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Parthenium Hysterophorus as a Sustainable Reinforcement Material for Polymer Composites

Monika S.[1], Dr. E. Devaki[2], Karthika B.[3], Narmathavarsa V.[4], Srinithi A.[5]
[1]Research Scholar, [2]Associate Professor & Head of the Department, [3]Research Scholar, [4]Research Scholar, [5]Teaching Assistant
Department of Costume Design and Fashion P.S.G. College of Arts & Science

***Abstract:** Parthenium hysterophorus, an invasive weed, is rapidly spreading across tropical and subtropical regions, causing significant ecological and health issues. Despite its negative impact, recent research highlights its potential as a sustainable, low-cost lignocellulosic material for polymer composites. This paper explores the chemical composition, physical properties, and processing techniques of parthenium, focusing on its use as a reinforcement in thermoset and thermoplastic matrices. Parthenium biomass is primarily composed of cellulose, hemicellulose, and lignin, which make it suitable for composite applications. Surface treatments, such as alkali treatment, enhance the bonding between parthenium fibers and polymer matrices, improving mechanical interlocking. The resulting composites show enhanced mechanical properties, including increased tensile strength and flexural stiffness, with potential applications in automotive and engineering sectors. Additionally, parthenium-derived lignin has been explored for use in nanocomposites, offering UV-blocking and antioxidant properties. The paper discusses the environmental benefits of utilizing parthenium, such as reduced reliance on synthetic fibers, and highlights the challenges in ensuring consistent fiber quality and moisture sensitivity. Future research should focus on standardizing fiber extraction methods and developing hybrid composites to further enhance the performance of parthenium-based materials. In conclusion, parthenium presents a promising, eco-friendly alternative for polymer composites, contributing to the development of sustainable and biodegradable materials.*

***Keywords:** Parthenium hysterophorus, Polymer composites, Natural fibers, Lignin-based nanocomposites, Sustainable materials.*

I. INTRODUCTION

Parthenium hysterophorus, commonly known as "fool's weed" or "Congress grass," is a highly invasive species with a global reach. It poses significant threats to biodiversity, agriculture, and public health, particularly in tropical and subtropical regions like India. The plant's rapid growth and spread have earned it the reputation of being an environmental nuisance. Despite its negative ecological impact, recent studies have turned attention to its potential for use as a sustainable resource in polymer composites. Parthenium's lignocellulosic nature primarily composed of cellulose, hemicellulose, and lignin presents an opportunity to repurpose this weed as a low-cost material for composite applications. These composites, in turn, could play a pivotal role in promoting environmental sustainability through the use of natural fibers and biodegradable materials, reducing the reliance on synthetic polymers.

Parthenium hysterophorus, native to the Americas, has become a notorious invasive species in many parts of the world, particularly in India, Africa, and Australia. Its spread has had serious ecological, agricultural, and health impacts. Ecologically, it disrupts native plant species and reduces biodiversity by outcompeting local flora. Agriculturally, it reduces crop yields by contaminating fields and degrading soil quality. From a health perspective, it is known to trigger allergic reactions in humans, such as asthma, dermatitis, and hay fever. The plant's rapid proliferation and its persistence have made it a persistent challenge for land management and farming.

Fig:1 Parthenium hysterophorus

However, parthenium's high biomass productivity, year-round availability, and low cost present an opportunity to transform this unwanted species into a valuable raw material. Researchers have proposed using parthenium fibers as reinforcements in polymer composites, offering a sustainable alternative to synthetic fibers such as glass and carbon fibers. This approach not only addresses the ecological problem posed by the weed but also creates opportunities for producing lightweight, biodegradable, and low-cost composite materials for various industrial applications.

Polymer composites are widely used in industries such as automotive, construction, packaging, and consumer goods due to their lightweight, high strength, and durability. The use of natural fibers, such as parthenium, to reinforce polymer matrices aligns with the growing demand for environmentally friendly materials that reduce the carbon footprint and reliance on fossil fuels. Additionally, as parthenium is an invasive weed, utilizing it in composites provides an added ecological benefit by mitigating its negative environmental impact.

II. CHEMICAL COMPOSITION OF PARTHENIUM BIOMASS

The chemical composition of parthenium biomass plays a crucial role in determining its suitability for use in composite materials. Parthenium is primarily a lignocellulosic material, composed of cellulose, hemicellulose, lignin, and small amounts of extractives and ash. These components are key to its potential as a reinforcement material for polymer matrices.

