3....5$; $j = 1, 2, 3....9$). The simplified decision matrix is given as:

$$\delta_{5\times 9} = \begin{bmatrix} 57.96(\delta_{11}) & 2.56(\delta_{12}) & .. & 0.1652(\delta_{19}) \\ 53.00(\delta_{21}) & 2.66(\delta_{22}) & .. & 0.1176(\delta_{29}) \\ 51.87(\delta_{31}) & 2.78(\delta_{32}) & .. & 0.1646(\delta_{39}) \\ 51.52(\delta_{41}) & 2.94(\delta_{42}) & .. & 0.2017(\delta_{49}) \\ 50.90(\delta_{51}) & 2.97(\delta_{52}) & .. & 0.2618(\delta_{59}) \end{bmatrix} \quad (9)$$

Firstly, the projection values were determined using Eq. (2) and listed in Table 3. Thereafter, the entropy, dispersion value and weight for each criterion were determined using Eqs. (3)-5, and presented in Table 4. The entropy values are determined as:

$$\Sigma_{C-1} = (-0.621) \times (-1.6083) = 0.9988$$
$$\Sigma_{C-2} = (-0.621) \times (-1.6079) = 0.9985$$
$$\vdots$$
$$\Sigma_{C-9} = (-0.621) \times (-1.5752) = 0.9782$$

Table 3
Projection values of each alternative.

Alternatives	Projection Value, Π_{ij}								
	C1	C2	C3	C4	C5	C6	C7	C8	C9
PLA0	0.2185	0.1840	0.1994	0.1843	0.2086	0.1704	0.2675	0.2047	0.1814
PLA1	0.1998	0.1912	0.2007	0.1886	0.1963	0.1849	0.2159	0.2022	0.1291
PLA2	0.1956	0.1999	0.2012	0.2010	0.1991	0.2113	0.1832	0.1999	0.1807
PLA3	0.1942	0.2114	0.2003	0.2096	0.1987	0.2158	0.1645	0.1978	0.2214
PLA4	0.1919	0.2135	0.1984	0.2165	0.1973	0.2176	0.1689	0.1954	0.2874

Table 4
Dispersion values, entropy and criterion weight.

Alternatives	$\Pi_{ij}\ln(\Pi_{ij})$, $\lambda = \frac{1}{\ln(5)} = 0.621$								
	C1	C2	C3	C4	C5	C6	C7	C8	C9
PLA0	-0.3323	-0.3115	-0.3215	-0.3117	-0.3269	-0.3016	-0.3527	-0.3247	-0.3096
PLA1	-0.3218	-0.3164	-0.3223	-0.3146	-0.3196	-0.3121	-0.3310	-0.3232	-0.2643
PLA2	-0.3191	-0.3218	-0.3226	-0.3225	-0.3213	-0.3285	-0.3109	-0.3218	-0.3092
PLA3	-0.3183	-0.3285	-0.3221	-0.3275	-0.3211	-0.3309	-0.2969	-0.3205	-0.3338
PLA4	-0.3168	-0.3297	-0.3209	-0.3313	-0.3203	-0.3319	-0.3004	-0.3190	-0.3583
$\sum \Pi_{ij}\ln(\Pi_{ij})$	-1.6083	-1.6079	-1.6094	-1.6076	-1.6092	-1.605	-1.5919	-1.6092	-1.5752
Σ_j	0.9988	0.9985	0.9995	0.9983	0.9993	0.9966	0.9886	0.9994	0.9782
ϕ_j	0.0012	0.0015	0.0005	0.0017	0.0007	0.0034	0.0114	0.0006	0.0218
ω_j	0.0280	0.0350	0.0117	0.0397	0.0164	0.0794	0.2664	0.0140	0.5094

The dispersion values are determined after entropy and used for weight calculation. The summation of dispersion values is calculated first as,

$$\sum_{j=1}^{9} \phi_j = 0.0012 + 0.0015 + 0.0005 + 0.0017 + 0.0007 + 0.0034 + 0.0114 + 0.0006 + 0.0218 = 0.0428$$

Finally the weight for each criterion was computed using Eq. (5) as,

$$\omega_{C-1} = \frac{0.0012}{0.0428} = 0.028$$
$$\omega_{C-2} = \frac{0.0015}{0.0428} = 0.035$$
$$\vdots$$
$$\omega_{C-9} = \frac{0.0218}{0.0428} = 0.5094$$

The order of criterion weight used in the ranking of PLA-wood waste biocomposites was obtained as C9 (0.5094) > C7 (0.2664) > C6 (0.0794) > C4 (0.0397) > C2 (0.035) > C1 (0.028) > C5 (0.0164) > C8 (0.014) > C3 (0.0117).

