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Hybrid Polymer Composites Reinforced with Coconut Shell Fillers and Silica Fume: Synergistic Effects of Industrial By-Products: A Comprehensive Review

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Abstract

The increasing requirement of sustainable and high-performance engineering materials has led to increased research in hybrid polymer composites comprising sustainable fillers in the form of renewable biomass or industrial by-products. Among the various bio-fillers that exist, coconut shell filler is gaining much prominence due to its low density, high content of lignin, hardness, and abundance as agricultural waste. Another industrial by-product that is rich in amorphous silica and possesses high potential for improving the mechanical and thermal properties of polymer composites is silica fume. The combination of these sustainable fillers in polymer composites represents an excellent option for developing eco-friendly composites with enhanced performance properties, along with waste utilization and conservation of resources. This review article highlights some of the important advancements in hybrid polymer composites reinforced with coconut shell fillers and silica fume. The effects of these hybrid fillers on tensile, flexural, impact, hardness, wear, thermal stability, water absorption, and microstructure behavior are explained in detail by the use of information provided from the literature. In addition, advanced analytical methods such as scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), x-ray diffraction (XRD), thermogravimetric analysis (TGA), and dynamic mechanical analysis (DMA) are analyzed in terms of the mechanisms that govern the composite behavior. Lastly, the existing difficulties concerning dispersion, compatibility, moisture sensitivity, and mass production issues associated with hybrid polymer composites are pointed out, along with the future perspectives of the area, which include the utilization of nanofillers, biopolymers, additive manufacturing, and circular materials design.

Keywords: Hybrid polymer composites, coconut shell fillers, silica fume, industrial by-products, sustainable composites, mechanical properties

INTRODUCTION

The increasing trend in the field of sustainable engineering has sparked the interest in developing environmentally friendly polymer composites that use renewable sources of natural filler and industrial by-products. The existing synthetic reinforcements are highly effective in terms of providing good mechanical properties; however, their expensive manufacturing process, non-biodegradability, and high environmental footprint have urged scientists to find sustainable substitutes for them. The natural fillers extracted from agricultural wastes have been proved to be the effective reinforcement due to the fact that they are renewable, cost-effective, light-weight, and easily available. The use of such fillers in the matrix of polymers helps not only in reducing the cost of material but also in waste management and creation of green composites [1].

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There is much interest in coconut shell as a green reinforcement filler due to its high lignin content, low density, high hardness, and easy accessibility as an agricultural waste product. By proper treatment of coconut shell as powder or ash, the particles of the coconut shell can be blended with thermoset and thermoplastic polymers, thereby increasing their rigidity, hardness, wear resistance, and stability [2]. Some researches have shown that proper amount of fillers improves mechanical properties of materials, while excess of fillers causes agglomeration of particles, poor interface bonding, and low impact resistance. The surface treatment of fillers such as alkalization and silanization has also been mentioned to increase adhesion between fillers and matrix materials [3].

Silica fume, which is a byproduct formed during the manufacturing of silicon metal and ferrosilicon alloys through an ultrafine material process, is increasingly being used as a filler material in polymer composites because of its high amorphous silica composition and very fine particle size. This is because silica fume helps in improving filler dispersion, interface bonding, thermal stability, and crack propagation resistance in polymer matrices by minimizing the formation of micro voids in the polymer matrix. Therefore, silica fume is an excellent second level reinforcing material for making performance-based sustainable hybrid polymer composites. In addition, the use of this industrial byproduct is in line with the concepts of the circular economy [4].

While many research works have been done for polymer composites containing either coconut shell or silica fume as reinforcing agent separately, there are very few comprehensive reviews available that consider both reinforcing agents together. In the majority of the existing literature, most of the review articles are mainly concerned with the review of natural fibre-reinforced composites or industrial waste as fillers separately and the combination of both as reinforcing agents is rarely considered. The connection of the processing techniques, interfacial features, characterization methods, and performance of the polymer composite system is yet to be comprehensively reviewed. This review article attempts to discuss the recent advances in the hybrid polymer composite system reinforced with coconut shell and silica fume [5].

