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A Review on Mechanical Improvements and Environmental Benefits of Rice Husk Reinforced Polymer Composites

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Abstract

The continuous advancement in science and technology necessitates the development of engineering materials tailored to specific requirements and cost-effective with minimal energy consumption. Consequently, there has been a surge in research dedicated to the fabrication of composite materials. Traditionally, the inclusion of synthetic fibers like glass or carbon is a common practice to reinforce composites and impart the necessary properties. However, their slow biodegradability poses environmental concerns, driving interest in natural fibers as substitutes. Rice husk (RH), a byproduct of rice milling, stands out as one of the most abundant agricultural wastes globally. Incorporating rice husk into polymer matrices is cost-effective and offers improved mechanical properties, low density and biodegradability etc. Various surface treatment techniques like alkaline treatment, benzoylation, acetylation and silane treatment etc., are explored to improve the integration of rice husk with base polymer, thereby imparting improved mechanical properties to composites. The present article provides an extensive review of literature regarding the prospective use of rice husk as reinforcement in various polymer matrices, highlighting primarily the mechanical attributes of polymer composites. Existing literature spanning the last 20 years has been extensively explored to analyse the impact of utilizing RH on the mechanical attributes of RH-reinforced polymeric materials. Future research directions are also highlighted, emphasizing the need for further exploration and optimization of rice husk-based composites for diverse industrial applications.

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introduction

Advancements in science and technology have made it essential to develop engineering materials that are both strong and light weight, tailored to specific requirements and cost effective with minimal energy usage. The need for such high

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performance engineering materials has prompted a lot of research in developing composite materials. Recently, the composite sector has been expanding swiftly and has made a substantial impact on the materials industry. Composite materials result from the blending of two or more materials which may differ physically and chemically from each other but on combining create a product with optimal properties suitable for particular tasks. Specifically, polymer composites consist of a base polymer resin combined with various additives to achieve particular functions or objectives.[1]

Conventionally, synthetic fibers like glass or carbon fibers are utilized for reinforcing composites and for providing desired properties. However, in this era of global environmental awareness, the main disadvantage of these composites is their slow biodegradability. The need for sustainable development has fostered an inclination towards the utilization of natural alternatives instead of synthetic fibers such as glass in polymer composites. Researchers are recently focussing on natural fibers because they are biodegradable, readily available, economical, and lightweight.[2]

Natural fibers are grouped into two primary classes based on their source i.e. animal fibers and plant fibers. Plant fibers have gained more attention in research. Previous studies have reported a variety of plant fibers, including bast, wood, seed, leaf, fruit and grass or stalk fibers, etc.[3,4]

Employing natural fibers in composites offers several important benefits such as affordability, sustainability, lightweight nature, non-hazardous characteristics, non-abrasiveness, biodegradability, and recyclability.[2,5,6] Despite this, the integration of natural fibers presents certain disadvantages including susceptibility to deterioration within the processing temperature range of the polymer matrix.

This early thermal breakdown of agro-fibers imposes constraints on the permissible processing temperature, restricting it to below 200°C, thereby limits the range of polymers compatible with agro-fibers.[1,7] Additionally, when designing composites with agro-fibers for specific applications, it is crucial to account for other factors, like their inadequate moisture resistance. The hygroscopic nature of cellulose, the chief component in plant fibers, leads to changes in dimensions and subsequent degradation in mechanical performance of the composite.[5,8–10] Integrating the fibers into the polymer with a strong bond is essential to reduce these detrimental effects. The introduction of compatibilizer can prove to be an effective strategy for attaining such strong adhesive forces. Among various compatibilizers e.g. maleic anhydride grafted polymers, silane coupling agents, epoxy resins, organosilanes, isocyanates etc.,[11–15] the maleic anhydride-grafted polypropylene (MAPP) has frequently been employed to enhance the adhesion at the interface of polymer matrices and agro-fibers. However, the continuous research is going on in exploring new alternatives.[1,16,17]

In this comprehensive review, the main focus is on the employment of rice husk (RH) in polymer composites. Paddy (unmilled rice) is among the most extensively harvested crops in the world leading to significant agricultural waste in the form of rice stalks and husks. Rice husk, a significant agricultural byproduct in major rice-producing nations, is generated as a secondary product during the rice milling process.[18] In the milling of raw paddy, the rice kernel is physically separated from other components like edible parts such as the germ and bran, as well as the inedible part, namely the rice husk.[8,19]

Despite their abundance, rice husk (RH) is usually discarded as waste and burnt in the fields, which causes environmental concern due to the release of toxic emissions, ashes, and vapours contributing to atmospheric contamination.[20] Recognizing the environmental impact, it becomes necessary to explore the use of RH in polymer composites. Figure 1 illustrates the various applications of RH in polymer composites. The inclusion of RH in polymer matrices leads to superior attributes, including toughness, decreased weight, eco-friendliness, flame retardancy, and resistance to atmospheric conditions. Moreover, this integration makes the final products cost-effective.[2,21–23] The use of extracted silica from rice husk has demonstrated success in enhancing the mechanical characteristics of composites.[24] The present study primarily centres on reviewing the literature related to the mechanical attributes of polymer composites strengthened with rice husk with a particular emphasis on assessing the effectiveness of various treatment methods in enhancing the compatibility of the base polymer and the RH filler.

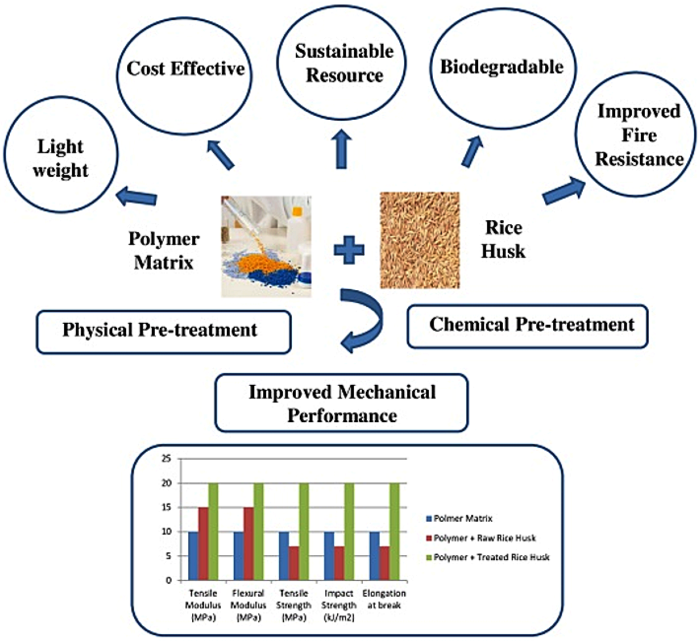

Fig. 1: Applications of RH in polymer composites.

