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Optimization of Bio-based Polymer Composites Using Grey Relational Analysis (GRA) Method

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Abstract *Bio-based polymer composites comprise polymers sourced from renewable biological origins like plants, algae, or bacteria, combined with reinforcing agents such as natural fibers or nanoparticles. They serve as eco-friendly substitutes for traditional petroleum-based plastics, lessening environmental concerns and lessening dependence on finite fossil resources. Employing bio-based polymers diminishes carbon footprint and decreases reliance on non-renewable materials, fostering a more circular and sustainable economy. Natural fibers like hemp, flax, or kenaf are commonly integrated as reinforcements due to their robustness and biodegradability. These composites are widely applicable across industries like automotive, construction, packaging, and consumer goods. They're utilized in automotive interiors to reduce weight and bolster fuel efficiency, in construction for insulation, panels, and structural elements, and in packaging as biodegradable alternatives to conventional plastics, thus lowering environmental impact. Despite their environmental merits, challenges persist, including optimizing mechanical properties, scaling up production, and managing end-of-life disposal. Ongoing research and innovation endeavor to overcome these hurdles, making bio-based polymer composites more competitive and sustainable on a global scale. Research significance: Bio-based polymer composites research is crucial for tackling environmental issues and pushing forward sustainable materials technology. These composites combine renewable resources with polymer matrices, resulting in less reliance on fossil fuels, decreased carbon footprints, and improved biodegradability compared to traditional options. They offer eco-friendly alternatives in packaging, automotive, construction, and biomedical fields. Delving into their characteristics, manufacturing techniques, and effectiveness allows for the creation of novel materials that lessen environmental harm while meeting diverse needs, thus aiding in building a more sustainable and robust future. Methodology: Grey Relational Analysis (GRA) is a technique employed to examine the correlation among numerous variables, especially in scenarios where data might be scant or uncertain. It gauges the extent of linkage between variables by evaluating their likeness or disparity patterns. GRA empowers decision-makers to pinpoint influential elements, rank actions, and refine procedures in intricate systems like engineering, finance, and management. Through the conversion of qualitative and quantitative data into grey numbers, GRA addresses uncertainties and offers valuable insights for problem-solving, decision-making, and performance improvement across various domains, facilitating more knowledgeable and efficient decision-making strategies. Alternative: PLA (Polylactic Acid) Composites, Hemp Fiber Reinforced Composites, Kenaf Fiber Reinforced Composites, Soy Protein-based Composites, Cellulose Nanocrystal Composites, Bamboo Fiber Reinforced Composites, Corn Starch-based Composites, Algae-based Composites. Evaluation preference: Mechanical Strength, Environmental Impact, Biodegradability, Renewable Resource, Cost-effectiveness. Results: From the result it is seen that Cellulose Nanocrystal Composites is got the first rank whereas is the Corn Starch-based Composites is having the lowest rank.*

Keywords*: PLA (Polylactic Acid) Composites, Hemp Fiber Reinforced Composites, Kenaf Fiber Reinforced Composites.*

1. INTRODUCTION

Renewable biopolymers have attracted considerable attention in academic and industrial circles. They involve using polymeric materials sourced from renewable origins, such as lignocellulosic fibers from annually replenished resources, presenting a sustainable option for economically and environmentally favorable materials.