LITERATURE REVIEW

The utilization of agricultural waste as filler in polymer composites has gained wide recognition due to the benefits it offers in terms of enhancing material behavior while mitigating environmental concerns. Kalla et al. found that the coconut shell powder was a useful filler for epoxy composites due to its high lignin content, low density, and good hardness, which provide stiffness and wear resistance at optimal filler loading. In addition, Sapuan et al. found that there was enhancement in mechanical properties of the epoxy composites with coconut shell filler; however, high filler loading lowered the tensile and impact strength due to agglomeration of the filler [6].

The use of industrial by-products has also been recognized as an excellent reinforcement choice for composite materials due to their performance and sustainability benefits [7]. These include silica fume, which has been identified as an interesting secondary reinforcement material due to its extremely fine particles and high amorphous silica. The use of silica fume in composites has been shown to result in improved interface adhesion, matrix densification, and thermal stability due to filling of voids in the polymer matrix. Even though silica fume is extensively researched in cement-based materials, relatively little is known about its use in polymer-based hybrid composites.

Hybrid reinforcement methods have become an area of research interest in recent years because they involve the use of agricultural waste along with industrial waste for synergistic enhancement of composite properties [8]. Various combinations of coconut shell-based fillers have been used along with fly ash, nano-silica, rice husk ash, and other mineral fillers with enhanced mechanical and thermal properties than composites reinforced with one filler alone. However, the joint use of coconut shell fillers with silica fume has not garnered much attention from researchers in the past.

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Although significant advances have been made in the field of sustainable polymer composites, there still remain several issues that require research. The majority of the existing research studies concentrate on only one type of filler - either coconut shell or silica fume. Moreover, there is not enough data about the correlation between the processing, modification of the filler surfaces, modern characterization techniques, and mechanical properties. That is why the goal of this review is to summarize the current literature on the topic, analyze the existing information, identify research gaps, and make some suggestions for future studies [9].

COCONUT SHELL FILLERS AND SILICA FUME AS SUSTAINABLE REINFORCEMENTS IN HYBRID POLYMER COMPOSITES

Due to the increasing importance of sustainable material development, there has been a trend towards the use of agricultural waste and industrial by-products as reinforcing materials for polymer composite applications. One of the many natural reinforcements that has received much consideration is coconut shell owing to its excellent mechanical properties, renewable character, and abundance. Another material that has proven effective as a reinforcing agent is silica fume, which is a very fine industrial by-product of silicon and ferrosilicon alloys. This material is characterized by very high amorphous silica content and high pozzolanic activity [10].

Coconut Shell Fillers

Coconut shell is an agricultural residue obtained in large amounts during the processing of coconuts in different countries across the globe. Formerly, considered as a waste, coconut shells have now become useful sustainable reinforcing fillers in polymer composites because of their high content of lignin, light weight, hardness, and good wear resistance. Coconut shell, after appropriate processing such as cleaning, drying, milling, sieving, and surface treatment, can be made into powder or ash form and used in composites.

Adding coconut shell fillers into matrices such as epoxy, polyester, polypropylene, and polyethylene is known to increase stiffness, hardness, abrasion resistance, and dimensional stability of the composites. Further, surface treatments like alkali and silane treatments have been found to make the filler more compatible with the matrix through decontamination and roughening of the surface to ensure higher stress transfer efficiency. Nevertheless, addition of excess amount of fillers has caused particle agglomeration and high moisture absorption, leading to lower tensile and impact strengths. It follows that the choice of proper filler and processing method is key to getting balanced properties of the composite. Figure 1 illustrates the sequential processing route adopted for preparing coconut shell fillers for polymer composite applications. The process includes cleaning, drying, crushing, grinding, sieving, and surface treatment before incorporation into the polymer matrix. Each processing stage contributes to improving particle size uniformity, reducing impurities, and enhancing filler–matrix compatibility, thereby promoting better mechanical performance and interfacial bonding in the fabricated composite materials [11].