Rice Husk Composition

Rice husk is mainly composed of cellulose that features a broad spectrum of dimensions.[25] It comprises of hemicellulose, cellulose, silica, lignin, solubles and moisture. The percentage composition and physical characteristics of RH are detailed in Table 1.[18,19,26]

Table 1: Percentage Composition and Physical Characteristics of Rice Husk.

Components	Percentage Composition (%)
Cellulose	25-48
Hemicellulose	18-25
Lignin	12-31
Silica (SiO_2)	15-17
Solubles	2-5
Moisture Content	5-10
Physical Characteristics of Rice Husk	
Particle size	20-50 (μm)
Surface Area	1 -50 (m^2/g)
Density	0.09-3 (g/cm^3)

Rice husk primarily comprises elemental substances like Carbon 37.05%, Hydrogen 4 to 5%, Oxygen 31 to 37%, Nitrogen 0.23 to 0.32%, Sulphur 0.04 to 0.08%, Silicon 9.01% and Silica 17 to 25%, ash 22.29%, bulk density 0.09 to 3 (g/cm^3) and hardness 5 to 6 (Mohr's scale).[27–29] Different researchers have reported different compositions of the Rice Husk. It relies on several factors such as the rice variety, climatic conditions, fertilizer type, soil properties, testing methods, and the production area's geography.[18,19,30,31]

Research has demonstrated rice husk to be composed predominantly of organic matter, comprising about 75 to 90% lignin and cellulose, with the remaining portion consisting of mineral elements like silica, alkalis, and minor constituents.[1,18,19,26,32,33]

Several methods have been reported by the researchers for the analysis of lignocellulosic biomass composition.[32–34] Krasznai *et.al*[34] presented a historical perspective on various compositional analysis techniques and their detailed progress over time, including the Weende Method (1859), the Klason Method (1923), the Saeman sulfuric acid method (1944), the Saeman gravimetric method (1954), and the Laboratory Analytical

Procedures (LAPs) designed by the National Renewable Energy Laboratory (NREL) (2000). Cai *et.al*[33] classified the methods of compositional analysis into three categories: analysis by sulfuric acid (H_2SO_4) hydrolysis; analysis by Near Infrared Spectroscopy (NIRS); and analysis by kinetics on thermogravimetry (TG). Sluiter *et.al*[35] determined the structural carbohydrate and lignin content in biomass using NREL Laboratory Analytical Procedures based on sulfuric acid hydrolysis. Jin *et.al*[36] reported the compositional analysis of rice straw using NIRS. Cai *et.al*[37] also reported various methods of analysis using kinetics based on the distributed activation energy model. In a recent study, Malik *et.al*[32] reported the analysis of rice husk biomass composition (cellulose – 38%, hemicellulose – 21%, lignin – 17%, ash – 15%, extractives – 8%, moisture content – 9.8%) using NREL standard methods.

Since, rice husk contains a similar quantity of cellulose but lower lignin and hemicellulose levels compared to wood, it can be subjected to higher processing temperature than wood.[1,18] Chemical examination of the non-organic part of rice husks has indicated that silica is the predominant component in its non-crystalline form, with small amounts of alkali and alkaline earth metal oxides, iron and aluminium oxides.[30,31] Rice husk exhibits exceptionally high ash content (10 to 20 %) in contrast to other biofuels. The ash consists predominantly of silica, ranging from 87% to 97%, is highly permeable and has low density along with an extensively large external surface area.[1,27] Its considerable silica content makes it a key material for industrial use.[1]

The rice husk serves as the tough outer layer enveloping the rice kernel, mainly covered in silica and marked by a thick outer layer and surface bristles. Additionally, a small portion of silica can be found in the central layer and the inner surface layer. The significant silica concentration in rice husk contributes to its enhanced rigidity and effective flame resistance.[18,21,31] Differences in the hemicellulose, cellulose, and lignin composition within rice husks from various rice varieties lead to variations in the mechanical characteristics of reinforced polymer.[11]

Surface Treatment Methods

A significant challenge has been observed in the preparation of RH composites which is attributed to their limited compatibility with hydrophobic matrices, primarily because rice husk has a hydrophilic nature and contains natural fats and waxes. Efficient integrations at the junction of rice husk and the base polymer are essential for ensuring effective stress distribution from the polymer structure to the strengthening material. This consequently leads to enhancements in the mechanical attributes of polymer blends containing rice husk.

According to research conducted by Yang and Kim,[38] RH-filled polypropylene-based composites have shown increased brittleness and reduced tensile strength, highlighting the adverse effects of low compatibility between RH and the matrix material. To resolve this issue, researchers have explored and suggested different pre-treatment methods. Depending upon the mode of action, the existing pre-treatment methods can be broadly categorized as follows:

Physical Pre-Treatment Methods

These approaches seek to alter the physical properties of the fiber, like its surface morphology, roughness, and porosity, without modifying its chemical composition. These methods include different processes such as the treatment of fibre surface with hot water, with high pressure steam followed by a rapid depressurization process, repeated freezing-thawing process, and exposure to ionized gas (Plasma treatment) etc. These processes modify the structural characteristics of the fiber and increase the accessibility of reactive areas of the fiber and the base polymer. Better interaction between the reactive sites of the additive and the base polymer results in enhanced adhesion and wetting which results in improved physical attributes of the blend. The appropriate pre-treatment method is determined by the distinctive features of fibers and the essential attributes of the resulting polymer blend. Hot water treatment helps to remove the surface impurities like oils, waxes, dust, and can partially remove the hemicellulose, which makes the fiber surface more accessible for bonding with hydrophobic polymer.[39,40] Steam treatment subjects natural fibers to high-pressure steam, followed by rapid depressurization. This process causes the rupture of the lignocellulosic structure, removes a portion of the lignin and hemicellulose, which makes the fiber more porous with increased surface area and enhances its bonding potential with the polymer.[11,19,41,42] Steam treatment has been successfully employed by the researchers on rice husk to enhance the compatibility of the filler in particle board production and composite panels with enhanced mechanical properties.[19] Panels made of rice husk treated with steam and phenol formaldehyde possess enhanced interfacial bonding and hence show superior modulus of rupture and elasticity compared to those treated with alkali.[11,43] The freeze-thaw process subjects natural fibers to repeated cycles of freezing (usually at temperatures below -20°C) and thawing (at or slightly above room temperature). The freezing process causes the moisture inside the fibers to swell, which forms the tiny fractures and amplifies surface roughness. Subsequent thawing releases the water, resulting in a more porous, rough-textured fiber surface, which leads to enhanced mechanical interlocking with the polymer.[44] In the past few years, the plasma treatment has proven to be a powerful tool for enhancing the binding properties between natural fibers and polymers. Plasma treatment[15,45] subjects the natural fibers to a plasma environment, which is created by applying energy commonly via an electric field to a gas such as nitrogen, oxygen, argon, helium etc. leading to the ionization of gas and the generation of reactive entities (free radicals, ions, electrons, and neutral atoms or molecules etc.). The type of reactive entities produced and their concentration depends upon the selection of gas and the operating conditions. Plasma treatment abrades the fiber's outer layer, which results in enhanced surface texture. It may introduce new functional groups (carbonyl, carboxyl, hydroxyl, amine etc.) onto the surface of the fiber, which may react with the base polymer, considerably improving adhesion at the interface. Additionally, plasma may induce cross-linking within the polymer networks on the surface of the fiber, leading to more stable linkages at the interface of the fiber and the polymer. Several studies[13–15,31,41,45–47] have highlighted the beneficial impact of plasma treatment on the binding strength between natural fibers and base polymers. This process is both safe for health and the environment, and it effectively enhances the surface properties of fibers. However, due to the requirement of expensive and specialized equipment, it has not been explored for large scale production of composites.[15,45]