After finding the weight for the selected criterion, a ranking was determined using SAW technique. The decision matrix was first normalized using Eq. (6) and is presented in Table 5. As criterion weights have great significance in the SAW technique, a weighted normalized decision matrix was constructed using Eq. (7) and presented in Table 6. The final ranking was done on the basis of score index (θ_i) the value of which was determined for each biocomposite alternative using Eq. (8) as,

$$\theta_{PLA0} = 0.028 + 0.0302 + 0.0116 + .. + 0.0622 + .. + 0.3626 = 0.8246$$
$$\theta_{PLA1} = 0.0256 + 0.0313 + 0.0117 + .. + 0.0675 + .. + 0.5094 = 0.9240$$
$$\vdots$$
$$\theta_{PLA5} = 0.0246 + 0.0350 + 0.0115 + .. + 0.0794 + .. + 0.2288 = 0.6167$$

The score index values and corresponding ranking of the biocomposite alternatives are calculated and presented in Fig. 7. The biocomposite alternatives with the highest value of the SAW score index have been ranked on top and vice versa. The set of biocomposite alternatives order on the basis of SAW score index is: PLA1 > PLA0 > PLA2 > PLA3 > PLA4. It has been observed that biocomposite alternative PLA1 with 2.5 wt.% wood waste has the highest value of the SAW score index (0.9240); therefore, it is the most feasible biocomposite alternative of all. On the other hand, the SAW score index remains lowest for PLA4 (0.6167), having 10 wt.% wood waste content.

3.3. Validation using other MCDM approaches

Furthermore, the ranking results of the proposed entropy-SAW methodology were compared to those of other common MCDM methodologies to strengthen and validate its applicability. The ranking results obtained by the entropy-SAW approach were compared with VIKOR (Chauhan et al., 2018), MEW (Singh, 2021a), COPRAS (Roozbahani et al., 2020), MABAC (Sonar and Kulkarni, 2021), MOORA (Singh, 2021b), PSI (Chauhan et al., 2018) and TOPSIS (Singh, 2021c) approaches. Fig. 8 compares the ranks based on the MCDM methodologies discussed above. No change in the ranks of the biocomposite alternatives observed by any of the MCDM approaches (Fig. 8) demonstrates that the biocomposite alternative PLA1 outperformed all the other ones, as it ranks first across all methods. In contrast, the biocomposite alternative PLA4 is the worst, ranking last according to all the

Table 5
Normalized decision matrix.

Alternative	C1	C2	C3	C4	C5	C6	C7	C8	C9
PLA0	1.0000	0.8620	0.9910	0.8511	1.0000	0.7832	1.0000	0.9540	0.7119
PLA1	0.9144	0.8956	0.9977	0.8710	0.9410	0.8497	0.8072	0.9657	1.0000
PLA2	0.8949	0.9360	1.0000	0.9280	0.9545	0.9711	0.6846	0.9769	0.7145
PLA3	0.8889	0.9899	0.9953	0.9677	0.9528	0.9913	0.6151	0.9875	0.5830
PLA4	0.8782	1.0000	0.9859	1.0000	0.9462	1.0000	0.6315	1.0000	0.4492

Table 6
Weighted normalized decision matrix.

Alternative	C1	C2	C3	C4	C5	C6	C7	C8	C9
PLA0	0.0280	0.0302	0.0116	0.0338	0.0164	0.0622	0.2664	0.0134	0.3626
PLA1	0.0256	0.0313	0.0117	0.0346	0.0154	0.0675	0.2150	0.0135	0.5094
PLA2	0.0251	0.0328	0.0117	0.0368	0.0157	0.0771	0.1824	0.0137	0.3639
PLA3	0.0249	0.0346	0.0116	0.0384	0.0156	0.0787	0.1639	0.0138	0.2970
PLA4	0.0246	0.0350	0.0115	0.0397	0.0155	0.0794	0.1682	0.0140	0.2288

