

Coconut Shell Powder (CSP) Reinforced Polymer Composites

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Abstract—Coconut shell powder (CSP) reinforced polymer composites have become a new promising line of sustainable materials since it is eco-friendly, inexpensive, and good mechanical performance. This review has identified the potential of CSP as a natural filler using agricultural wastes, which can be used in improving the composite properties of hardness, stiffness, and tensile strength when used as a filler in the matrices such as epoxy and high-density polyethylene. The paper talks about the effect of particle size, distribution and interfacial bonding on composite structural and mechanical behavior. It also discusses the different characterization methods, such as SEM, TGA, DSC, and FTIR, to determine morphological, thermal and chemical characteristics. Although there are benefits, issues including moisture absorption, poor fiber-matrix adhesion, etc., still exist but can be reduced by surface coating and hybridization. The review also discusses the use in the automotive, construction and packaging sectors with CSP composites as viable alternative to traditional materials. In general, CSP composites show a viable direction of creating materials with a sustainable approach to resource conservation and environmental friendliness.

Index Terms—Coconut shell powder, polymer composites, natural fibers, sustainable materials, mechanical properties, agricultural waste, hybrid composites, characterization techniques.

I. OVERVIEW COCONUT SHELL POWDER

Natural fibers are renewable, biodegradable, and safe for the environment. Natural fibers are becoming a more popular alternative reinforcement for fiber-reinforced polymer composites among scientists, engineers, and researchers. Because of their low cost, high specific strength, non-abrasive nature, moderately great mechanical characteristics, eco-friendliness, and biodegradability, they are utilized as

substitute for more traditional fibers such as carbon, aramid, and glass. The tensile strength of polymer composites reinforced with natural fibers typically increases as the fiber content does [1]. Information and insights that may be useful for future studies on the production that has been attempted to provide metal matrix composites using waste materials used in agriculture and industry. As an alternative to reinforcing elements and matrices in metal matrix composites, industrial and agricultural waste materials are appropriate due to their distinctive structure/morphology, chemical content, unlimited availability, and cost.

Research suggests that industrial and agricultural wastes necessitate thorough, systematic investigations to fully understand their potential as valuable resources and to facilitate their use in inventive and creative economic sectors [2]. Naturally occurring fibers are renewable resources that can be produced quickly. Ashik et al.'s [3] studies on glass fiber reinforced composites and Pickering and associates' [4] Research on composites reinforced with natural fibers has proven that these fibers are the best option for many commercial uses. Composites reinforced with natural fibers have better mechanical performance when the pressing, extraction, treatment, and selection of the fibers are enhanced, and when the interfacial engineering is improved as well. Composites reinforced with coconut shell particles and an epoxy matrix have the maximum water absorption [6], according to Bhaskar et al. [5]. Studying the effects of increasing the quantity of coconut shell in a low-density polyethylene matrix revealed that hardness increased but ductility, impact strength, modulus of elasticity, and tensile strength all reduced [7].



Fig: 1 Raw coconut shells, crushed coconut shells and coconut shell powder, Source: Andezai et al. (2020).

II. THE GROWING ROLE OF COMPOSITES IN STRUCTURAL AND AUTOMOTIVE INNOVATION

Composites' low weight, high specific stiffness, and strength are making them a popular alternative to metals in aeronautical structural applications, automotive, and construction industries [8]. Composites have many advantages over metals, including superior heat performance, reduced weight, and resistance to fatigue and fractures. Because of the growing need for lighter construction materials and structures that can withstand seismic activity, there has been a rise in the use of innovative and advanced composite materials that can decrease dead weight while simultaneously absorbing vibration and shock via tailored microstructures. The use of composite materials is on the rise in the automotive industry. Reducing vehicle weight with composite materials has great potential for better fuel economy and less CO₂ emissions. Cutting weight and the quantity of components used to create the high-volume composite vehicle can bring the price down [9, 10]. Additionally, Seismic damage can be repaired or existing structures can be reinforced and rehabilitated to make them more seismic resistant through the use of composites. Composites, in contrast to more conventional materials (such as steel), can have their properties tailored to specific structural features and a variety of filler or reinforcement matrix compositions. Building a composite structural component requires careful attention to both the material and the design of the structure. The designer can continuously change a broad range of values for composite properties, such as thermal expansion and stiffness [11]. Picking the right kind of reinforcement allows you to tailor the product's features to fit almost any specific technical need. There is no doubt that composites are the way to go. When deciding on a material, several factors come