Scientists and engineers are exploring ways to harness the natural strength and functionalities of co-fibers and nanoparticles within these green polymers to develop novel bio-based composites. However, a significant hurdle in this endeavor is ensuring the eco-friendliness of these biocomposites, which entails characteristics like ecological properties, full degradability, and stability. [1] The bio-based polymer composites industry is witnessing impressive expansion, fueled by the imperative of sustainable practices and the desire to decrease dependence on finite resources such as crude oil. In the past two decades, there has been a notable upsurge in research aimed at pioneering bio-based materials. Initially, the emphasis was on fundamental structures, typically involving conventional thermoplastics bolstered by natural fibers. Yet, the focus has progressively transitioned towards intricate blends, meticulously formulated with bio-based matrices and reinforcements, or entirely derived from bio-based sources. In the domain of bio-based biomedical applications, PLA and its derivatives reign supreme in research endeavors. [2] Renewable agriculture and bio-based feedstocks are gaining attention due to their potential to reduce reliance on fossil fuels and lower greenhouse gas emissions when combined with traditional petroleum-based products. However, incorporating natural fibers into polymers presents challenges such as increased water absorption and inferior thermal properties. To match the performance of conventional composites, innovative approaches are needed. Rather than relying on expensive chemical or physical modification techniques, there's a growing trend toward utilizing waste, residues, and by-products from processes. The addition or reinforcement of natural fiber-polymer composites (NFPCs) holds promise for improving stability and resilience, effectively addressing these limitations. [3] Bio-based polymers, sourced from renewable materials, encompass a variety of natural substances like cellulose, proteins (such as starch, chitosan, wool, silk, and gelatin), fats, lignin, polynucleotides, and polyisoprenoids. These materials, derived from renewable sources, are classified based on their origin. Biopolymers, created by living organisms and plants via intricate biosynthetic pathways utilizing carbon dioxide, are crucial for resource sustainability as they degrade and recycle naturally. However, certain natural polymers like rubber, lignin, and humus degrade slowly, posing environmental concerns. Leveraging this understanding, developing synthetic and semi-synthetic polymeric materials, along with hybrid compositions, can drive the production of environmentally sustainable plastic products. [4] In recent years, there's been a growing focus on developing bio-based polymeric materials to promote sustainability in industrial practices. Our research team is currently dedicated to exploring the potential of various agro-industrial by-products to create efficient and eco-friendly bio-based polymeric materials. A key aspect of our work involves assessing biodegradability, particularly in controlled environmental conditions. We're studying how the structure and properties of biodegradable compounds and natural fibers interact, as demonstrated. Their research highlighted the significant influence of fiber properties and their interaction with polymers on the effectiveness of these biomaterials. We've specifically looked into natural fiber composites based on polyesters (such as Bionel), polysaccharides (like Biocell), and thermoplastic starch (including Bioplast and Mater-Py) composites, as explored by Wollerdorfer and Bader. Our findings have shown a moderate increase in tensile strength in polyester blends containing up to 25% fiber content. Furthermore, we've conducted evaluations of fiber length distribution (FLD) after solvent extraction from the polymeric matrix using optical microscopy. This analysis has revealed that FLD significantly depends on the type of polymeric matrix, which is influenced by its chemical characteristics and processing methods. [5] Climate change has spurred the uptake of sustainable and renewable approaches in development, notably in the use of biodegradable materials like natural fibers (NFs). NFs are now being seen as a practical replacement for synthetic fibers in reinforced polymer compounds, leading to the emergence of natural fiber reinforced plastics (NFRPs). These NFRPs are gaining traction in today's composite industry due to their abundance, cost-effectiveness, lightweight nature, and environmentally friendly attributes. NFs provide a range of economic, technical, and ecological advantages over synthetic fibers in polymer composites, making them promising substitutes for conventional reinforcements.[6] Over the last century, synthetic resins have played a vital role in engineering plastics. However, there's a rising interest in developing bio-based materials and refining processes, driven by factors such as dwindling petroleum reserves, stricter environmental regulations, and heightened global consciousness of sustainability. Many modern chemicals and materials, including polymers and plastics, are derived from petroleum, but at current consumption rates, conventional reserves are expected to run out within 50 years. Consequently, there's a shift towards leveraging renewable resources for polymer production, potentially outpacing petroleum-based alternatives in the plastics market. This chapter aims to examine advancements in utilizing renewable resources for resin and polymer production, along with their diverse applications. [7] Bio-based polymers are sourced from natural materials, with corn starch and vegetable oils being prominent examples. They offer a promising solution to environmental challenges posed by petroleum-derived polymers. Consequently, eco-friendly biodegradable polymers have garnered significant interest for diverse applications. To enhance their heat and mechanical properties, these materials are frequently bolstered with micro or nanoscale fillers. Much research is dedicated to developing and analyzing composites and nanocomposites utilizing biodegradable polymers in response to this trend. [8] Bast fiber composites, incorporating substances such as flax, jute, and kenaf, provide several advantages including weight reduction, improved specific impact, flexibility, and acoustic characteristics. They can be cost-effective if designed correctly. Although they have found success in non-structural automotive applications, their mechanical attributes lag behind more prevalent reinforcements such as glass and carbon fibers, particularly in structural roles. Nonetheless, combining these bast fibers with high-performance fibers through hybridization techniques shows great promise for bolstering their mechanical performance in structural applications. [9] Polypropylene (PP) is commonly utilized as a base material in the production of biocomposites, typically combined with natural fillers in granular form. Although polymer producers rarely employ PP in fine powder form, a study was conducted to evaluate how using polymer powder affects the properties of composites made with date palm flour. The investigation focused on assessing the mechanical, physical, and thermal properties of newly developed composites consisting of date palm powder (DPP) and PP in both powder (PW) and pellet (PL) forms. Samples were created using a laboratory-scale single-screw extruder followed by compression molding. The experimental analysis, which included scanning electron microscopy (SEM), demonstrated the importance of the powder's distribution within the PP matrix in achieving robust interfacial strength and uniform blending in biocomposite materials. This optimization contributes to improved efficiency in the manufacturing process. [10] The burgeoning popularity of biopolymers underscores the necessity of comprehending their environmental impact across their entire life cycle to promote widespread acceptance. It's imperative for consumers and manufacturers to delve into more eco-friendly methods concerning the utilization, production, and disposal of these materials. This compilation of articles consolidates various discoveries derived from peer-reviewed life cycle assessments (LCAs) and commonly utilized LCA databases. LCAs function as invaluable instruments in quantifying the environmental sustainability of bio-based polymers from their inception to their disposal. Through the examination of LCAs and LCA databases, this compendium offers valuable insights to both researchers and the polymer industry, steering endeavors towards enhancing the sustainability of bio-based polymer applications through refined design, utilization, and disposal practices. [11] Interest in using bio-based composites is growing due to the rising global demand for fiber products, depletion of tree resources, and increased environmental awareness. Researchers are actively exploring ways to create composites from agricultural residues such as cereal stalks, paddy husks, coconut fiber, maize, and peanut shells. These residues are attractive due to their abundance and potential to replace wood. Utilizing agricultural residues offers economic, environmental, and technological advantages. However, there are gaps in knowledge that require further research to enable commercial production. This study aims to evaluate the suitability of sunflower stalks, maize stalks, and bagasse fibers as reinforcement for various applications. Additionally, it examines how different grades of coupling agents affect the mechanical properties of these composites. [12] This recent advancement has prompted interest in developing eco-friendly alternatives to traditional materials by using bio-based composites. However, there's a crucial need for better understanding the mechanical and long-term properties of these composites, particularly their tendency to deform over time, known as creep deformation. A recent study addresses this by examining a bio-derived polymer matrix reinforced with three types of natural fiber textiles. It investigates how mechanical and creep deformation properties vary based on the type and orientation of the textile. Furthermore, the study explores the application of time-strain superposition, a method for accelerated testing to understand creep behavior. The results indicate that these bio-based composites demonstrate mechanical properties similar to many conventional construction materials. Additionally, using time-strain superposition appears promising for efficiently collecting and analyzing creep data for bio-based composites. Overall, comprehensive comparisons of mechanical properties and environmental impacts suggest that these materials offer environmentally friendly alternatives to conventional ones. [13] Bio-based polymeric materials, a novel category, are crafted through biological, chemical, and physical processes, utilizing renewable biomass sources like crops, trees, or plant residues. These materials boast distinctive traits such as eco-friendliness, renewability, and biodegradability, setting them apart from traditional polymers. Biopolymers, sharing similar origins, have sparked significant interest among researchers. Particularly, stimuli-responsive bio-based polymeric systems are gaining attention for their adaptable nature across various fields. This review delves into recent advancements in these systems, highlighting their applications and advantages over conventional polymers. Moreover, it explores emerging uses such as intelligent drug delivery, responsive food packaging, and innovative water treatment, with a special focus on the realm of intelligent drug delivery. [14] Bio-based polymers, renowned for their ability to biodegrade, their compatibility with living organisms, and their effectiveness against bacteria, are extensively utilized across various sectors such as pharmaceuticals, water treatment, and food packaging. This review aims to provide an up-to-date summary of research concerning stimuli-responsive bio-based polymers and their practical applications. Particularly noteworthy are their applications in smart drug delivery systems, which leverage the distinctive attributes of bio-based polymers. These polymers are sourced from renewable materials, including microbes, plants, and animals. Notable examples of bio-based polymers sourced from microbes encompass polylactic acid (PLA), microbial polyesters, and polysaccharides like cellulose. Additionally, microbially synthesized bio-based polymers such as hydroxyacrylic acid, hydroxyvalerate (AHV), poly-3-hydroxybutyrate (PHB), polyhydroxyalkanoates (PHAs), and copolyesters are significant. Botanical sources contribute prevalent bio-based polymers like cellulose, hemicelluloses, and lignins. Starch-based polymers, primarily obtained from plants, also constitute a substantial area of research interest. [15].