Chemical Pre-Treatment Methods

Different chemical pre-treatment methods have been reported by researchers to strengthen the linkage between the fiber surface and the polymer base such as alkaline treatment known as mercerization, acetylation, the addition of compatibilizers e.g. maleic anhydride, benzoylation, silane treatment, peroxide treatment and permanganate treatment etc.[1,48,49] Of the various chemical treatments available, the alkaline treatment, known as mercerization, is especially notable for its efficacy and affordability.[18,19] When subjected to alkaline treatment using a NaOH solution, the fiber undergoes a process where its inherent fats and coatings are eliminated from the outer layer. This action exposes the reactive sites of the fiber, enhancing its ability to interact with the matrix material.[18,19,43,50–56] A significant decrease in hemicellulose and lignin content on treating with (2 to 8% weight to volume) NaOH solution has been reported.[18,19,51] The process of mercerization enhances the surface texture of the fiber which connects more efficiently to the polymer structure and enhances the physical performance of the blended material. The physical characteristics of the hybrid material depends on variables like alkali concentration, treatment temperature, and treatment duration.[11,57]

Benzoyl chloride is another chemical frequently used in fiber treatment, in addition to alkaline processes. Benzoylation involves the introduction of a benzoyl functional group at the fiber’s surface, which reduces the moisture affinity of the fiber and enhances its interaction with the non-polar base polymer.[58] Alkaline and benzoylation treatments have been studied on rice husk by various researchers.[18,59] Chemical treatment of rice husk with acetic anhydride i.e. acetylation has also been reported for increasing hydrophobicity of fibers obtained by cross-linking of acetic anhydride with hydroxyl groups of rice husk.[11,60,61] The procedure of acetylation induces plasticization in cellulose fibers. It also enhances the size stability and water resistance of the polymer blend. It has been observed that the application of benzene diazonium salt to RH diminishes its hydrophilic properties and improves its integration with the polymer material.[11,18,19]

Maziad *et al.*[62] explored how including a silane bonding agent influenced the properties of a polymer base strengthened with rice husk. They revealed that the treatment of rice husk with silane led to superior mechanical performance compared to non-treated samples. In an another study,[63] the incorporation of silane-treated rice husk into a polymer matrix of natural rubber exhibited a small enhancement in both flexural and tensile strength in comparison to those treated with the alkaline medium. In the bifunctional configuration of silanes, the alkoxysilane part engages with the hydroxyl groups, while the other terminal group participates in copolymerization with the polymer base. These chemical interactions promote the efficient distribution of loads across the filler and the polymer resin, thereby yielding a material characterized by enhanced mechanical properties.[19]

It has been reported that rice husk and rice straw composites exhibit improved performance when compatibilizers such as maleic anhydride are incorporated.[11,49,59,62,64–67] Rosa and co-authors[67] prepared maleated polypropylene (MAPP) composites with a maximum of 40 weight% loading of rice husk. As per the study, the integration of MAPP enhanced both the loss modulus and storage modulus of the product. Compatibilizers possess both hydrophobic and hydrophilic functional groups that interact with the reinforcement and the polymer to enhance their compatibility, resulting in better bonding and superior mechanical traits of the blended materials.[19] Research studies[68–71] have reported the method of permanganation where mercerized cellulose fibers were soaked in acetone solutions containing varying amount of potassium permanganate ($KMnO_4$). Permanganate treatment establishes radical centers within the cellulose present in natural fibers, which enhances its interaction with the base polymer. In addition to these methods, other compatibilizers and treatments including stearic acid, isocyanates, sodium chlorite and triazine derivatives, etc. can be used for treating cellulose depending upon the specific requirement in the corresponding composites.[11]

Though chemical methods are effective, they lead to issues like environmental effects, workplace safety, and managing toxic waste. The use of toxic chemicals also prompts regulatory and health concerns. Despite these drawbacks, chemical methods are still commonly used due to their confirmed efficiency and consistency in commercial production. To lower their ecological impact, it is essential to seek greener chemical alternatives and optimize waste management strategies, balancing their benefits with a reduction in environmental damage.[15]

General Applications of Rice Husk

Rice husk (RH) possesses a high calorific value of 15217.20 KJ/Kg, and boiler efficiency comparable to that of coal. Therefore, Rice Husk proves to be a more cost-effective fuel than coal.[72] The heat energy generated through the ignition and gasification of RH may be applied in multiple applications e.g. in steam generation and electricity generation.[73,74] Rice Husk exhibits good potential for electricity generation, as 1 ton of RH can produce 1 MWH of electricity. Additionally, it can also function as a substitute energy source for domestic power requirements. Due to the high silica (silicon dioxide) amount found in RH, it has emerged as a valuable resource for various silicon compounds. RH is also utilized in the preparation of advanced materials such as SiN, silanes, SiC, Mg_2Si, Si_2N_2O, elemental Si etc.[75,76] Rice husk can be employed as an organic fertilizer to enhance the crop yield as well as water utilization efficiency in agricultural fields. Because of the high content of dietary fibre (more than 30%), rice husk proves to be an abundant provider of proteins and minerals, rendering it a viable ingredient in the creation of functional foods. Utilization of rice husk in brick production increases porosity, which results in to superior thermal insulation.[77] Studies have shown that rice husk can be processed to generate activated carbon with a microporous structure via physical or chemical activation methods.[78–81] Rice husk possesses insolubility in water, good structural strength and excellent chemical stability because of the high content of silica. This characteristic qualifies it for an important role in the purification of water and wastewater treatment. Sorbents derived from rice husk have been found effective in removing six heavy metals, including Cu, Fe, Cd, Mn, Pb and Zn.[82] Additionally, rice husk acted as an excellent adsorbent for eliminating various contaminants like pesticides, colorants, phenolic compounds, organic substances etc.[83,84] Rice husk has also been recognized as a successful source for bioethanol production.[1,76,85]