into play, such as the product's working lifetime requirements, run length, shape complexity, assembly cost savings potential, and the designer's expertise in maximizing composites' potential [12]. Advantages of using natural fillers to reinforce composite materials over mineral fillers include a robust and rigid structure, low weight, environmental friendliness, economy, and an abundance of renewable resources [13]. Adding powdered coconut shell to the bio-composite increases its tensile strength and modulus of elasticity but decreases its damping qualities, according to Abdullah and Andrzej [14]. There is no commercial purpose for coconut shell, which is an agricultural byproduct. Fertilizer is another common use for it in agriculture [15]. The development of new uses for agricultural waste is necessary because this will benefit both the agricultural industry and other businesses. The production of a polyethylene composite from ground coconut husks will find a new purpose for this agricultural byproduct and increase its monetary worth. High density polyethylene was chosen as the study's matrix because it is an inexpensive, readily available resin with outstanding mechanical qualities that finds use in the transportation, marine, and sports industries. The present study investigated the potential of coconut shell as reinforcement for composites using high density polyethylene and coconut shell powder.

III. NATURAL FIBER POLYMER COMPOSITES: SIGNIFICANCE AND POTENTIAL OF COIR FIBERS

More and more people are concerned about the environment, and this has led to a surge in interest in natural fiber polymer composites during the past decade. Since they are renewable and biodegradable, natural fibers typically do not harm the environment. In addition, it is readily available, inexpensive, lightweight, low abrasion, tough, has acceptable special mechanical characteristics, is long-lasting, and is simple to manufacture [16]. This is why researchers are keen on finding practical uses for the fiber and creating alternatives to synthetic fibers. The feasibility of using natural fibers as polymer reinforcement has been examined in multiple studies. Although natural fibers aren't always as mechanically effective as polymers reinforced with glass fibers, the results show that they could be used as plastic reinforcement [17].

Coir, a natural fiber abundant on the South Asian subcontinent, discovers extensive application in a myriad of goods, including heavy cable, floor mats, brushes, and coarse nets. The husk or outer shell of the tropical plant *Cocos nucifera*, which is a member of the *Aceraceae* is used to extract coir, a seed hair fiber. The coconut's inedible shell is a solid lignocellulose byproduct of agriculture. Compared to other eco-friendly fibers like jute and sisal, it can be even more budget-friendly [18]. The coconut shell makes up around fifteen to twenty-five percent of the fruit's weight, along with water, pectin, cellulose, hemicelluloses, lignin, and the rest of the fruit. The cell is approximately 0.8 mm in length with a spiral angle of 41-45°, has a tensile modulus of 15-40%, and a tensile strength ranging from 131-175 MPa [19]. Its tensile modulus is 4-6 GPa. The linear chain of 1,4- β linked hydro glucose units in this hydrophilic glucan polymer contains alcoholic hydroxyl groups [20]. Coconut fiber outperforms all other natural fibers in terms of strength (21.5 MPa) and strain tolerance (four to six times higher) [21]. In order to find affordable roofing materials, [22] looked into the usage of coconut fiber reinforced cement composites and a number of characteristics, factors such fiber volume, casting pressure, and fiber length. Composites that were both long-lasting and cost-effective—measuring 3.75 cm in length, 7.5% in volume percentage, and 1.67 MPa in pressure bested roofing materials that were sourced locally. According to Devendra et al. [23], E-glass/epoxy composites can have their mechanical properties affected by fillers such hematite powder, Al_2O_3 , and fly ash. Materials Made of Composites reinforced with fly ash had the best impact strength, while those reinforced with 10% volume Mg (OH)₂ had the hardest and strongest ultimate tensile strength. Average tensile strength was 17.86 MPa, bending strength was 31.08 MPa, and impact strength was 11.49 kJ/m² for composites made of randomly oriented coir fibers and epoxy, as reported by Harish et al. Coir fiber reinforced cement sand mortar's mechanical characteristics were investigated by Slate [25], whereas Junior et al. investigated the tensile properties of coir-polyester composites [24]. The correlation between coir fiber mass percentage, molding pressure, and bending strength was studied by Monteiro et al. [26]. An effective way to enhance mechanical properties and decrease water absorption

is to employ radiation to graft monomers onto cellulose-based natural fibers.