2. MATERIALS & METHODS

Alternatives:

1. PLA (Polylactic Acid) Composites

Polylactic Acid (PLA) Composites: PLA, a biodegradable polyester sourced from renewable materials like corn starch or sugarcane, forms the base for composites. These blends, integrating PLA with natural fibers or fillers, enhance mechanical properties. They're widely used in packaging, textiles, biomedical devices, and automotive parts due to their biodegradability and decent mechanical performance.

2. Hemp Fiber Reinforced Composites

Hemp Fiber Reinforced Composites: Derived from the hemp plant, hemp fibers boast high strength and stiffness. When integrated into polymer matrices like PLA or epoxy resins, they enhance mechanical properties such as strength, stiffness, and impact resistance. These composites find applications in automotive parts, construction, and consumer goods.

3. Kenaf Fiber Reinforced Composites

Kenaf Fiber Reinforced Composites: Kenaf, a fast-growing plant, yields fibers with commendable mechanical properties. Similar to hemp fiber composites, kenaf fiber-reinforced composites offer lightweight, biodegradability, and good thermal insulation. They're used in automotive interiors, furniture, packaging, and construction materials.

4. Soy Protein-based Composites

Soy Protein-based Composites: Sourced from soybeans, soy protein is renewable and biodegradable. Blending soy protein with other biopolymers or natural fibers produces composites with good mechanical properties and biodegradability, suitable for adhesives, coatings, films, and packaging.

5. Cellulose Nanocrystal Composites

Cellulose Nanocrystal Composites: Cellulose nanocrystals (CNCs) extracted from cellulose fibers significantly enhance mechanical strength, thermal stability, and barrier properties when incorporated into polymer matrices. They're utilized in packaging, coatings, biomedical materials, and structural components.

6. Bamboo Fiber Reinforced Composites

Bamboo Fiber Reinforced Composites: Renewable and abundant, bamboo fibers offer high strength-to-weight ratio, biodegradability, and affordability. These composites find applications in construction, furniture, automotive parts, and consumer goods.

7. Corn Starch-based Composites

Corn Starch-based Composites: Derived from corn, corn starch is a renewable and biodegradable polymer. Blending it with other polymers or natural fibers produces composites with good mechanical properties, used in packaging, disposable cutlery, and agricultural mulches.

8. Algae-based Composites

Algae-based Composites: Algae, renewable aquatic organisms, offer biopolymers and fillers for composite materials. Despite being in early stages, algae-based composites show potential in packaging, biodegradable plastics, and wastewater treatment.

Evaluation Parameters:

1. Mechanical Strength: The strength and durability of the composite material.

Mechanical Strength: Mechanical strength pertains to a material's capacity to endure external forces without fracturing or distorting. In bio-based polymer composites, bolstering mechanical strength is pivotal for their suitability across various applications. This can be realized through meticulous selection of reinforcement materials like natural fibers or nanoparticles, refining composite fabrication methods, and regulating composite composition. Augmenting mechanical strength enables bio-based polymer composites to meet the performance benchmarks of sectors such as automotive, construction, and aerospace, while diminishing dependence on conventional materials sourced from non-renewable reservoirs.

2. **Environmental Impact: The environmental friendliness and sustainability of the composite.**

Environmental Impact: Environmental impact evaluates how a material or product affects the environment throughout its lifecycle, spanning raw material extraction, manufacturing, utilization, and disposal. Typically, bio-based polymer composites exhibit lower environmental footprints compared to petroleum-based counterparts owing to their renewable sourcing and potential for biodegradation. By curbing greenhouse gas emissions, energy consumption, and pollution, bio-based composites aid in mitigating climate change and conserving natural resources, aligning with sustainability objectives and regulatory mandates aimed at curtailing environmental degradation.

3. **Biodegradability: The ability of the composite to decompose naturally over time.**

Biodegradability: Biodegradability denotes a material's propensity to decompose into natural constituents in the environment, often facilitated by microorganisms, fungi, or other biological mechanisms. Bio-based polymer composites frequently showcase enhanced biodegradability relative to conventional plastics, particularly when incorporating biodegradable polymers or natural fibers. This attribute proves beneficial in contexts where disposal and end-of-life management are significant concerns, such as single-use packaging and agricultural applications. Biodegradable composites contribute to reducing plastic pollution, alleviating strain on landfills, and fostering the transition to a circular economy by facilitating material reuse.