Table 2: Effect of Increasing Rice Husk Loading on Polymer Mechanical Characteristics: Reported Studies

Polymer Matrix	Fillers	Materials	Tensile Modulus (MPa)	Flexural Modulus (MPa)	Tensile Strength (MPa)	Impact Strength (kJ/m^2)	Elongation at break (%)	Additional Information	Year of Publication	Ref
PS (Polystyrene)	GMA-RH	Glycidylmethacrylate modified Rice Husk (40 wt % to 60wt%) (5 mm/min)	Increased `~(2900-3300)	Increased ~(1600-1900)	Decreased ~(13-11)	Increased ~(27-32) J/m	–	Chemical modification of RH using GMA improved the flexural, tensile and impact strength of composite.	2000	[86]
PP (Polypropylene)	RHP/Talc	Rice Husk Powder /Talc (60 Php) Php: per hundred part of polymer (5mm/min)	Increased ~ (1000-2100)	Increased ~ (1500-2100)	–	Decreased ~(400-100)	Decreased ~(11-3)	The RHP composites exhibited lower tensile modulus, lower flexural modulus, lower yield strength and greater elongation at break in comparison to talc composites	2002	[26]
PP (Polypropylene)	RHF/RHP	Rice Husk Flour /Rice Husk Powder (40 wt%) (10 mm/min)	Increased –	–	Decreased ~(30-20)	Decreased ~(18-12)	–	Brittleness elevated on increasing crosshead speed, and plastic deformation occurred with higher test temperatures.	2004	[38]
Poly(propylene-co–ethylene) (PP-co-PE)	RH/PP-g-MMI	Rice Husk/ polypropylene with grafting of 1 percent monomethyl itaconate (50 wt%/5 wt%)	Increased (890-1181)	–	Increased (24-28)	–	Decreased (74-3)	Tensile strength improved in the presence of compatibilizer.	2005	[87]
PP (Polypropylene)	MAPP/CRH	Maleic Anhydride grafted PP/Chopped Rice Husk (3/40) php (5 mm/min)	Increased (800-1064) (+33%)	Increased (600-1200) (+100%)	–	Almost constant	Decreased (-99%)	Flexural Strength increased and yield strain & energy-at-break decreased with RH loading	2006	[88]

PP (Polypropylene)	MAgPP/ RH	Maleic Anhydride grafted PP/Rice Husk (3 wt%/30 wt%) (10 mm/ min)	Increased -	–	Almost same	Almost same	–	Adding a compatibilizing agent recovered the tensile strength and tensile modulus, although it did not improve the impact strength.	2007	89
PVC	RH/CARBOXYLATED PLASTICIZER	Rice Husk/ Carboxylated plasticizer (20 wt% to 60 wt%)/40 phr (20 mm/min) Particle size : 150 µm	Increased (35.7-94.7)	–	Decreased (6.2–2.8)	–	–	Smaller particle size of filler lead to better mechanical properties	2008	90
PP (Polypropylene)	MAPP/ RH	Maleated PP/ RH (2 wt%/30 wt%) (2 wt%/40 wt%) (1.5 mm/min)	Increased ~(1600-1800)	Almost same	Increased ~(26-27)	Decreased ~(27-17) J/m	–	Mechanical properties increased on addition of coupling agent	2009	91
PP (Polypropylene)	MAPP/ RHF	Maleated PP/ Rice Husk Flour (1.2 wt%/40 wt%)	Increased (950-1810) (+90.5%)	–	Decreased (32-22) (-31%)	–	Decreased (12-2) (-83.3%)	Tensile strength improved in the presence of maleated PP, showed maximum improvement for ratio MAPP/RH = (0.03).	2009	67
PE (Polyethylene)	Treated RH at pH= 6/7/ 10.5	RH treated with benzenediazonium salt at pH = 6/7/10.5 (40 wt%) (10 mm/min)	Increased (1.78-2.32) GPa	Increased ~(1.1-2.4) GPa	Decreased ~(17.8-15.8)	Increased ~(20-35) J/m	–	Tensile strength, Tensile modulus, flexural modulus and impact strength were highest for RH treated at pH =10.5	2010	54
PLA (Poly Lactic Acid)	RH	Rice Husk (20 wt%) (3 mm/min)	–	Increased (3.4-4) GPa	–	Decreased (37-30) J/m	–	Kenaf fibers provided better outcomes than RH regarding the mechanical features of composites. Chemical	2010	92

								Modification recommended for enhancing RH Performance.		
SBR/LLDPE (Styrene-Butadiene Rubber/ Linear Low density Poly Ethylene) (50/50) wt%	MAH/ DCP/RH	Maleic Anhydride/Dicumyl Peroxide/Rice Husk (2.5/3/25) phr (50 mm/min)	Increased ~(12-19)	–	Increased ~(3-10)	–	Increased ~(80-130)	Mechanical performance improved with RH loading up to 25 phr (part per hundred parts of rubber)	2010	93
PVC (100 phr)	RH/impact modifier	Rice Husk/ Acrylic Impact Modifier (20/8) phr (20 mm/min)	Increased ~ (1.3-1.5) GPa	Increased ~(2.5-3.5) GPa	Decreased ~(55-45)	Decreased ~(6-5)	–	The mixture with 8 percent impact modifier and 20 percent RH loading demonstrated the optimal balance between toughness and stiffness.	2010	94
Epoxy	GF/RH	Glass Fiber/RH (40/15) wt%	–	–	Decreased (362.5-144.35)	–	–	Flexural strength decreased from 388.8 MPa to 269.5 MPa on adding 15 wt% to Epoxy/GF (40 wt%).	2011	95
NR/HDPE (Natural Rubber/High Density Polyethylene) (60/40) wt%	RhiNaLE	The rice husk was subjected to 5% NaOH treatment and subsequently coated with a toluene-based solution of Liquid Epoxidized Natural Rubber (LENR). (10 wt%)	Increased ~(56-68)	–	Increased ~(7.2-6.8)	Decreased ~(26-24)	–	Rice husk modified with 5% NaOH and then with 10% LENR demonstrated the greatest enhancement in tensile strength, rigidity, and impact strength in comparison to untreated rice husk and those treated only with NaOH.	2011	50
UPR (Unsaturated Poly-	RH	Rice Husk (15-20) wt%	Decreased ~(1500-	–	Decreased ~(13-12)	–	–	Tensile modulus decreased at loading	2012	96