Silica Fume as a Functional Industrial By-Product

Silica fume is an ultra-fine powder generated as a byproduct in the manufacturing process of silicon metal and ferrosilicon alloys. Silica fume is mainly composed of amorphous silicon dioxide and exhibits a very high specific surface area that enables it to be used as a reinforcing agent in polymer-based composites due to the small sizes of particles that effectively fill voids in the polymer matrix [12].

It has been demonstrated that the addition of silica fume in polymer-based composites results in improved tensile strength, flexural strength, hardness, thermal stability, and wear resistance of composite structures. Moreover, silica fume ensures an effective load transfer and crack resistance due to higher density of composite microstructure. Despite the vast amount of research carried out on cement-based composites, there are few publications related to the use of silica fume in hybrid polymer-based composites. This opens the perspective of developing sustainable polymer-based composites by utilizing silica fume together with natural fillers such as coconut shell powder Table 1 presents a comparative summary of coconut shell fillers and silica fume based on their origin, chemical composition, particle size, density, and functional contribution to composite reinforcement. The comparison highlights the complementary roles of these materials, where coconut shell fillers primarily improve lightweight reinforcement and toughness, while silica fume enhances matrix densification and interfacial adhesion [13].

The complementarity between the coconut shell fillers and silica fume is illustrated by Table 1 below. The coconut shell filler provides lightweight reinforcement and increases the toughness of the material while the silica fume densifies the matrix and improves the interfacial bond strength.

Synergistic Reinforcement Mechanism

The combination of coconut shell fillers and silica fume results in various mechanisms of reinforcement that improve the properties of polymer composites. Coconut shell fillers function as the main reinforcing component as they help to increase stiffness, hardness, and impact strength, while silica fume fills in the micro-pores and reinforces the interface between the filler and the polymer matrix. As a result, the combination of such reinforcement mechanisms improves the efficiency of load transfer, prevents cracking and ensures better thermal stability and wear resistance of the composite material.

Figure 1. Processing route for coconut shell fillers used in hybrid polymer composites.

Table 1. Comparison of coconut shell fillers and silica fume used in hybrid polymer composites.

Property	**Coconut shell fillers**	**Silica fume**
Source	Agricultural waste	Industrial by-product
Main constituent	Cellulose, lignin	Amorphous SiO_2
Density	Low	Moderate
Particle size	50–500 µm	0.1–1 µm
Main contribution	Toughness and lightweight reinforcement	Matrix densification and improved bonding
Sustainability	Renewable	Recycled industrial waste

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Therefore, hybrid polymer composites filled with coconut shell fillers and silica fume perform much better than conventional composites filled with a single reinforcing component. Figure 2 schematically illustrates the synergistic reinforcement mechanism developed by combining coconut shell fillers with silica fume in a polymer matrix. The illustration demonstrates how coconut shell particles act as the primary reinforcement, whereas silica fume fills microvoids and strengthens the filler–matrix interface, resulting in improved load transfer efficiency, crack resistance, and overall composite performance [14].

PROCESSING AND FABRICATION TECHNIQUES OF HYBRID POLYMER COMPOSITES

The process of manufacture is very important in dictating the properties of the mechanical, thermal, and durable nature of hybrid polymer composite materials. Selecting the right manufacturing procedure will result in the dispersion of fillers, good interfacial bonding, minimization of voids, and overall structural strength. The method of manufacture will basically depend on the nature of the polymer matrix used, the type of fillers, reinforcing materials present, and the engineering application to be adopted. Various methods of manufacturing have been applied in the past few years [15].

Hand Lay-Up Technique

The hand lay-up technique represents one of the simplest and most cost-effective composite fabrication methods used for polymer composites. According to the hand lay-up technique, the polymer matrix is mixed with the coconut shell filler and silica fume through mechanical stirring for obtaining a well-dispersed composite. The mixture is placed in the mould and then rolled manually for removing air bubbles. The next step is curing of the composite under ambient or high temperatures depending on the polymer used [16].