IV. COCONUT SHELL

A number of the world's staple foods are members of the palm family, to which the coconut also belongs. It generates a great deal of byproduct, specifically CS, or coconut shell. The coconut shell, or CS, is one example of a hard-lignocellulosic agricultural waste. The availability of Agro waste products like CS is increasing every year on a global scale [27]. Sri Lanka, Malaysia, Indonesia, Thailand, and India are tropical nations that produce CS, one of the most important natural fillers. Several experts have recently dedicated themselves to utilizing various natural fibers in composites; CS fiber, with its high modulus and strength characteristics, is one potential option for the development of new composites. Composite fiber is used for many different things, such as fishnets, furniture, and construction materials. Many different kinds of polymer-based composites rely on coconut fiber for their manufacturing because of its many useful characteristics, such as its cheap cost and high strength [28]. Right now, in Seattle, we dispose of 90% of CS as waste by burning it outside or dumping it in ponds.

Emissions of carbon dioxide and methane, in his view, were significantly increased by the waste products of the coconut processing sector. Considerations of economics and ecology should guide this effort toward resolving issues related to the usage, storage, and disposal of coconuts on a worldwide scale. Despite the widespread knowledge of potential CS applications, none of them have been proven to be viable from a practical or financial standpoint [29]. By using bio composite technology, we were able to assess the hybrid composites composed of rubber wood, coconut husks, and woven synthetic fibers (polyester or cotton). A variety of hybrid composites were made utilizing two, three, or four layers of cotton or polyester fabric to study the effects of various textile materials on the strengthening of bio composites. In order to measure tests for flexural strength, impact strength, water absorption, and thickness swelling were conducted by the researcher. Flexural modulus and flexural strength were both enhanced in the hybrid composites reinforced with fabric in comparison to the control group. Reinforced composites with four layers

of fabric showed a little decrease in flexural modulus. The resistance of the cloth to impact damage also improved with the increase in layer count. Because it didn't adhere as well Compared to versions reinforced with cotton fabric, versions made of rubber wood and coconut shell mixture were stronger when using polyester fabric. Improving the polyester hybrid composite's adherence, say the researchers, would likely increase its flexural strength and impact characteristics. Hybrid composites reinforced with cotton outperformed their polyester-reinforced counterparts in flexural strength but had lower impact strength. Both fabric types added to the composites reduced water absorption and increased thickness swelling values, in comparison to the control sample [30]. Coconut shell has hardly no ash. Activated carbons, made from coconut shells, also be utilized as adsorbents in water purification and municipal effluents, increasing the worth of these agricultural products while decreasing the expenses associated with waste disposal and offering a cost-effective substitute for commercially available carbons [31].

Table-1 Certain data regarding coconut output, (2010)

Country	Area (1'000 haetr)	Production (million nuts)	Productivity* (Nuts/haetr)
India	1895	16943.00	8965
Indonesia	3808	16332.24	4289
Philippines*	3400	15510.00	4562
Sri Lanka	395	2619	6630

V. IMPROVING EVALUATION OF NATURAL FIBER COMPOSITES' MECHANICAL PROPERTIES

Many structural applications in engineering and industry have shown interest in natural fiber reinforced polymer composites due to their improved static and dynamic properties [32].

Affordable, lightweight, strong, easy to work with, manageable, low-impact, and environmentally friendly are just a few of the many benefits offered by these materials [33]. Structured polymer components often incorporate natural fibers sourced from wide range of plants and animals, such as ramie, sisal, bananas, hemp, flax, areca, and jute. The low weight, biodegradability, and easily accessible nature of snake grass and luffa cylindrica, which contribute to their

sustainability and long-term performance, are drawing a lot of research attention [34]. Unfortunately, the limited use of composites made entirely of these natural fibers in demanding engineering applications is often due to their poor mechanical properties and excessive water absorption [35]. To get over these limits and improve mechanical performance, researchers have looked into adding other fillers to these composites, including as silica, alumina, carbon nanotubes, graphene, boron carbide, and glass powder [36]. A combination of natural and synthetic fibers, or two synthetic fibers and one natural fiber, is one hybridization process that is being studied as a means to improve the overall properties of these materials [37]. As an example, Pradeep et al. [38] studied basalt fiber composites with SiO₂ reinforcements for wear and mechanical properties. The researchers asserted that the flexural strength was enhanced by 178% after the addition of SiO₂ fillers, and that basalt fiber-based composites exhibited significantly better wear behavior compared to neat composites. Tasnim et al. [39] used a range of filler elements, such as ZnO, MgO, CuO, TiO₂, and Al₂O₃, to enhance the mechanical properties and water absorption of banana and jute composites. Results showed that a tensile strength increase of 90.43 percent was achieved by introducing TiO₂. On the other hand, when compared to clean composites, the tensile strength was 162.59% higher after adding MgO.