4. **Renewable Resource: The extent to which the raw materials used in the composite are renewable.**

Renewable Resource: Renewable resources are replenishable within a human lifespan and can be sustainably harvested without causing long-term harm to ecosystems. Bio-based polymer composites harness renewable resources like plant fibers, agricultural residues, and biodegradable polymers sourced from biomass. By leveraging renewable feedstocks, these composites diminish reliance on finite fossil fuels, promote agricultural diversification, and bolster rural economies. Moreover, renewable sourcing enhances the sustainability profile of bio-based materials and fosters enduring environmental stewardship.

5. **Cost-effectiveness: The economic efficiency of producing and using the composite.**

Cost-effectiveness: Cost-effectiveness refers to the equilibrium between the production cost of a material or product and its performance or benefits. Attaining cost-effectiveness is pivotal for the widespread adoption of bio-based polymer composites in commercial spheres. Influential factors encompass the availability and cost of raw materials, manufacturing processes, scalability, and market demand. While initial expenses for bio-based materials might be higher due to research and development outlays, economies of scale, technological advancements, and regulatory incentives can drive down costs over time, rendering bio-based composites increasingly competitive vis-à-vis conventional materials. Ultimately, realizing cost-effectiveness ensures that bio-based polymer composites stand as economically viable alternatives for industries seeking sustainable solutions.

3. GREY RELATIONAL ANALYSIS (GRA)

Grey Relational Analysis (GRA), sometimes referred to as Gray Correlation Analysis, is a methodology used to tackle challenges associated with data envelopment analysis within facility management. It proves particularly useful in situations where decision-making involves layout and dispatch rules. In illustrating its practical use, GRA primarily involves a step-by-step comparison of different performances, termed sequential translation. This process begins with associated formation, where alternative performances are sequentially evaluated. Next, grey values representing these performances are compared against a reference row, enabling the computation of correlation coefficients. Finally, these grey values are interconnected through coefficients, reference sequences, and relative quality assessments for each comparison sequence. [16] GRA can be applied to improve drilling process parameters, specifically for enhancing surface roughness and burr height of workpieces. This is done by utilizing grey-related analysis alongside an orthogonal sequence within experimental design. By employing grey analysis of machining parameters, various performance characteristics like surface hardness and burr height can be determined and optimized in accordance with relevant standards. It's worth noting the scarcity of published research assessing the influence of cutting parameters on different performance characteristics using grey-related analysis. [17] Deng introduced grey relational analysis in 1989, which has since been widely explored by researchers for optimizing various process parameters. Applications range from die-sinking EDM machining and shape analysis to determining optimal parameters for yield stress and elongation in polycarbonate composite injection molding. Researchers often combine the Taguchi method with grey-related analysis to present and enhance analysis results, especially in turn functions. Grey relational analysis has found utility in optimizing processes like extrusion for particle-reinforced materials and final dry grinding for high purity graphite, demonstrating its effectiveness in improving machining parameters. [18] Grey correlation analysis utilizes a weighted average approach, considering multiple criteria in real-world applications, particularly in decision-making processes such as goods ordering. This method involves comparing data sets at different levels globally and locally. One of its key strengths lies in its ability to adapt to various parameters within the model, thereby reducing potential side effects on the system. By employing ordered pairs and connecting resulting domains, this paper introduces a domain-combination technique tailored for the Grey correlation analysis model. [19] The Istanbul Stock Exchange (ISE) utilizes gray correlation analysis (GRA) to prioritize shares of companies listed in the financial sector index. GRA is globally recognized for its ability to maintain hierarchical structures while ensuring comparability across different markets. To ensure fairness, all criteria are equally distributed as decision parameters. However, when dealing with complex decision models that involve weighting performance characteristics across multiple hierarchical levels, adjustments may be necessary to maintain accuracy and fairness. [20] Gray correlation analysis (GRA) plays a crucial role in refining wastewater treatment options and is closely associated with selection analysis. Its effectiveness shines in managing difficult situations, like dealing with incomplete or uncertain data. GRA stands as a pivotal component in gray system applications, especially in tackling intricate connections among numerous performance factors. Through optimizing relationships among these factors, GRA adeptly handles interdependencies to enhance overall effectiveness. [21] Gray relational analysis is utilized in addressing issues associated with turning functions, providing a method for identifying optimal cutting parameters by employing the Taguchi method as a performance metric for gray relative quality. This methodology entails an initial examination of optimization using the Taguchi method and gray relational analysis, succeeded by a thorough exploration of selecting cutting and turning parameters to assess machine performance during operational tasks. [22] In gray correlation analysis, electrode wear starts from a baseline of zero and is then adjusted to a standardized gray level, which is termed correlation formation. The process of identifying optimal machining parameters using gray relational analysis is outlined systematically, ultimately resulting in the selection of the best machining parameters, taking into account diverse performance criteria. [23] The benefits of employing the Grey Relational Analysis (GRA) method, as evidenced by primary data, are firmly situated within the realm of multi-attribute decision making (MADM), especially in correlation analysis (GRA). The computations required are simple and readily understandable. Within business settings, GRA facilitates managerial decision-making and is esteemed as one of the most efficient techniques. [24] In the enhancement of wire electrical discharge machining (WEDM) for processing reinforced materials, gray relational analysis is utilized to identify parameters associated with various functional aspects, such as surface removal rate, maximum surface area, and hardness across 203 particles. This approach also considers shear stress and incorporates crucial parameters like cutting speed, feed rate, depth of cut, and machining duration. [25]

Step 1. Design of decision matrix and weight matrix

For a MCDM problem consisting of m alternatives and n criteria, let $D = x_{ij}$ be a decision matrix, where $x_{ij} \in R$

$$D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

Step 2. Normalization of decision matrix

The normalization of two types of data i.e., better when higher type or better when lower is evaluated using equation 2 or 3 respectively. After normalization the data ranges from 0 to 1.

$$M_{ij} = \frac{N_{ij} - \min(N_{ij})}{\max(N_{ij}) - \min(N_{ij})} \tag{2}$$

$$M_{ij} = \frac{\max(N_{ij}) - N_{ij}}{\max(N_{ij}) - \min(N_{ij})} \tag{3}$$

Where $i, j = 1,2,3, \cdots, n$

Step 3. $Deviation = the \max value\ after\ normalization - value\ of\ the\ current\ row$ (4)

Step 4. Calculation of Gray relation coefficient

$$C_{ij} = \frac{\Delta_{min} - \xi \Delta_{max}}{Current\ value - \xi \Delta_{max}}, where\ \xi\ is\ distinguishing\ coefficient \tag{5}$$

Step 5. Calculation of Gray relation grade

It’s the average of Gray relation coefficient.