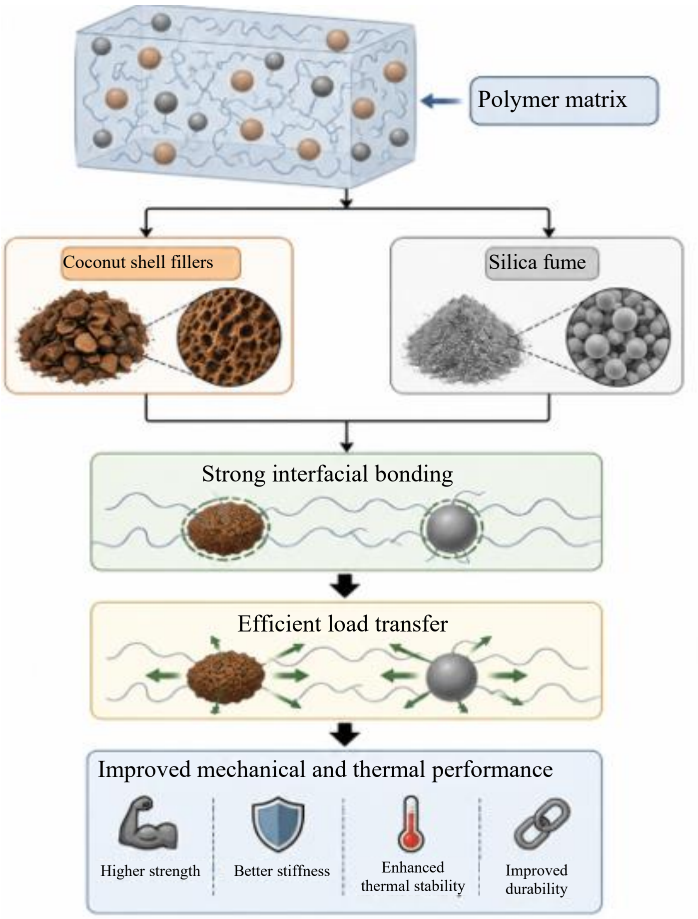

Figure 2. Reinforcement mechanism of coconut shell fillers and silica fume in polymer composites.

Figure 3. Hand lay-up fabrication process for hybrid polymer composites.

The hand lay-up technique is extensively used for experimental studies due to low expenses and simplicity of fabrication. However, the quality of the composite highly relies on the operator's skills, while high concentrations of fillers can cause poor mixing and formation of voids. Figure 3 presents the complete hand lay-up fabrication procedure adopted for producing hybrid polymer composites reinforced with coconut shell fillers and silica fume. The sequence includes matrix preparation, filler incorporation, mixing, mould casting, roller compaction, and curing, all of which contribute to achieving uniform filler distribution and minimizing internal voids within the composite.

Compression Moulding

Compression moulding is perhaps the most commonly employed technique in making superior quality hybrid polymers. In this technique, the mixture of polymer and fillers is inserted into the heated steel mould and is compressed under pressure and temperature conditions. Pressure helps in enhancing the filling capacity of the filler material and results in increased denseness along with better bonding of the matrix polymer and the reinforcing filler. As compared to the hand lay-up technique, composite produced by compression moulding possesses better dimensional precision, higher density, and improved mechanical strength [17].

Injection Moulding and Advanced Manufacturing

Injection moulding technology is mainly used for the manufacturing of hybrid polymer composites made up of thermoplastics. Polymer pellets are first melted and then mixed with the coconut shell fillers and silica fume to be fed into a closed cavity of the mould through injection at a very high pressure. This technology provides fast manufacturing, good dimensional accuracy and very high consistency and hence is ideal for mass industrial manufacturing.

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Table 2. Comparison of fabrication techniques used for hybrid polymer composites.