ester Resin)		(2 mm/min)	1300)					more than 15 wt%, whereas tensile strength increased at loading greater than 20 wt%.		
Cashew nut shell resin (CNSR)	RH	Rice Husk was subjected to 3N HCl and then treated with 4N NaOH solution. (30 wt%) (5 mm/min)	Increased ~(330-830)	–	Increased ~(10-35)	Increased ~(2.1-7)	Increased ~(3.25-4.6)	Mechanical properties decreased as the particle size increased.	2012	[97]
HDPE (High Density Pol -yethylene)	MAgPE /RH	Maleic Anhydride grafted Polyethylene/Rice Husk (40 wt%) (5 mm/min)	–	–	Increased ~(18.8-23.4)	Decreased ~(15-10.6)	–	Tensile Strength, Flex -ural Strength and Impact strength enhan -ced on addition of MAgPE	2012	[65]
PP/NBRr (Polypropylene/Acrylonitrile butadiene (70/30)	RHP	Acetic Anhydride treated Rice Husk Powder (5-30) wt% (5 mm/min)	Increased ~(760-850)	–	–	–	Decreased ~(7-4.2)	Tensile modulus and elongation at break values increased in the presence of acetic anhydride.	2012	[98]
Recycled PE/ Virgin PE (Polyethylene) (45/20)	RH	Rice Husk (35 wt%) (200 rev/min)	Increased ~(220-550)	Increased ~(1.2-3) GPa	Decreased ~(30-20)	Decreased ~(600-100) J/m	–	Tensile strength increased up to 10 wt% of RH loading.	2013	[99]
PP (100 phr)	RH/MA PP	Rice Husk flour/ Maleic anhydride grafted polypropylene (100 phr/ 4 wt%) RH treated with 1% NaOH	Increased ~(450-790)	Increased ~(1400-2250)	Increased ~(36-37.5)	–	–	Mechanical Performance was improved up to 4 wt% of MAPP and 100 phr of RHF. At higher loading, decrease in properties observed.	2013	[100]
LDPE (Low Density Poly -ethylene)	RH/MMT /MaPE (5/3/4)	Rice Husk/ Mon -tmorillonite Nanoclay/Maleic	Increased (163.4 – 242.3)	–	Decreased (14.6-9.9)	–	Decreased (220-72)	Mechanical properties were further improved on addition of MaPE.	2014	[101]

	wt%	Anhydride modified Polyethylene								
Recycled HDPE	RH/MAPE	Rice Husk/Maleic anhydride grafted polyethylene (40 wt% /4 wt%) (5 mm/min)	Increased (256.821-429.143)	Increased (652.061-1717.508)	–	Decreased (6.171-3.326)	–	Flexural Strength increased with increase in RH loading. Mechanical Properties improved by using coupling agent.	2014	102
rHDPE (Recycled HDPE)/rPET (Recycled Polyethylene Terephthalate) (75/25) wt%	RH/MAPE/E-GMA	Rice Husk/Maleic anhydride grafted polyethylene/ethylene-glycidyl methacrylate (80 wt%/3 phr/5phr) (5 mm/min)	Increased ~(250-1650)	Increased ~(1000-5100)	Increased ~(18-20)	Decreased ~(7-2)	Decreased ~(30-3)	Addition of E-GMA compatibilizer increased the overall mechanical properties of composites.	2015	103
polyhydroxybutyrate (PHB) (80 wt%)	RHt	Hot water treated Rice Husk (20 wt%) 10 mm/min)	Increased (732-754)	–	Increased (9.5-16.1)	Increased (18.6-19.5) J/m	Increased (5.67-6.95)	Mechanical properties were not influenced by fiber treatment.	2018	39
Epoxy Resin	Alkali treated RH	Alkali Treated Rice Husk (20 wt%) (8% NaOH treatment)	Increased (+68.07%)	Increased ~(1220-1620)	Increased (+36.63%)	Increased ~(1.1-2.7)	Increased ~(3.68-3.89)	Mechanical properties were improved up to 8% concentration of NaOH, Higher percentage lead to deterioration of properties.	2018	104
Polypropylene (PP)	RH/MAPP or RH/m-TMI-g-PP	Rice Husk/ maleated Polypropylene or Rice Husk/ m-isopropenyl α–α-dimethylbenzyl-isocyanate grafted Polypropylene ((10-50) wt%/5 wt%) (50 mm/	Increased RH/MAPP (1.9-2.7) GPa or RH/m-TMI-g-PP (1.9-3.47) GPa	Increased RH/MAPP (1700-2700) N/mm^2 or RH/m-TMI-g-PP (1800-3000) N/mm^2	Decreased RH/MAPP (33-29) N/mm^2 or RH/ m-TMI-g-PP (34-32) N/mm^2	Decreased RH/MAPP (22-16) J/m or RH/m-TMI-g-PP (20-15) J/m	–	Tensile and flexural properties were enhanced in presence of compatibilizers. m-TMI-g-PP showed better results than MAPP.	2018	105