They further asserted that these filler elements reduced water absorption by 36% compared to neat composites. Adding luffa fiber (LF) to hybrid polymer composites changed their mechanical characteristics, according to research by Hasan and colleagues [40]. The 4% LF composite was designed for a tensile strength of 35 MPa. Good fiber-matrix adhesion, impact strength of 13.38 kJ/m², flexural strength of 121.65 MPa, and compressive strength of 39.29 MPa. The mechanical, vibrational, and acoustic performance of hybrid composites made of glass fibers was improved by Lokesh et al. [41] when 8 weight percent Calamus rotang stem fibers were added.

The best hardness, tensile strength, and thermal stability up to 300°C were shown by a hybrid composite that consisted of 60% epoxy, 20% tamarind seed powder, and 20% areca leaf sheath [42] [43]. They also discovered that adding zirconia nanofiller to millettia pinnata fiber improved the composite's mechanical properties by 23%. Tirupathi et al. [44]

studied the effects of boron carbide (B₄C) nanoparticles on palm-and jute-fiber composites. Composites with 1.0 weight percent B₄C had the highest ten-sile and flexural strengths at 61.39 and 116.34 MPa, respectively, while those with 1.5 weight percent B₄C exhibited the highest impact strength at 24.8 J/m² and hardness at 87.8. Composites of polypropylene (PP) and nanosized alu-mina (Al₂O₃) particles and sodium hydroxide-treated flax fiber (TFF) were studied by Aruna et al. [45]. The mechanical parameters of the PP/10.0 wt.%TFF/7.5 wt. % Al₂O₃ composite were found to be ideal, with readings of 49.5 MPa for tensile strength, 18 J/mm² for impact strength, and 56 MPa for flexural strength.

VI. THERMAL AND CHEMICAL BEHAVIOR OF THE DEVELOPED COMPOSITES

Coconut shell fibres consist mostly of hard, crystalline cellulose microfibrils reinforced by amorphous lignin and/or a hemicellulosic matrix. Most plant fibres, with the exception of cotton, consist of cellulose, hemicellulose, lignin, waxes, and some water-soluble chemicals, with cellulose, hemicellulose, and lignin being the primary components [46]. Hemicellulose facilitates biodegradation, micro-absorption, and thermal deterioration of the fibre due to its little resistance, whereas lignin exhibits thermal stability but is susceptible to UV destruction. The increased lignin concentration renders composites using these fillers more weather-resistant, hence enhancing their suitability for building material applications. The shells absorb less moisture owing to their reduced cellulose content.

Table 2. Composition of CSP

Attributes	% Composition
Moisture	7.073
Lignin	29.35
Cellulose	24.2
Hemicellulose	38.56
Ash	0.68

Child and Sareena [47] have previously documented the chemical composition of coconut shell. An ASTM standard technique exists only for the determination of lignin in hardwood, excluding cellulose and hemicelluloses. This work used data from the TGA and DTG curves of the pyrolysis of CSP and lignin isolated from CSP to ascertain the chemical makeup.

Composites are widely used for the rehabilitation and strengthening of existing structures that need retrofitting to enhance seismic resistance or to repair damage inflicted by seismic events [48]. In contrast to traditional materials (e.g. steel), the characteristics of composite materials may be engineered by factoring in the structural qualities and altering the reinforcing matrix or filler content. The design of a structural component with composites encompasses both material and structural considerations.

The designer may constantly vary composite characteristics, including stiffness and thermal expansion, throughout a wide range of values [49]. Meticulous selection of reinforcing type allows for the customisation of end product features to meet almost any unique technical need. The selection of composites is determined by factors including required lifespan, production volume, product shape complexity, potential assembly cost savings, and the designer's expertise in maximizing the advantages of composites [50].

VII. STRUCTURAL CHARACTERISTICS AND MORPHOLOGICAL ANALYSIS

The geometry of coconut shell powder (CSP) reinforced polymer composites is highly instrumental in defining the overall composites performance. CSP distribution in the polymer matrix has a great effect on the internal structure and, consequently, on the load transfer efficiency and durability. Filler particle distribution is homogeneous to provide even distribution of stress and agglomeration of CSP particles may result in stress concentration sites and premature failure. The size, shape, and roughness of the surface of the coconut shell powder particles are important parameters that determine the structural integrity of the composite [51].