Fabrication technique	Advantages	Limitations	Typical applications
Hand Lay-Up	Low cost, simple process	Non-uniform filler distribution	Laboratory research
Compression moulding	High strength, low porosity	Higher equipment cost	Structural components
Injection moulding	High production rate, dimensional accuracy	Suitable mainly for thermoplastics	Automotive and consumer products
Resin Transfer moulding	Excellent surface finish, good fibre wetting	Complex mould preparation	Aerospace and marine applications
3D printing	Complex geometries, reduced material waste	Limited material compatibility	Functional prototypes and customized components

Table 3. Factors affecting tensile properties of hybrid polymer composites.

Parameter	Influence on tensile strength
Filler loading	Moderate loading improves strength
Particle size	Fine particles improve bonding
Surface treatment	Enhances interfacial adhesion
Processing technique	Improves filler distribution
Polymer matrix	Determines load transfer efficiency

Latest technological advancements have also brought about modern methods such as RTM, resin infusion and 3D printing [18]. Table 2 compares the commonly employed fabrication techniques used for hybrid polymer composites, together with their advantages, limitations, and typical engineering applications. The comparison demonstrates that the selection of an appropriate manufacturing technique significantly influences filler dispersion, composite quality, dimensional accuracy, and mechanical performance.

Table 2 outlines some of the most common methods used in the preparation of hybrid polymer composite materials. The choice of the processing method plays an important role in determining the quality of the prepared composite materials.

MECHANICAL PROPERTIES OF HYBRID POLYMER COMPOSITES

The mechanical behaviour of hybrid polymer composites depends mainly on the nature of the polymer matrix material, reinforcement material, fillers, size of the particles and the method of processing. It has been established that the use of coconut shell fillers and silica fume improves the mechanical behaviour of polymer composites. The dual reinforcement effect provided by the natural fillers and industrial waste materials improves the tensile, flexural, impact and hardness of the polymer composites [19].

Tensile Properties

One of the critical factors employed in assessing the load-bearing ability of hybrid polymer composites is tensile strength. The coconut shell filler makes the material stiff due to its rigid lignocellulosic nature while silica fume promotes interfacial bonding through filling up of microvoids present in the polymer matrix. Together, these two additives make stress transfer from the matrix to the fillers more efficient thereby improving tensile properties of the composite. However, the overuse of filler leads to agglomeration, stress concentration and poor dispersion leading to reduced tensile strength. Thus, proper selection of the right amount of filler is key to maximizing mechanical strength. Figure 4 illustrates the principal factors governing the tensile behaviour of hybrid polymer composites. Parameters such as particle size, filler dispersion, interfacial bonding, and efficient stress transfer collectively contribute to improved tensile strength, while poor dispersion and filler agglomeration adversely affect the overall mechanical response of the composite. Table 3 summarizes the major factors affecting the tensile properties of hybrid polymer composites. Proper optimization of filler loading, particle size, surface treatment, processing technique, and polymer matrix selection is essential for maximizing tensile strength and achieving reliable structural performance.