Cellulose, the main structural component of plant fibers, is known for its strength and stiffness, making it an ideal candidate for reinforcing polymer composites. Hemicellulose, a complex carbohydrate, complements cellulose by providing flexibility and improving the bonding between fibers and the polymer matrix. Lignin, a phenolic polymer, contributes rigidity and thermal stability to the material but can also hinder fiber-matrix bonding if not properly modified.

Studies have shown that parthenium biomass contains around 78% holocellulose (cellulose + hemicellulose) and approximately 17.2% lignin. These values suggest that parthenium is a suitable candidate for use as a reinforcement in composite materials, especially in applications where the demand for strength and stiffness is moderate. Additionally, parthenium fibers have cellulose contents ranging from 50% to 56%, depending on the type of chemical treatment applied to the fibers. Although this is lower than that of bast fibers such as jute and hemp, it is still sufficient for creating semi-structural composites.

Apart from its cellulose and lignin content, parthenium also contains a variety of secondary metabolites, including sesquiterpene lactones (such as parthenin), flavonoids, and sterols. These compounds contribute to the plant's allelopathic and toxic properties, which make it undesirable for some applications. However, these compounds can be removed or reduced during the processing of the biomass, improving the quality and functionality of the fibers for use in composites. For instance, alkali treatment has been shown to improve the fiber-matrix bonding by removing surface waxes and other extractives while preserving the cellulose content.

III. PHYSICAL CHARACTERISTICS OF PARTHENIUM FIBERS

The physical properties of parthenium fibers, including their morphology, density, and surface characteristics, are essential for determining their performance as reinforcement materials in polymer composites. Parthenium fibers are typically obtained from the stem and coarse aerial parts of the plant through retting or alkaline treatment, followed by mechanical separation.

Parthenium fibers exhibit a low density, which is similar to other natural fibers. This low density is beneficial for producing lightweight composites, which is an essential property in industries such as automotive and aerospace, where weight reduction is a key factor. The low density of the fibers contributes to an increase in the specific strength and stiffness of the composite materials, making them ideal for medium-load structural applications.

Surface morphology studies of parthenium fibers reveal that, after alkali treatment, the fibers have rough, fibrillated surfaces. These rough surfaces enhance the mechanical interlocking between the fibers and the polymer matrix, leading to better stress transfer from the matrix to the fibers. The alkali treatment removes surface waxes, pectins, and extractives, which increases the surface energy of the fibers and exposes cellulose microfibrils. This treatment improves the wetting of the fibers by thermoset and thermoplastic resins, resulting in better bonding between the fibers and the polymer matrix.

However, one challenge with parthenium fibers is their inherent hydrophilicity, which is due to the hydroxyl groups in cellulose and hemicellulose. This hydrophilicity leads to moisture uptake, which can cause dimensional instability in the composite material. To address this issue, surface treatments, such as chemical modification or the use of moisture-resistant matrices, are required to ensure the stability and durability of the composite materials.

IV. PROCESSING AND COMPOSITE FABRICATION

The fabrication of parthenium-reinforced polymer composites involves various processing techniques, including the incorporation of short fibers, powders, or chemically modified lignin fractions into polymer matrices. These processing methods influence the final mechanical properties of the composite materials.

In thermoset composites, short parthenium fibers have been incorporated into epoxy matrices using traditional hand lay-up methods followed by compression molding. This technique has been widely used to fabricate test specimens for evaluating the tensile properties of the composites. The incorporation of parthenium fibers into the epoxy matrix results in significant improvements in mechanical properties, particularly in terms of tensile strength and modulus.

In thermoplastic systems, parthenium fibers have been compounded with polymers such as PLA and ABS, followed by the production of filaments and 3D printing using fused deposition modeling (FDM). This approach has been used to fabricate test coupons with different raster orientations, allowing researchers to study the influence of fiber alignment on the mechanical properties of the composites. The results indicate that composites reinforced with parthenium fibers exhibit enhanced tensile and flexural properties compared to unfilled thermoplastics.

In addition to fibers, alkali-extracted parthenium lignin has been used as a capping agent in the synthesis of ZnO nanocomposites. This demonstrates the potential of parthenium lignin to act as a functional additive in polymer matrices, improving properties such as UV-blocking behavior and weathering resistance.

The preprocessing of parthenium biomass typically involves drying, chopping, alkali treatment (e.g., 5-10 wt% NaOH), washing, and oven drying. These steps improve the dispersion of fibers in the polymer matrix and reduce the degradation of the fibers during processing. Proper preprocessing is essential for ensuring the high-quality production of parthenium-based polymer composites.