		min)								
Epoxy Resin	RH	Alkali treated Rice Husk (10 to 20) wt% (5% KOH) (1 mm/min)	Decreased ~(616.46-290)	–	Decreased ~(66.5-24)	Increased ~(900-1500) J/mm^2	Decreased –	Loading of Rice husk particle at 10 weight percentage showed best results	2019	[106]
poly (butylene adipate co terephthalate) (PBAT)/ Polybutylene succinate (PBS) (36/24)wt%	TPRH/ CS/MA/ DCP	Thermoplastic rice husk/calcium stearate/maleic anhydride/ Dicumyl peroxide (40/0.5/2/0.4) wt% (5 mm/min)	Increased (16.1±2.63 to 200.43 ±14.73)	–	Decreased (38.99±7.25 to 14.27± 1.13)	–	Decreased (1421.93± 123 to 12. 99±2.34)	Formulation containing ratio 24:36:40 (PBS/ PBAT/TPRH) exhibited best mechanical properties.	2020	[107]
recycled high-density polyethylene (rHDPE)	RH	Alkali treated RH (50 wt%) (0.5 M NaOH) (5 mm/min)	Increased ~(420-858)	Increased ~(2215-2500)	Increased ~(5.8-10.8)	Increased ~(1.25-2)	–	UV/O_3 treatment resulted in to better mechanical performance of the composite foam, in comparison to harsh acid treatment.	2020	[108]
Low Density Polyethylene (LDPE)	RH or RHA	Rice Husk or Rice Husk Ash (20 to 40) wt% (50 mm/min)	–	–	Decreased RH- (8.03-6.42) N/mm^2 RHA (9.26-8.79) N/mm^2	–	–	Rice husk ash composites showed higher tensile strength in comparison to rice husk composites.	2022	[109]
Recycled high-density polyethylene (rec-HDPE) (87 wt%)	RH or WF/ MAPE	Rice Husk Powder or Wood Flour Powder/ Maleic anhydride polyethylene (10/3) wt% (1.5 mm/sec)	Increased (+15.8%)	Increased (+51.9%)	Increased (+11.9%)	Increased (+32.65%)	–	Composite with formulation 10 wt% RH reinforced rec-HDPE showed the best mechanical properties.	2023	[110]
Polypropylene (PP)	LFF/BFF /RHP	Long Flax Fibers /Short Basalt	Increased (0.78-4.54)	Increased (0.75-4.85)	Increased (20.12-46.	–	Decreased (66.24±4.4	Incorporation of 6% RHP enhanced the	2023	[111]

		Fibers / Micro Rice Husk Powder (LFF2/ 30 wt%/ 6 wt%)	GPa	GPa	21)		to 6.50± 1.03)	tensile strength by 8% and the tensile modulus by 9.4%., relative to the LFF2/30%BF/PP composite		
Recycled Low Density Polyethylene (RLDPE)	RH	Rice Husk (4mm) (40 to 50) wt%	Increased (256-417) N/mm^2	–	Increased (5.2-8.2) N/mm^2	–	–	RH particles of size 4 mm showed better mechanical performance in comparison to RH particles of size 2 mm.	2023	[112]
Epoxy (50 wt%)	SBF / RH or WP	Sugercane BagasseFiber / Rice Husk or Wood Powder (30/ 5 to 20) wt%	Decreased ~(5.42-5.08) GPa	–	Increased ~(15.58-17.26)	Decreased ~(27-22)	–	SBF/WP showed better mechanical performance in comparison to SBF /RH in Epoxy composite	2023	[113]
poly (butylene adipate coterephthalate) (PBAT) (70 wt%)	AARH	Acrylic grafted Rice Husk (30 wt%) (5 mm/min)	Increased (19.56-21 .87)	–	Decreased (25.19-19.09)	–	Decreased (2601.38-1936.98)	The mechanical prop -erties achieved with the addition of 30% acrylic-grafted rice husk are comparable to those obtained using commercial lignin.	2023	[114]

Mechanical Characteristics of Polymer Composites Reinforced with Rice Husk

Reported studies showing the influence of increasing Rice Husk (RH) loading on mechanical characteristics of reinforced polymer composite have been tabulated in Table 2. The mechanical characteristics examined include tensile modulus, flexural modulus, tensile strength, impact strength, and elongation at break. These properties are very important indicators of a material's performance in various applications. Existing literature spanning the last 20 years has been extensively explored to analyse the contribution of utilizing RH to the mechanical characteristics of RH-integrated polymer composites.

Table 2 reveals that higher loading of untreated rice husk in composites leads to increased tensile modulus and flexural modulus, accompanied by a decline in tensile strength, impact strength, and elongation at break. The variation of tensile strength with higher loading of RH content has been shown graphically (Figure 2) by Yang *et al.*[89] It was proposed that the decline in tensile strength with higher rice husk flour content is because of the weak interaction at the interface of the non-polar base polymer and the hydrophilic filler. The addition of compatibilizers significantly improved the tensile strength as shown (Figure 3) by Yang *et al.*[89] for tensile strength of RHF (30 wt%) reinforced PP composites at different contents of compatibilizers. Similar results for tensile and flexural strength (Figures 4 a & b) have also been reported by Raghu and co-authors[105] for PP/RH composites.

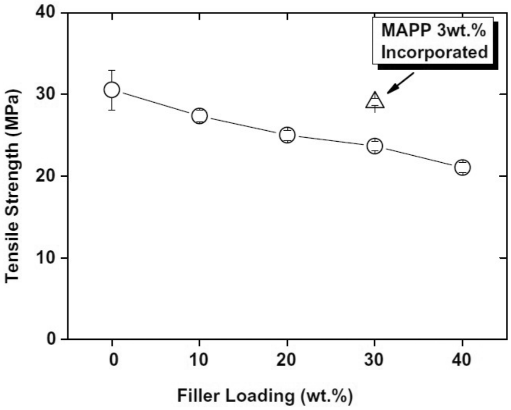

Fig. 2: Tensile strength of PP composites at various loading of RH[89]

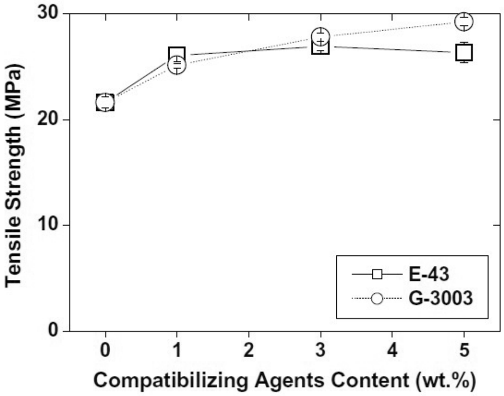

Fig. 3: Tensile strength of PP/RHF (30 wt%) with weight percent of compatibilizing agents[89]