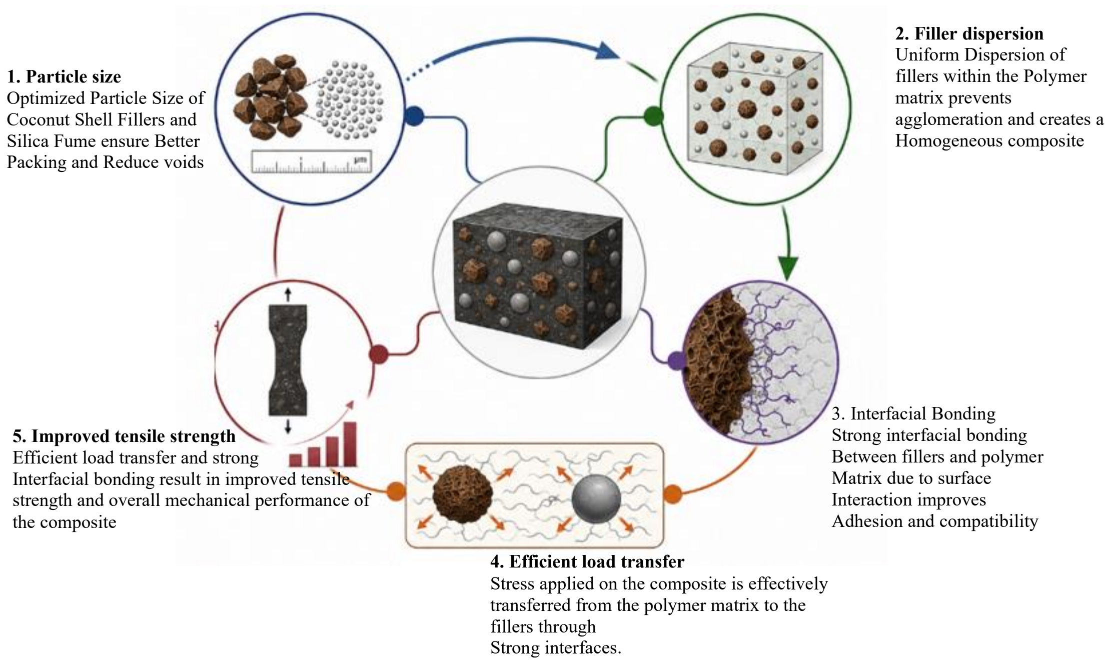

Figure 4. Factors influencing the tensile behaviour of hybrid polymer composites.

Flexural Properties

Flexural strength is a mechanical property that affects the ability of hybrid polymer composites to withstand bending forces without failing. The addition of coconut shell fillers increases the rigidity of the composite due to their stiff lignocellulosic nature, while silica fume ensures strong interface by minimizing the formation of microvoids in the interface. The net result of these reinforcements increases the stress distribution under bending forces hence improving flexural strength and modulus of the composite. The level of improvement depends on the amount of filler, particle size, processing conditions, and compatibility of the matrix and reinforcing materials.

A number of studies have shown that moderate filler loading gives optimum flexural properties while high filler loading leads to particle agglomeration and poor interfacial regions hence initiating cracks during bending. Surface modifications like alkali and silane treatment are done to enhance the dispersing and interfacing of the fillers, thus giving better flexural properties to the hybrid polymer composite. Hence, it is very important to get an optimum blend and process of fabrication to obtain hybrid polymer composites with good flexural properties. Figure 5 illustrates the factors influencing the flexural behaviour of hybrid polymer composites under bending loads. The figure demonstrates that efficient stress distribution, improved interfacial bonding, and enhanced crack resistance collectively contribute to superior flexural strength and stiffness of the composite system. Table 4 summarizes the primary parameters influencing the flexural performance of hybrid polymer composites. The information indicates that optimum filler content, homogeneous particle dispersion, effective surface treatment, and appropriate processing methods are essential for improving flexural strength and minimizing premature failure.

The factors affecting the flexural properties of hybrid polymer composites are summarized in Table 4 below. Optimizing these factors plays a very vital role in enhancing flexural strength.

Impact Strength

Impact strength is one of the crucial parameters that define the energy absorbing capability of the hybrid polymer composites under sudden loadings. Coconut shell fillers enhance the energy absorbing capacity due to the rigid nature of these fillers, while silica fume increases the interface between fillers and matrix by reducing voids in the matrix. It helps in delaying the initiation and propagation of cracks.

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As a result, it increases the impact resistance of the composite. But high filler content may lead to particle agglomeration and poor bonding, thus adversely affecting impact resistance. Table 5 summarizes the principal factors governing the impact strength of hybrid polymer composites. Appropriate filler dispersion, strong interfacial adhesion, and optimized filler loading significantly improve energy absorption capacity and delay crack initiation during impact loading.

The factors responsible for affecting the impact strength of hybrid polymer composites have been summarized in Table 5. Effective filler dispersion and bonding at the interface greatly enhance the energy dissipation capability and fracture toughness of the composite.