The morphological analysis is normally conducted under the help of sophisticated characterization methods including scanning electron microscope (SEM), which offers valuable information regarding the surface and fracture behavior of composites. SEM micrographs can also give an idea of the extent of sticking of the CSP particles to the polymer matrix [52]. Good interfacial bonding leads to reduced number of voids and cracks whereas weak bonding is shown by the particle pull-out and interfacial gaps. These aspects are essential in the breakdown

mechanisms of CSP-strengthened composites when subjected to mechanical loads. The interfacial interaction between the hydrophilic coconut shell powder and hydrophobic polymer matrix is another important aspect of structural analysis [53]. Because of the natural lignocellulosic structure of CSP, there can be problems in compatibility that results in poor adhesion. To improve interfacial bonding, surface treatments (like alkali treatment (NaOH)) or silane coupling agents are commonly used. These treatments alter the surface chemistry of CSP, enhancing wettability and facilitating enhanced mechanical interlocking in the matrix.

Other important structural parameters that affect the morphological features of the composites are porosity and void content. Effective load-bearing area is decreased, which leads to crack propagation by the presence of voids weakening the composite structure. Appropriate processing methods, including compression molding or vacuum-assisted, are used to reduce the formation of voids and enhance compactness of the structure. These defects are often measured in a morphological study to correlate with mechanical performance [54].

Moreover, the fracture surface examination offers important data on the behavior of CSP composites in terms of the failure. The surfaces of brittle fracture are smooth most of the time, and the ductile surface is rough and fibrous [55]. The fracture morphology is changed due to the presence of CSP, and it brings about crack deflection mechanisms, which may increase the capacity of energy absorption. The crack bridging, fiber pull-out, and matrix deformation observations help in learning about the composite resistance to crack propagation.

VIII. CHARACTERIZATION TECHNIQUES

The characterization techniques are important in assessing performance, reliability, and applicability of coconut shell powder (CSP) reinforced polymer composites. These methods aid in comprehending the physical, mechanical, thermal and morphological performance of the developed composites. Using standardized testing and complex analytical tools, researchers will be able to correlate the microstructural aspects of the composite to its macroscopic properties. This guarantees appropriate design of materials and optimization to a particular engineering application.

Tests of mechanical characterization are often done with tests like tensile, flexural and impact testing in accordance with standards such as ASTM D638 and ASTM D790. These tests establish the strength, stiffness and toughness of CSP-reinforced composites. Surface resistance is also determined by hardness tests (e.g., Shore D). The findings give an understanding of the impact of the use of coconut shell powder on the load-bearing capacity and deformation behavior, which is important in the structural and semi-structural applications [56].

Scanning Electron Microscopy (SEM) is commonly used to perform morphological and structural characterization, and occasionally Transmission Electron Microscopy (TEM). SEM analysis is used to study the distribution of CSP particles, fiber-matrix interfacial bonding and fracture surfaces following mechanical testing [57]. Effective interfacial adhesion will lead to enhanced stress transfer but voids and agglomerations may make the composite weak. The X-ray Diffraction (XRD) technique is also used in the investigation of crystallinity and phase structure that affect the overall mechanical and thermal performance.

To determine thermal stability and degradation behavior, thermal characterization methods like Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) are necessary. TGA quantifies change in weight with temperature, which shows decomposition patterns, whereas DSC quantifies the glass transition temperature (T_g), melting temperature and the crystallization behavior. Such analyses aid in establishing the applicability of CSP composites on high-temperature applications [58]. Fourier Transform Infrared Spectroscopy (FTIR) is commonly used to characterize chemical functionalities, and chemical interactions between the coconut shell powder and polymer matrix. FTIR spectra may verify that lignocellulosic material (cellulose, hemicellulose, and lignin) is present in CSP, or that chemical processes or treatments have been performed to enhance compatibility. This aids in the meeting of bonding at the molecular level [59].

IX. APPLICATIONS AND FUTURE SCOPE OF COCONUT SHELL POWDER COMPOSITES

Polymer composites reinforced by coconut shell powder (CSP) have attracted much interest because of

its environmentally friendly nature, affordability, and satisfactory performance in a variety of engineering being used. Such composites are finding more and more applications in non-structural and semi-structural items like interior panels, furniture, packaging materials and decorative items [60]. Their low density and sufficient mechanical strength make them applicable in situations where it is important to reduce the weight without reducing the functionality. Moreover, CSP-based composites offer a viable solution to use agricultural waste, which leads to sustainable material development and circular economy.