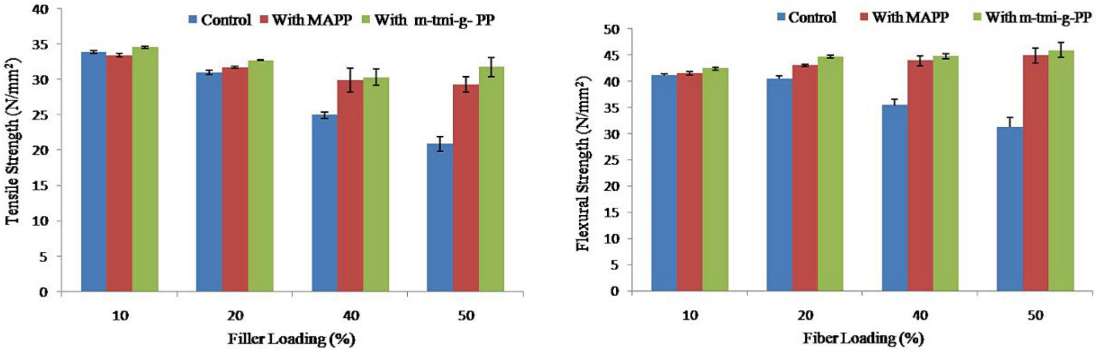

Fig. 4: (a) Tensile strength and (b) Flexural strength of PP/RH composites with untreated PP; Polypropylene grafted with MAPP; and Polypropylene grafted with m-TMI-g-PP compatibilizers[105]

It was found that the inclusion of compatibilizers enhanced the flexural and tensile properties of composites effectively. The action mechanism of compatibilizer (Figure 5) has been proposed by Yang *et al.*[89] It has been suggested that the compatibilizers form chemical bonds with the hydrophilic filler and are integrated into the polymer matrix by wetting.

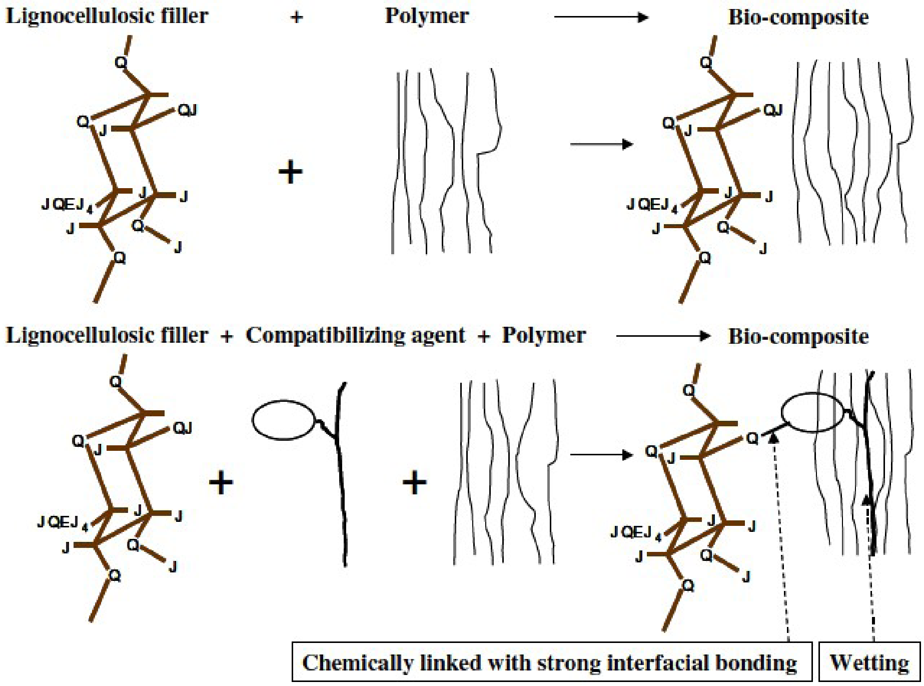

Fig. 5: The action mechanism of compatibilizer in enhancing affinity at the interface of hydrophobic base polymer and hydrophilic filler[89]

From various reported results (Table 2), it can be interpreted that incorporation of pre-treated or modified rice husk or compatibilizers leads to enhanced mechanical performance of the polymer blend. Pre-treatment or modification of rice husk and inclusion of compatibilizers is very crucial in enhancing the mechanical characteristics of RH-reinforced composites. It facilitates better adhesion of RH-filler with the base polymer thereby improves the interfacial bonding and overall composite performance. Toro and co-authors[87] analysed the influence of adding the compatibilizer PP-g-MMI to RH/PP-Co-PE (rice husk-reinforced poly(propylene-co-ethylene)). The inclusion of 5 wt% of PP-g-MMI to RH/PP-Co-PE resulted in a significant increase in tensile modulus, from 715 MPa to 1181 MPa, and tensile strength, from 16 MPa to 28 MPa. The Scanning electron microscopy (SEM) analysis indicated enhanced adhesion and greater phase consistency at the interface of RH and PP-Co-PE components within the composite, which was attributed to the inclusion of PP-g-MMI. Similarly, Razavi-Nouri and co-authors[88] investigated the mechanical performance of chopped RH (CRH) in PP. The formulation containing 3 php (part per hundred parts of polymer) of MAPP and 40 php of RH exhibited a notable increase of approximately 33% in tensile modulus, 16% in flexural strength, and 100% in flexural modulus, while the decrease in the impact strength was negligible. Further, Premalal and his team[26] evaluated the mechanical performance of PP strengthened with rice husk powder and talc. They found that increasing the loading of both fillers improved Young's modulus and flexural modulus but reduced yield strength and elongation at break. At similar loading levels, talc enhanced the moduli and yield strength more effectively than the rice husk powder. This difference was attributed to talc's finer particle metrics and greater surface profile, which enhanced the bonding at the interface of the reinforcing material and the polymer substrate. In addition, Rosa *et al.*[67] explored the impact of maleated polypropylene (MAPP) on polypropylene composites strengthened with rice husk flour. The inclusion of the compatibilizer MAPP resulted in improved tensile strength for all filler loadings. This improvement was due to the reaction involving the –OH functionalities of the rice husk and the acidic anhydride moieties of MAPP. The formulation containing 1.2 wt% of MAPP and 40 wt% of rice husk, with a MAPP/RH ratio of 0.03, demonstrated the most significant enhancement in mechanical performance. Therefore, the proportion of coupling agent to filler is essential in determining the final attributes of the composite. Moreover, Raghu and others[105] examined the effects of compatibilizers—MAPP and m-TMI-g-PP on rice husk (RH)-filled polypropylene composites. The inclusion of 5 wt% of either compatibilizer, combined with 40-50% of RH filler, showed a 40% rise in tensile strength for MAPP and a 52% rise for m-TMI-g-PP in comparison to the composites with no compatibilizer. Interestingly, m-TMI-g-PP exhibited enhanced performance compared to MAPP, which resulted from the reaction involving the –OH functionalities of RH and the isocyanate moieties of m-TMI-g-PP. They mentioned that the carbamate ester bond formed between the m-TMI-g-PP and the –OH functionalities of RH is stronger than the anhydride ester linkage formed between the MAPP and the –OH group of RH. In a report by Tong and co-authors,[102] the mechanical characteristics of recycled HDPE (rHDPE) were evaluated by integrating RH along with MAPE as a compatibilizer. The composite containing 40 wt% RH filler exhibited the maximum tensile modulus of 429.143 MPa and the maximum flexural modulus of 1717.508 MPa. However, the pure HDPE composite demonstrated the highest impact strength (6.171 kJ/m²) compared to the RH-reinforced composites. The decline in impact strength was related to the restriction of base polymer flow in the presence of the filler, leading to increased brittleness in the resultant composite. Additionally, Bisht and others[104] examined the impact of alkali (NaOH) treatment on the RH flour-filled epoxy resin. The mechanical performance of the material was improved with increasing NaOH concentration, reaching an optimal level at 8% NaOH. The composite containing 20 wt% RH modified using 8% NaOH exhibited a remarkable increase in tensile modulus and tensile strength, by 68.07% and 36.63%, respectively, in comparison to the pure epoxy. Furthermore, flexural properties, impact strength, and elongation at break were significantly enhanced with higher loading of RH treated with 8% NaOH. The observed increase in tensile strength, impact strength and elongation at break with RH loading contradicted previously reported results and was attributed to the alkali treatment, which increased the roughness and hydrophobicity of the filler, enhancing its compatibility with the epoxy resin. However, at concentrations above 8% NaOH, the mechanical properties declined due to the degradation of rice husk properties from excessive alkali exposure. In a recent study by Shah and co-authors,[110] rice husk and wood flour were incorporated in recycled high-density polyethylene (rec-HDPE) to assess their influence on the mechanical, thermal, and flammability characteristics of the composites. The findings indicated an improvement in mechanical characteristics with increasing filler content. The composite (rec-HDPE/RH/MAPE) with a composition of 87/10/3 wt% displayed the best mechanical characteristics, showing enhancements of 15.8% in tensile modulus, 51.9% in flexural modulus, 11.9% in tensile strength, and 32.65% in impact strength compared to unfilled rec-HDPE. The SEM analysis further confirmed a homogeneous distribution of rice husk within the base polymer, with no evidence of agglomeration. The application of MAPE as a compatibilizer enhanced the interactions at the interface of RH and rec-HDPE, resulting in superior mechanical attributes for the composite. Various studies reveal that the careful formulation optimization while considering various parameters like filler-to-polymer ratio, compatibilizer concentration, and processing conditions, is very essential for achieving desired mechanical characteristics of polymer composite. Incorporation of other additives, such as montmorillonite nanoclay can further enhance mechanical properties through synergistic effects. When utilized with recycled polymers like rec-HDPE, the combination of rice husk (RH) and compatibilizers showed marked improvements in the mechanical features of the base polymer. Such combinations can result in high-performance, innovative, and environmentally benign materials suitable for a range of industrial applications.