4. ANALYSIS AND DISCUSSION

TABLE 1. Bio polymer composites

	Mechanical Strength	**Environmental Impact**	**Biodegradability**	**Renewable Resource**	**Cost-effectiveness**
PLA (Polylactic Acid) Composites	85.0	90.0	80.0	95.0	75.0
Hemp Fiber Reinforced Composites	90.0	95.0	85.0	90.0	85.0
Kenaf Fiber Reinforced Composites	85.0	90.0	80.0	85.0	75.0
Soy Protein-based Composites	80.0	85.0	75.0	80.0	70.0
Cellulose Nanocrystal Composites	90.0	95.0	90.0	95.0	85.0
Bamboo Fiber Reinforced Composites	85.0	90.0	85.0	95.0	80.0
Corn Starch-based Composites	80.0	85.0	75.0	90.0	70.0
Algae-based Composites	75.0	80.0	70.0	80.0	65.0

Table 1 presents a comparative analysis of various bio-based polymer composites in terms of mechanical strength, environmental impact, biodegradability, renewable resource utilization, and cost-effectiveness. Each composite material is assigned a score out of 100 for each attribute. Hemp fiber reinforced composites exhibit the highest mechanical strength (90.0) and environmental impact (95.0) scores, indicating their robustness and positive ecological footprint. Similarly, cellulose nanocrystal composites demonstrate excellent mechanical strength (90.0) and environmental impact (95.0), highlighting their potential as sustainable alternatives. Biodegradability scores are relatively high across most composites, with cellulose nanocrystal composites and hemp fiber reinforced composites leading in this aspect. Renewable resource utilization is also notable, with bamboo fiber reinforced composites and cellulose nanocrystal composites scoring the highest. Cost-effectiveness varies among the composites, with hemp fiber reinforced composites and cellulose nanocrystal composites scoring well in this regard. hemp fiber reinforced composites and cellulose nanocrystal composites emerge as strong contenders, offering a balanced combination of mechanical strength, environmental sustainability, biodegradability, renewable resource utilization, and cost-effectiveness. These findings underscore the potential of bio-based polymer composites in promoting sustainable materials development across diverse industries.

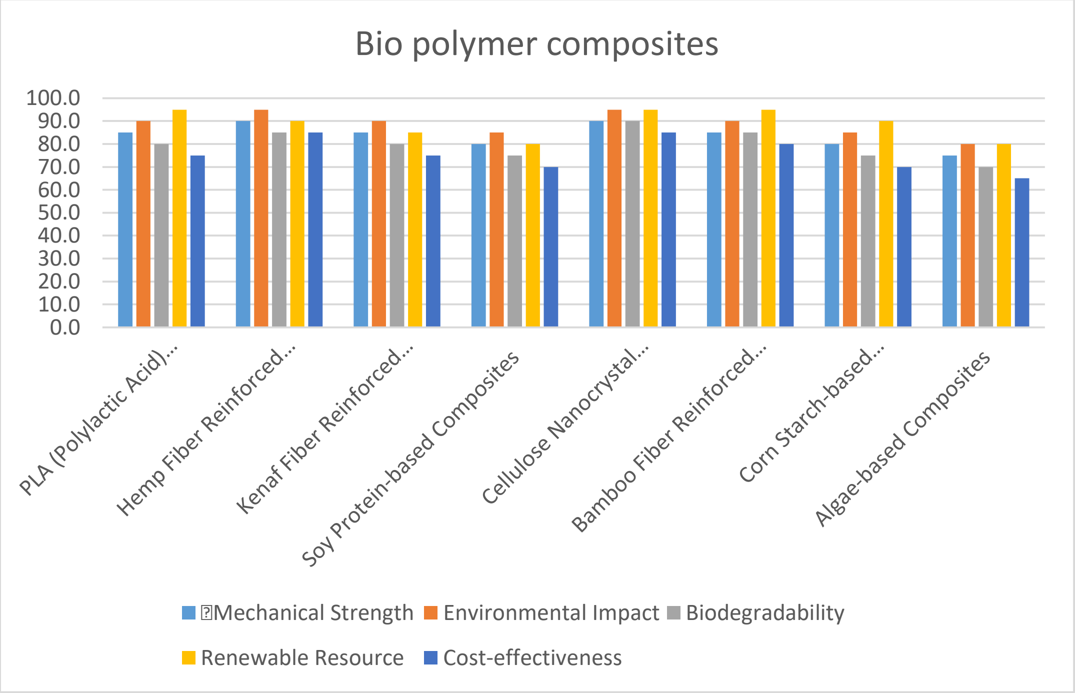

FIGURE 1. Bio polymer composites

Figure 1 illustrates the comparative performance of various bio-based polymer composites across different attributes, including mechanical strength, environmental impact, biodegradability, renewable resource utilization, and cost-effectiveness. Each composite is represented by a bar chart showing the percentage value of each attribute. The color-coded bars differentiate between the attributes, with blue indicating mechanical strength, orange representing environmental impact, gray denoting biodegradability, yellow signifying renewable resource utilization, and dark blue representing cost-effectiveness. This visualization allows for a quick assessment of each composite's strengths and weaknesses in terms of sustainability, performance, and economic viability. It provides valuable insights for decision-making in material selection and development processes, helping stakeholders identify the most suitable bio-based polymer composites for specific applications based on their desired attributes.