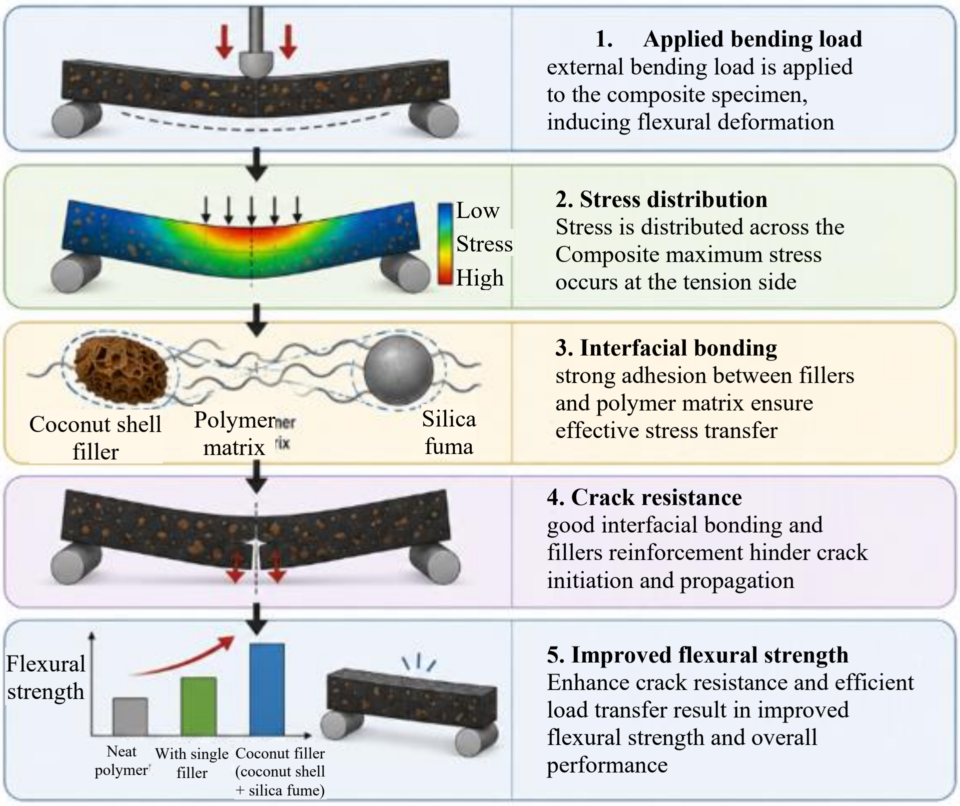

Figure 5. Factors influencing the flexural behaviour of hybrid polymer composites.

Table 4. Factors affecting flexural properties of hybrid polymer composites.

Parameter	Effect on Flexural Performance
Filler content	Moderate content improves bending strength
Particle dispersion	Uniform dispersion reduces stress concentration
Surface treatment	Improves filler–matrix bonding
Polymer matrix	Influences stiffness and flexibility
Processing method	Controls void formation and composite quality

Table 5. Factors affecting impact strength of hybrid polymer composites.

Parameter	Effect on Impact Strength
Filler loading	Optimum loading improves energy absorption
Particle dispersion	Uniform dispersion delays crack propagation
Interfacial bonding	Strong bonding enhances impact resistance
Surface treatment	Improves filler compatibility
Polymer matrix	Influences toughness and ductility

MICROSTRUCTURE AND THERMAL PROPERTIES OF HYBRID POLYMER COMPOSITES

Scanning Electron Microscopy (SEM)

SEM is extensively used for characterization of morphological structure and interfacial bonding in hybrid polymer composites. SEM reveals important details about the filler dispersion, formation of voids, crack formation, and the interaction of coconut shell fillers, silica fume, and polymer matrix. Good filler dispersion and interfacial bonding in SEM results are typically associated with better mechanical behavior, while particle agglomeration and microvoid formation cause early failure [18].

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR spectroscopy is used to identify the functional groups in the polymer composites and to study the chemical interactions occurring between polymer matrix and the reinforcement fillers.