Conclusion

Rice husk is an abundantly available field residue which is obtained as a byproduct of rice milling. Its integration into polymer composites offers an excellent opportunity to convert this waste into a valuable resource which contributes to sustainability and environmental conservation. Various studies have shown that the inclusion of rice husk in polymer composites improves different mechanical characteristics, such as tensile modulus, flexural modulus, tensile strength, and impact strength. Most of the research findings suggest that the higher loading of untreated rice husk in composites leads to increased tensile modulus and flexural modulus, accompanied by reduction in impact strength, tensile strength, and elongation at break. However, the incorporation of treated or modified rice husk or compatibilizer improves all the mechanical characteristics of polymer composite. The compatibilizers like maleic anhydride polyethylene (MAPE), and m-TMI-g-PP improve mechanical properties of the polymer composites by enhancing filler dispersion and interfacial adhesion. Further, the pre-treatment of RH with the alkali can boost tensile and flexural properties by increasing surface roughness and hydrophobicity, although excessive treatment may degrade the filler. The comparison between RH and other fillers, such as talc, highlights the importance of filler characteristics in determining the composite performance. In recycled polymers like rec-HDPE, the use of RH with a compatibilizer leads to marked improvements in tensile and flexural strength, emphasizing the importance of compatibilizer/filler ratios in optimizing the mechanical performance of the material. These formulations may result in innovative, high-efficiency materials that are both sustainable and suitable for numerous industrial applications. Careful optimization of formulation along with consideration of diverse parameters like the ratio between filler and base polymer, the concentration of compatibilizer, and the conditions of processing, is crucial for attaining the preferred mechanical characteristics of polymer composites. Moreover, the appropriate pre-treatment approach must be selected according to the specific requirements, along with the fiber and polymer characteristics, and the necessity to balance performance, cost, and ecological impact.

Future Prospects

The future prospects for utilizing rice husk in polymer composites is bright driven by its sustainability, improved mechanical properties, cost efficiency, biodegradability, eco-friendly nature, and versatile applications. These factors suggest the rice husk-integrated polymers as valuable materials for sustainable and advanced engineering in the future. Rice husk is a cost-effective raw material, particularly in regions where rice cultivation is predominant. Its utilization in polymer composites results in lower production costs compared to conventional fillers or reinforcement agents, which makes these materials more economically viable. Polymer composites that include rice husk offer a greener alternative to conventional materials, especially in applications where biodegradability is desired, such as packaging or disposable items. Moreover, the use of rice husk in recycled polymers, yielding exceptional mechanical properties, presents an effective approach for developing high-performance materials while simultaneously promoting environmental conservation by reducing waste and the demand for new materials. The integration of rice husk into a variety of polymer matrices presents vast potential for diverse applications across industries, such as automotive components, building materials, agricultural equipment, and consumer goods. To fully exploit its potential, further research and optimization of the formulation are necessary. Factors such as the ratio between filler and polymer, the concentration of compatibilizers, and the processing conditions must be carefully adjusted to achieve the desired mechanical performance. Additionally, it will be important to select the appropriate pre-treatment methods for fibers and polymers to effectively balance performance, cost, and ecological considerations. Greener chemical alternatives and optimized waste management strategies will be essential for minimizing ecological damage while maximizing the benefits of rice husk-reinforced polymer composites. As research and innovation continue to progress, the focus on refining these composites will enhance their suitability for a broader spectrum of applications.

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Informed Consent Statement
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Clinical Trial Registration
This research does not involve any clinical trials.

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- **Dr. Meera:** Visualization, Methodology.
- **Dr. Malvika Kadian:** Writing, review & editing.
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