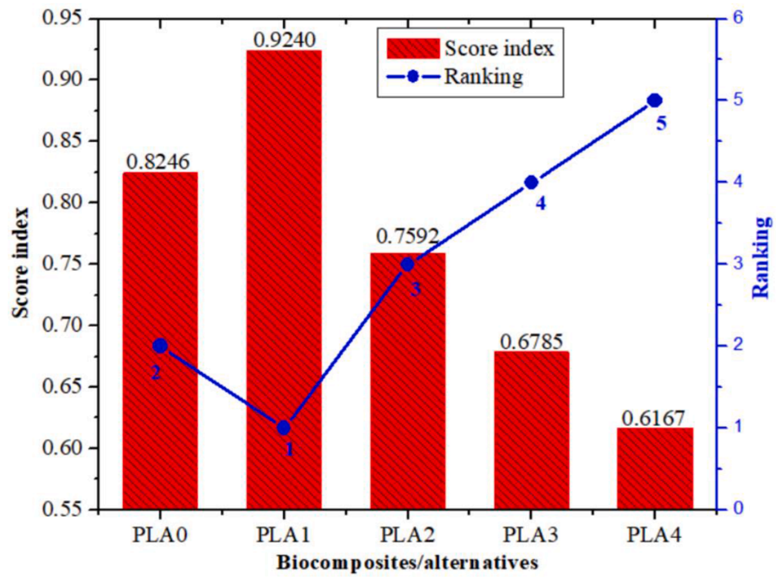

Fig. 7. Score index and ranking of the biocomposite alternatives.

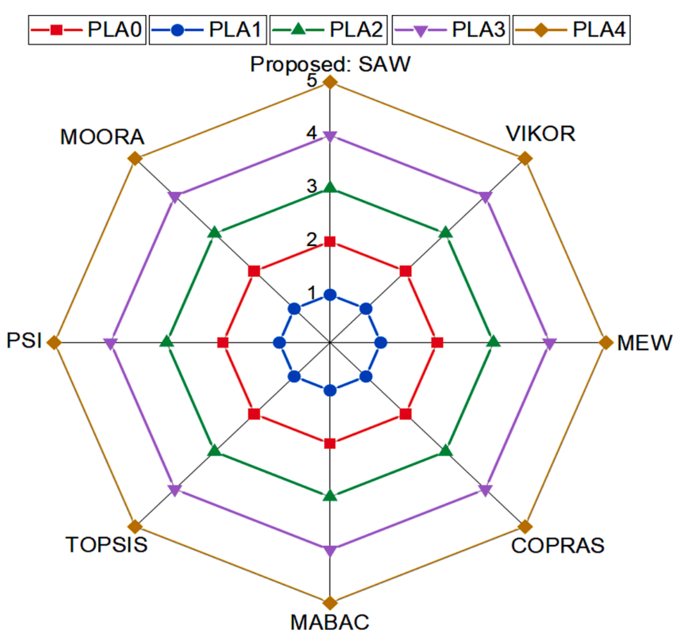

Fig. 8. Alternatives ranking using various MCDM approaches.

methods. As a result, we can conclude that the proposed ranking is valid and reliable.

4. Conclusions

Poly(lactic acid)-based biocomposites filled with wood waste (0, 2.5, 5, 7.5, and 10% by weight) were prepared by extrusion and injection molding. The prepared samples' physical, mechanical and sliding wear properties were determined experimentally. The results showed that there is a considerable compositional dependence in the various properties, however, with no obvious trends. The strength values and the toughness of the PLA-based samples deteriorated when wood waste was incorporated, while the stiffness of the composites improved in the same time. The wear of the biocomposite first reduced with the inclusion of 2.5 wt.% wood waste and increased after that. Considering all these variations in the properties it was found rather difficult to prioritize the biocomposites based on their performance and choose the best from the alternatives. Therefore, a multi-criteria decision-making approach including entropy and simple additive weighting was introduced to rank the prepared samples. The evaluation results show that the biocomposite containing 2.5 wt.% wood waste exhibits the best combination of the evaluated properties. The optimal solution was validated with other decision-making approaches, and the results of the proposed entropy-simple additive weighting approach proved reliable. The study shows that the simple additive weighting technique strengthened by the entropy method is a robust tool in biocomposite design, which is expected to be helpful without extensive laboratory experiments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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