X-Ray Diffraction (XRD)

The XRD technique is used for identifying the crystalline structure and phases present in the hybrid polymer composites. The use of silica fume and coconut shell filler contributes to the crystallinity of the polymer matrix that directly impacts its stiffness and mechanical properties. Table 6 provides a summary of the major characterization techniques employed for evaluating hybrid polymer composites. Each analytical technique offers specific information regarding morphology, chemical interactions, crystalline structure, thermal stability, and viscoelastic behaviour, thereby enabling a comprehensive assessment of composite performance.

Thermogravimetric Analysis (TGA)

The technique TGA is employed to study the thermal stability and the process of degradation of the hybrid polymer composites. The inclusion of silica fume results in increased thermal resistance because it retards the process of decomposition, whereas coconut shell filler increases the thermal insulation property of the composite material.

Dynamic Mechanical Analysis (DMA)

This technique is employed for studying the viscoelastic behavior of the polymer composites, which include measurements of storage modulus, loss modulus, and damping properties. Hybrid composites incorporating coconut shell fillers and silica fume result in high stiffness of the material and load-carrying capacity [17].

ENGINEERING APPLICATIONS OF HYBRID POLYMER COMPOSITES

Hybrid polymer composites strengthened with coconut shell filler and silica fume have attracted much interest in various engineering areas due to their light weight, high specific strength, superior thermal stability, enhanced wear resistance, and environmental sustainability. In the automotive field, the composites have been extensively used as interior panels, dashboards, bumper parts, and door trims to lower the weight of cars and save on fuel consumption. The combination of strength and lightness, together with corrosion resistance, has made them applicable in the aerospace and maritime sectors as cabin panels, light structures, and protective covers. Hybrid polymer composites have been frequently used in the construction industry in partition panels, roof panels, insulation, and decorative structural elements, thanks to their improved durability and dimensional stability. Besides, good electric insulation, processability, and affordability have increased their application in electrical enclosures, consumer goods, furniture, sports equipment, and casings of electronics [16].

Table 6. Characterization techniques and their significance.

Technique	Purpose	Information Obtained
SEM	Surface morphology	Filler dispersion, cracks
FTIR	Chemical analysis	Functional groups, bonding
XRD	Crystal structure	Crystallinity, phase identification
TGA	Thermal analysis	Thermal stability
DMA	Viscoelastic behaviour	Storage modulus, damping

CHALLENGES AND FUTURE PERSPECTIVES

However, in spite of the substantial development reached in the area of hybrid polymer composites based on coconut shell fillers and silica fume, there are certain problems that need to be addressed. Being natural, fillers are generally hydrophilic and this can lead to an increase in moisture absorbance and poor interaction with hydrophobic polymer matrices. Moreover, filler agglomeration, poor dispersion, and different sizes can negatively influence the mechanical and thermal properties of the composite materials. Future scientific efforts in this field should be devoted to advanced surface treatment of fillers, appropriate filler content in the matrix, use of nanofillers, and development of biopolymers as polymer matrixes. The implementation of additive manufacturing technology, machine learning-based materials design, and recyclable polymer matrices will certainly facilitate the development of new hybrid composites [20].

CONCLUSIONS

Hybrid polymer composites comprising coconut shell fillers and silica fume have been introduced as an innovative and sustainable material suitable for advanced engineering applications owing to their superior mechanical properties, low weight, and environment friendliness. This review paper highlighted recent trends in processing, fabrication, mechanical behavior, microstructure evaluation, and engineering applications of hybrid polymer composites made up of coconut shell fillers and silica fume. The co-reinforcement of coconut shell fillers and silica fume improves tensile strength, flexural strength, impact strength, hardness, wear resistance, and thermal stability as a result of better filler distribution and improved interface bonding. In addition to that, advanced characterization methods like SEM, FTIR, XRD, TGA, and DMA have proved that hybrid filler reinforcement is effective in improving performance of composites. Moreover, the use of agricultural and industrial wastes results in resource conservation and sustainable material development. While a lot of progress has been made so far, some issues like filler interaction, moisture absorption, and processing optimization need to be addressed. Future research work should concentrate on biopolymer matrices, nanofillers, new manufacturing processes, and recyclable composites.

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