TABLE 2. Normalized Data

Normalized Data				
Mechanical Strength	**Environmental Impact**	**Biodegradability**	**Renewable Resource**	**Cost-effectiveness**
0.666667	0.666667	0.5	0	0.5
1	1	0.75	0.333333	0
0.666667	0.666667	0.5	0.666667	0.5
0.333333	0.333333	0.25	1	0.75
1	1	1	0	0
0.666667	0.666667	0.75	0	0.25
0.333333	0.333333	0.25	0.333333	0.75
0	0	0	1	1

The normalized data in Table 2 represents the relative values of mechanical strength, environmental impact, biodegradability, renewable resource utilization, and cost-effectiveness for different bio-based polymer composites. Each row corresponds to a specific composite, with values ranging from 0 to 1, where 0 indicates the lowest and 1 the highest level of each attribute. For instance, the first composite exhibits moderate mechanical strength and environmental impact, moderate biodegradability, no utilization of renewable resources, and moderate cost-effectiveness. Conversely, the fourth composite demonstrates high mechanical strength, low environmental impact, low biodegradability, full utilization of renewable resources, and high cost-effectiveness. These normalized values provide insights into the sustainability and performance characteristics of each composite.

TABLE 3. Deviation sequence

Deviation sequence				
Mechanical Strength	**Environmental Impact**	**Biodegradability**	**Renewable Resource**	**Cost-effectiveness**
0.3333	0.3333	0.5000	1.0000	0.5000
0.0000	0.0000	0.2500	0.6667	1.0000
0.3333	0.3333	0.5000	0.3333	0.5000
0.6667	0.6667	0.7500	0.0000	0.2500
0.0000	0.0000	0.0000	1.0000	1.0000
0.3333	0.3333	0.2500	1.0000	0.7500
0.6667	0.6667	0.7500	0.6667	0.2500
1.0000	1.0000	1.0000	0.0000	0.0000

The deviation sequence in Table 3 represents the relative differences or variations of each attribute (mechanical strength, environmental impact, biodegradability, renewable resource utilization, and cost-effectiveness) from the average value across all composites. Positive values indicate attributes that are above the average, while negative values indicate attributes below the average. For instance, in the first row, the composite demonstrates higher mechanical strength, environmental impact, and cost-effectiveness than the average, but lower biodegradability and no utilization of renewable resources. Conversely, in the last row, the composite shows maximum values for all attributes except renewable resource utilization and cost-effectiveness, which are both below average. These deviation sequences provide insights into the relative strengths and weaknesses of each composite compared to the average performance.