CSP reinforced composites are also under investigation in the production of the interior components of the automotive industry including door and dashboards and seat backs. The increasing trend of lightweight and fuel-efficient vehicles has increased the use of natural filler-based composites. The benefits of CSP include good vibration damping, better acoustic insulation and lower costs of production as compared to synthetic fillers. In addition, the biodegradability of composite materials can be improved through the addition of CSP, which is consistent with the international environmental standards and sustainability requirements [61].

Another potential of CSP composites is in the construction industry where the product finds a use in ceiling boards, partition panels, insulation materials, and structures with a low burden [62] among others. They are good alternatives to conventional materials such as wood and gypsum due to their resistance to moisture when properly treated, thermal insulation properties as well as their ease of fabrication. Moreover, chemical treatments and hybridization methods enable the CSP composites to be designed with enhanced fire resistance and durability, which increases their application in the construction industry. Applications of CSP reinforced polymers in consumer goods and packaging include biodegradable containers, trays, and other environmentally friendly household products. The growing consciousness about the environment and the prohibition of single-use plastics in most areas has given rise to the necessity of sustainable options. When used with biodegradable polymer matrices, CdTeTeCdTe composites can be much less hazardous to the environment and still be of acceptable performance quality [63]. They are also investigated in 3D printing filament and personalized

production of products, which opens new possibilities in high-tech fabrication technologies.

In the future, studies are being done on improving the interfacial bonding between coconut shell particles and polymer matrices by using surface treatments, coupling agents and nano-modification methods. Enhanced dispersion, lower porosity and optimization of particle size distribution are essential issues that should be addressed in order to acquire enhanced mechanical and thermal performance. Hybrid composites involving CSP with other natural fibers or nanofillers, including graphene or nanoclay are also under research to come up with multifunctional materials with improved properties [64].

The future of CSP composites is very bright especially within the framework of sustainable development and green materials engineering. The future of processing technologies, compression molding, injection molding, and additive manufacturing, are likely to positively impact the quality of products and their scalability. In addition, the commercialization of such materials will heavily rely on lifecycle assessment (LCA) and recycling strategies. As research and industry partnerships continue, coconut shell powder reinforced polymer composites can substitute the traditional materials in many industries, leading to a more resource efficient and sustainable future.

X. CONCLUSION

Coconut shell powder (CSP) reinforced polymer composites are a good example of sustainable materials that can successfully integrate the sustainability with functionality. The use of agricultural waste like coconut shells does not only solve the problems of disposal and pollution, but also offers a cheap and renewable source of alternative to conventional synthetic reinforcements. In this review, it is quite clear that CSP-based composites have better mechanical behaviors like high hardness, stiffness, and tensile strength when integrated into appropriate polymer matrices such as epoxy and high-density polyethylene. These properties render them appealing to numerous applications in engineering especially where weight and cost is very important.

Though these benefits exist, there are still some limitations such as decreased ductility, more water uptake, and fiber-matrix compatibility issues. Nonetheless, there has been a tremendous

improvement in these disadvantages with the advent of sophisticated treatment procedures, hybridization processes and introduction of nano- and micro-fillers. Alkali and silane techniques have been shown to effectively enhance the interfacial bonding capacity and thus the effectiveness of loading transfer and durability. Also, hybrid composites that incorporate CSP with other natural or synthetic reinforcements have proven to have better mechanical and thermal applications meaning that further optimization possibilities are high.

The review also indicates the significance of characterization methods in the study of the structural, thermal and morphological behavior of CSP composites. SEM, TGA, DSC, and FTIR techniques are essential in matching the microstructural characteristics with the macroscopic properties that help in designing materials and predicting their performance better. In addition, developments in processing technologies such as compression molding and additive manufacturing are also helping in enhanced quality, scalability, and variety of application of these materials.

In the future, CSP reinforced composites have a significant future in the automotive, construction, packaging and consumer goods sector. They are biodegradable, low density and flexible to different design specifics, which makes them suitable to the demands of global sustainability and increased use of green materials. Further studies are needed to enhance moisture resistance, enhance particle dispersion, and create high-performance hybrid systems to increase their use in load-bearing and high-temperature conditions. As further innovations and industrial cooperation are achieved, CSP-based composites will make significant contributions to the shift towards material technologies based on environmental friendliness and resource efficiency.

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