V. MECHANICAL PROPERTIES OF PARTHENIUM-REINFORCED POLYMER COMPOSITES

A. Epoxy-Based Parthenium Composites

Parthenium-epoxy composites, particularly those reinforced with short fibers, have demonstrated significant improvements in mechanical properties compared to neat epoxy. The tensile strength and modulus of the composites generally increase with the fiber loading up to an optimum level. However, beyond this point, agglomeration of fibers and poor impregnation may lead to a decline in the mechanical properties of the composite. Similarly, flexural strength and impact resistance improve with moderate fiber fractions, reflecting effective stress transfer from the matrix to the fibers.

The best-performing parthenium-epoxy formulations show enhanced stiffness and strength, making them suitable for medium-load, lightweight structural components, such as those used in automotive and consumer product applications. One of the challenges associated with these composites is their increased water absorption due to the hydrophilicity of the parthenium fibers. This can reduce the overall performance of the composite, but it can be mitigated by selecting an appropriate matrix, treating the fibers to reduce moisture absorption, or hybridizing them with more hydrophobic fibers.

B. Thermoplastic Composites (PLA, ABS)

Thermoplastic composites made from short parthenium fibers and thermoplastic matrices like PLA and ABS show improved mechanical performance compared to unfilled polymers. The incorporation of parthenium fibers increases the tensile and flexural properties of the composites, with the fibers contributing to higher load-bearing capacity and stiffness. The orientation of the fibers during the 3D printing process also plays a crucial role in determining the mechanical performance, with load-aligned fibers typically resulting in the highest strength and modulus.

The thermoplastic parthenium composites are promising substitutes for conventional polymer materials in sectors such as automotive, where weight reduction is essential, and engineering applications, where cost efficiency and performance are critical.

C. Lignin-Based Parthenium Nanocomposites

Parthenium-derived lignin has been used to create lignin-ZnO nanocomposites with symmetric morphology and enhanced UV-blocking properties. The lignin acts as a stabilizing agent, controlling the particle size of ZnO nanoparticles and preventing their aggregation. These nanocomposites have shown promising results in improving the weathering resistance of polymer composites, extending their service life. This suggests that parthenium lignin can serve as a multifunctional additive, providing both mechanical reinforcement and additional functionalities such as UV protection and antioxidant properties.

VI. PHYSICAL, MECHANICAL BEHAVIOR AND STRUCTURE-PROPERTY RELATIONSHIPS

The performance of parthenium-reinforced polymer composites is strongly influenced by the fiber's chemical composition, morphology, and interfacial adhesion with the polymer matrix. Higher cellulose content and well-oriented cellulose microfibrils contribute to the stiffness and tensile strength of the composites, while the amorphous regions of hemicellulose and lignin provide ductility and flexibility.

The interfacial bonding between parthenium fibers and the polymer matrix is critical for ensuring effective stress transfer and enhancing the mechanical properties of the composite. Roughened fiber surfaces, achieved through chemical activation (e.g., NaOH treatment), improve the mechanical interlocking between fibers and the matrix, which enhances the overall tensile and flexural properties of the composite.

VII. ENVIRONMENTAL AND TECHNO-ECONOMIC CONSIDERATIONS

The utilization of parthenium in polymer composites offers numerous environmental and economic benefits. By converting parthenium into valuable materials such as fibers, lignin, and fillers, we can reduce the environmental impact of the plant while simultaneously creating new economic opportunities. Harvesting parthenium biomass helps manage its spread and reduces seed banks, complementing other control methods.

The use of parthenium in composites also contributes to reducing reliance on synthetic fibers and non-renewable fillers, which helps decrease the carbon footprint of composite materials. Furthermore, parthenium is a rapidly renewable resource that requires minimal cultivation inputs, making it an attractive alternative to conventional reinforcement materials.

VIII. CHALLENGES AND FUTURE PERSPECTIVES

Although parthenium has shown great promise as a reinforcement material for polymer composites, several challenges remain that need to be addressed before large-scale adoption can occur. Variability in the chemical composition of parthenium, influenced by factors such as location, season, and plant part, can result in inconsistent fiber quality and mechanical performance. Additionally, the moisture sensitivity and limited thermal stability of parthenium fibers restrict the processing windows and high-temperature applications of composites compared to traditional fibers like glass and carbon.

Future research efforts should focus on standardizing the fiber extraction, chemical treatment, and composite fabrication processes to ensure consistent and reproducible properties. Hybridizing parthenium fibers with other natural or synthetic fibers, developing suitable compatibilizers for the fibers, and conducting comprehensive life-cycle assessments will be crucial for improving the sustainability and performance of parthenium-based composites.