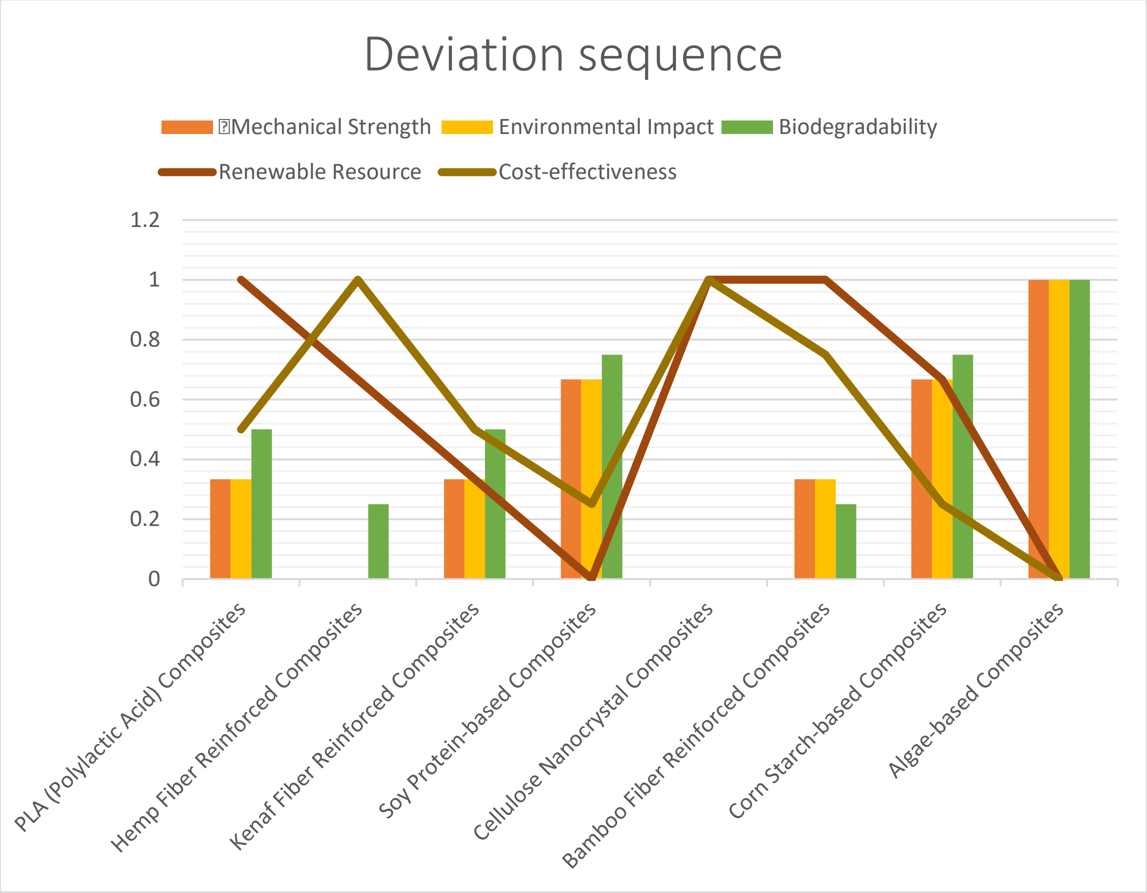

FIGURE 2. Deviation sequence

Figure 2 depicts the deviation sequence of various bio-based polymer composites across different attributes, including mechanical strength, environmental impact, biodegradability, renewable resource utilization, and cost-effectiveness. Each composite is represented by a line chart showing the deviation from the average value for each attribute. The color-coded lines differentiate between the attributes, with orange indicating mechanical strength, green representing environmental impact, brown denoting biodegradability, yellow signifying renewable resource utilization, and olive green representing cost-effectiveness. This visualization enables a comparative analysis of how each composite deviates from the average performance across different attributes. It provides insights into the relative strengths and weaknesses of each composite, aiding in decision-making processes for material selection and development based on specific attribute requirements.

TABLE 4. Grey relation coefficient

Grey relation coefficient				
Mechanical Strength	**Environmental Impact**	**Biodegradability**	**Renewable Resource**	**Cost-effectiveness**
0.6000	0.6000	0.5000	0.3333	0.5000
1.0000	1.0000	0.6667	0.4286	0.3333
0.6000	0.6000	0.5000	0.6000	0.5000
0.4286	0.4286	0.4000	1.0000	0.6667
1.0000	1.0000	1.0000	0.3333	0.3333
0.6000	0.6000	0.6667	0.3333	0.4000
0.4286	0.4286	0.4000	0.4286	0.6667
0.3333	0.3333	0.3333	1.0000	1.0000

Table 4 displays the grey relation coefficients, which quantify the degree of association between each attribute (mechanical strength, environmental impact, biodegradability, renewable resource utilization, and cost-effectiveness) and the ideal value for each attribute across all composites. A coefficient close to 1 indicates a strong relationship, suggesting that the attribute is similar to the ideal value. Conversely, a coefficient closer to 0 signifies a weaker relationship. For instance, in the second row, the composite exhibits high grey relation coefficients for mechanical strength and environmental impact, indicating strong associations with their respective ideal values. However, biodegradability, renewable resource utilization, and cost-effectiveness have lower coefficients, suggesting weaker relationships. These coefficients aid in evaluating the relative performance of composites across multiple attributes.

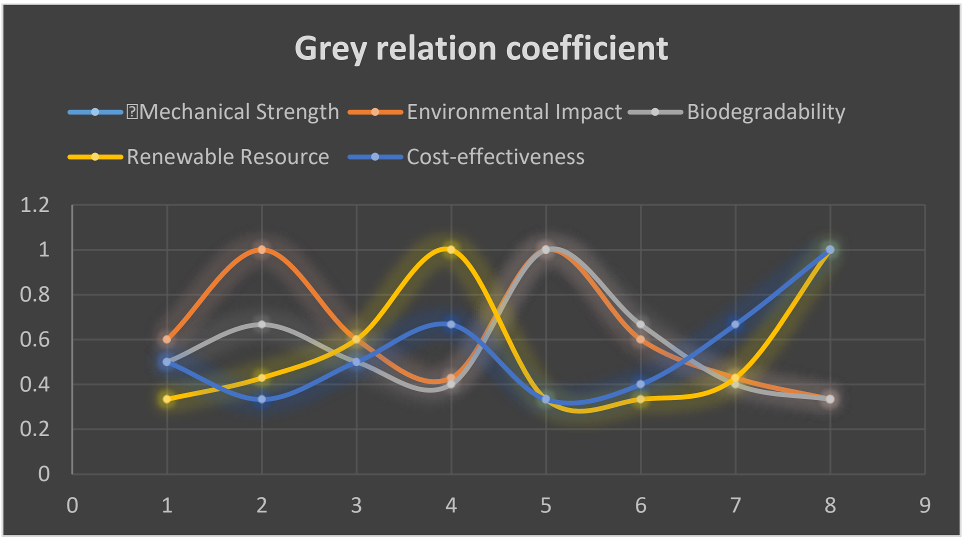

FIGURE 3. Grey relation coefficient

TABLE 5. GRG & Rank

	GRG	Rank
PLA (Polylactic Acid) Composites	0.506667	7
Hemp Fiber Reinforced Composites	0.685714	2
Kenaf Fiber Reinforced Composites	0.56	5
Soy Protein-based Composites	0.584762	4
Cellulose Nanocrystal Composites	0.733333	1
Bamboo Fiber Reinforced Composites	0.52	6
Corn Starch-based Composites	0.470476	8
Algae-based Composites	0.6	3

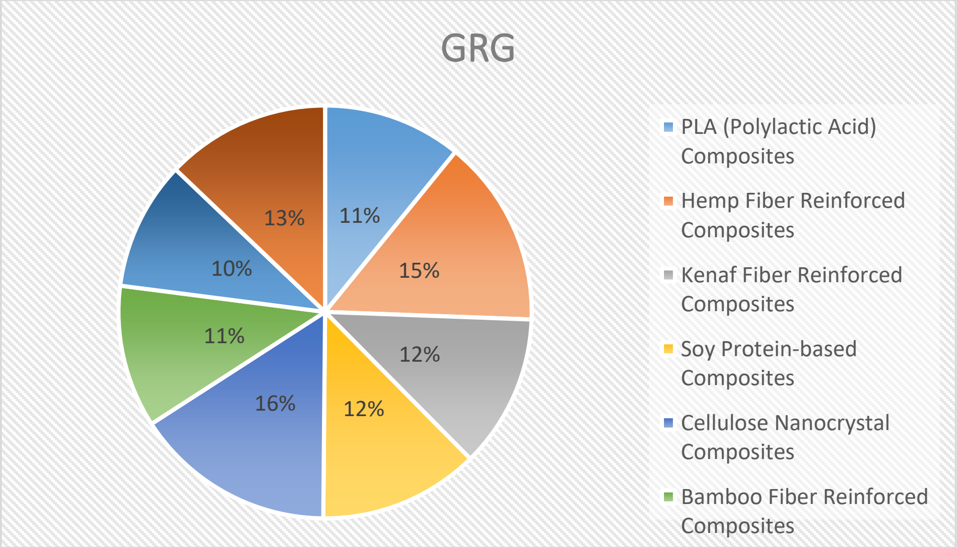

FIGURE 4. GRG

Figure 4 presents the distribution of Grey Relational Grades (GRG) for various bio-based polymer composites. Each composite is represented by a segment of the pie chart, with the percentage value indicating its contribution to the total GRG. The color-coded legend specifies the corresponding composites, allowing for easy identification of each segment. For example, Hemp Fiber Reinforced Composites contribute 13% to the total GRG, while Cellulose Nanocrystal Composites contribute the highest proportion at 16%. This visualization provides a clear overview of the relative performance of different composites based on their GRG values, enabling stakeholders to identify the most promising candidates for further consideration or investment.

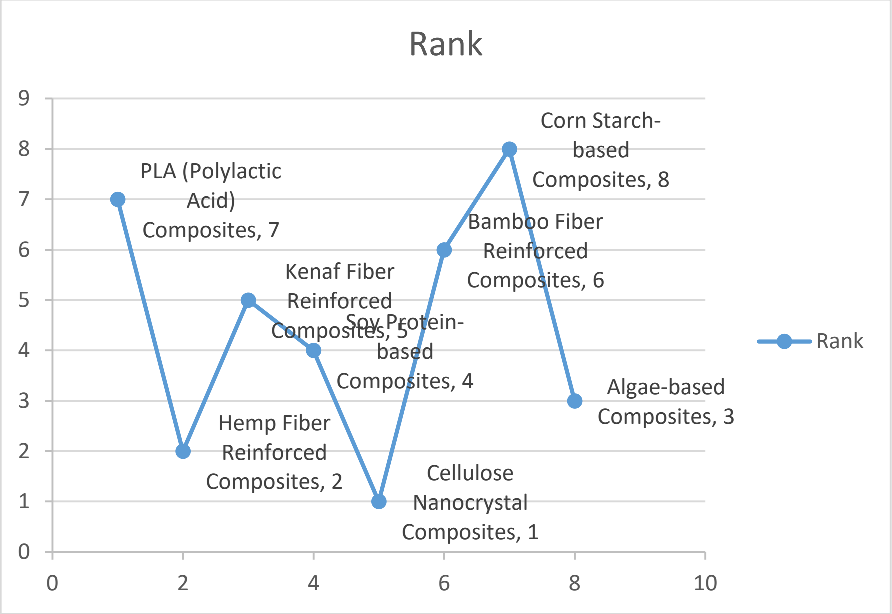

FIGURE 5. Rank

Figure 5 depicts the ranking of different bio-based polymer composites based on their performance across various attributes. Each composite is represented by a data point on the line chart, with the x-axis indicating the composite index and the y-axis representing the rank. The labeled data points provide information about the composite name and its corresponding rank. The graph visually demonstrates the relative performance of each composite, showing fluctuations in rank across the different composites. For instance, Cellulose Nanocrystal Composites rank the highest at position 1, indicating superior performance, while Corn Starch-based Composites rank the lowest at position 8. This visualization enables stakeholders to quickly identify the top-performing and lowest-performing composites, aiding in decision-making processes for material selection and further development.

5. CONCLUSION

Bio-based polymer composites offer a promising path for creating sustainable materials, with broad implications across industries. This field has attracted considerable attention for its potential to address environmental issues linked to traditional polymer composites derived from fossil fuels. By incorporating renewable resources like plant-based fibers and biodegradable polymers into polymer matrices, bio-based composites provide various environmental advantages. A significant benefit of bio-based polymer composites is their reduced dependence on finite fossil fuel reserves. By using renewable feedstocks, these composites help cut down greenhouse gas emissions and lessen the carbon footprint associated with material production. This aspect aligns with global efforts to move towards a more sustainable and circular economy, reducing reliance on non-renewable resources and mitigating environmental harm. bio-based polymer composites break down more easily compared to conventional petroleum-based ones. This is especially important in applications where disposal at the end of their lifespan is a concern, such as single-use packaging materials. Biodegradable composites offer a viable solution to reduce plastic pollution and alleviate pressure on landfills and marine ecosystems, promoting a cleaner environment. Bio-based polymer composites allow for innovative material design and performance enhancement. Researchers can adjust composite properties by varying the type, composition, and processing techniques of bio-based constituents. This flexibility facilitates the development of composites with desired characteristics, including mechanical strength, thermal stability, and barrier properties, suitable for various applications across industries like automotive, construction, packaging, and healthcare. Apart from environmental and performance benefits, bio-based polymer composites contribute to economic sustainability and resource efficiency. The use of agricultural by-products and other renewable feedstocks can generate new revenue streams for farmers and biomass industries. Additionally, the advancement of bio-based composite manufacturing processes can create jobs and bolster local economies, especially in rural areas abundant in biomass resources. Despite the many advantages, challenges persist in the widespread adoption of bio-based polymer composites. These include technological hurdles related to processing, compatibility issues between bio-based and synthetic components, and cost considerations associated with large-scale production. Overcoming these challenges will require interdisciplinary research, collaboration between academia and industry, and supportive policies and incentives to drive innovation and market acceptance. bio-based polymer composites hold significant promise as sustainable alternatives to traditional materials, offering environmental, economic, and performance benefits. Continuous research and development in this field are crucial to realizing their full potential and accelerating the transition towards a more sustainable and resilient future. By harnessing the capabilities of nature-based solutions, bio-based polymer composites can play a substantial role in addressing global challenges related to climate change, resource depletion, and environmental pollution.

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