IX. CONCLUSION

In conclusion, parthenium hysterophorus holds significant potential as a low-cost, sustainable reinforcement material for polymer composites. Despite the challenges, such as variability in fiber quality and moisture sensitivity, its abundant availability and eco-friendly characteristics make it a viable alternative to traditional synthetic fibers. With continued research and development, parthenium-based composites could play a vital role in creating lightweight, high-performance, and environmentally responsible materials for a wide range of industrial applications.

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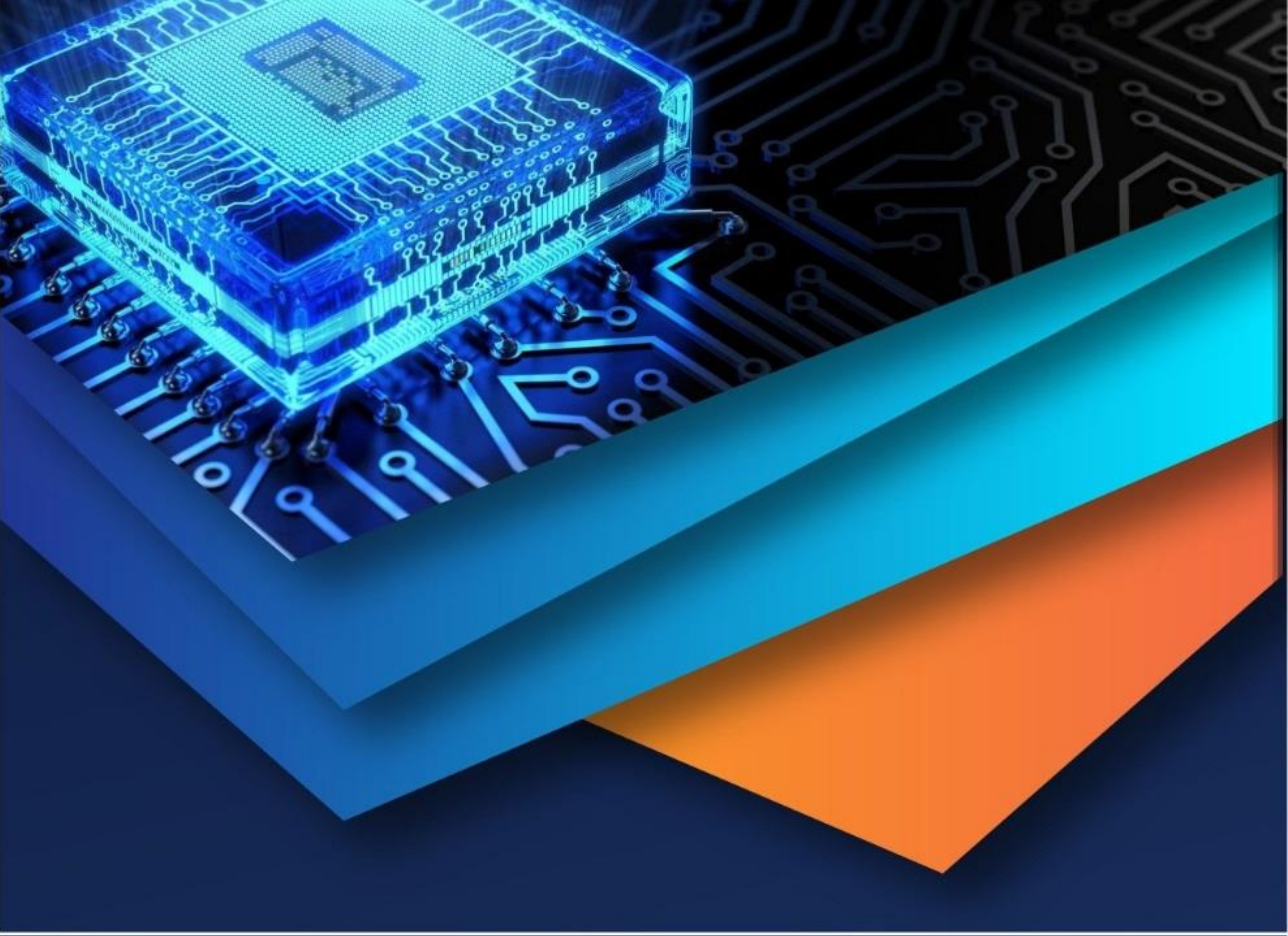

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