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A Review of Coconut Shell Powder as a Reinforcement Composite for Sustainable Abrasive Jet Machining

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Abstract: Researchers are looking to incorporate agro-waste products into composite systems as a result of the need for environmentally friendly resources in sophisticated production processes. A lignocellulosic by-product of processing coconuts, coconut shell powder (CSP) has become a popular and environmentally responsible filler for reinforcing polymers. The application of CSP-reinforced composites in Abrasive Jet Machining (AJM), an unusual machining technique renowned for its accuracy and low heat effect, is the main topic of this review paper. Rich in cellulose, hemicellulose, and lignin, CSP's composition offers favorable mechanical qualities such enhanced tensile, flexural, and wear resistance when it is included into polymer matrices. It is also a sustainable substitute for traditional fillers due to its hardness, biodegradability, and thermal stability. When CSP is added to epoxy, HDPE, and polyester matrices, the literature shows encouraging results, including improvements in strength, modulus, and machinability. Its function in AJM is still not well understood, though. By combining the results of previous research on CSP-reinforced composites and analyzing their potential for AJM applications, this work seeks to advance green engineering and circular economy principles in material removal procedures.
Keywords: Polymer matrix, agro-waste reinforcement, abrasive jet machining, natural fiber composites, coconut shell powder, and sustainable materials integrity of the surface.

I. INTRODUCTION

Agro-waste-derived reinforcements are the subject of a rising amount of study due to the increasing need for ecologically friendly production processes and renewable materials. Among these, the lignocellulosic biomass residue known as coconut shell powder (CSP) is notable for its great mechanical integrity, availability, and biodegradability. With over 54 billion coconuts produced worldwide each year, nations like the Philippines and India produce a lot of shell waste, which provides a cheap and dependable resource for sustainable composite development [6].

Mostly composed of cellulose, hemicellulose, and lignin, CSP improves mechanical performance and adds structural rigidity to polymer matrices like polyester, HDPE, and epoxy [2-10]. Researchers have found that CSP-reinforced composites exhibit notable gains in tensile, flexural, impact, and thermal stability [1-5]. These improvements are mostly dependent on the size of the CSP particles; nano- and micro-sized CSP particles show better matrix bonding, producing composites that can withstand demanding applications [3] Construction, automotive, packaging, and, more recently, high-wear applications like brake pads are just a few of the industries that have found use for CSP composites [9]. Their suitability for non-traditional machining techniques, especially Abrasive Jet Machining (AJM), is one area that is still little understood. AJM is frequently used for machining hard and brittle materials with little thermal distortion by using streams of abrasive particles moving at high speeds to degrade materials. The use of CSP as reinforcement in composite workpieces aimed toward AJM has two advantages: process sustainability and material efficiency [7-8]. According to studies, CSP can improve wear resistance and surface integrity in composite materials by acting as a functional filler [4-19]. Improved performance metrics like material removal rate (MRR), surface quality, and nozzle wear resistance may result from its incorporation into AJM-specific composites. Additionally, CSP provides hybrid reinforcing possibilities with synergistic effects when combined with other natural fillers, such as coir or tamarind shell powder [8].

In this review, the present knowledge of CSP as a reinforcement in polymer composites is consolidated, and its viability in abrasive jet machining is investigated. It highlights how CSP can help achieve global green engineering goals and the concepts of the circular economy while promoting sustainable composite production.

II. LITERATURE REVIEW

According to recent studies, adding 5–20% of coconut-shell powder (CSP) to common polymer matrices like epoxy, HDPE, polypropylene, and unsaturated polyester increases their tensile, flexural, and impact strengths while lowering their density and cost. For an epoxy composite loaded with 20 weight percent CSP, Adarsh et al. showed a ~25% improvement in flexural strength [1], and comparable trends have been noted for HDPE [10] and polypropylene [4]. Particle size (50–150 µm works better than coarser fractions) and surface treatments like 5% NaOH, which strengthen interfacial bonding, have a significant impact on how much improvement is seen [5].CSP composites also show superior resistance to wear and erosion due to the lignin-rich surface and Mohs hardness of 2-3 of the CSP particles. For instance, Vasu et al. found that a 15% CSP/HDPE blend increased Shore-D hardness by 30% [10], and that glass-fabric laminates hybridized with CSP withstand repeated impacts with little mass loss [5].

Its lignin content acts as a natural char former, giving the composites limited self-extinguishing ability. Thermogravimetric analyses place the onset of CSP degradation around 230 °C, comfortably above most polymer-processing temperatures. Properties are further improved by hybrid and nano-scale methods: CSP particles smaller than 100 nm have been shown to provide an extra 32% flexural-strength boost at loadings as little as 3 weight percent [13], and combining it with rice husk [7], tamarind shell [8], or coir fiber [19] frequently results in synergistic benefits. Notwithstanding these obvious mechanical and thermal advantages, hardly any published research has assessed CSP as a biodegradable abrasive or investigated CSP-reinforced composites under real-world Abrasive Jet Machining (AJM) settings. There are optimization studies for natural fiber composites in AJM that are based on Taguchi and RSM [17], but none of them separate the impact of CSP content on material removal rate, kerf shape, or nozzle erosion. Because of this, there are still important questions about (i) how CSP loading changes AJM machinability measures, (ii) if CSP particles smooth or fragment under high-velocity impact, and (iii) whether processed CSP grit may be used as a green abrasive in place of silica or alumina. By answering these queries, CSP may be positioned as a pillar of sustainable machining, fusing the performance requirements of precision erosion processes with the circular economy benefit of agro-waste valorisation.

III. OVERVIEW OF COCONUT SHELL POWDER

The tough outer shell of the coconut (Cocos nucifera) is used to make Coconut Shell Powder (CSP), a renewable and biodegradable filler material [12]. CSP, which is widely used in tropical nations like the Philippines, Indonesia, Sri Lanka, and India, has drawn notice as an inexpensive and sustainable substitute for synthetic reinforcements [18]. Its growing application in abrasive machining, construction materials, and polymer composites is consistent with the global movement toward environmentally friendly materials. Because of its mechanical strength, lightweight design, and compatibility with polymers, CSP is well-suited for a wide range of industrial applications [5].

A. How CSP is Produced

CSP is produced via a number of steps. To start, leftover coconut shells from farms or processing facilities are gathered and meticulously cleaned to get rid of dust and other organic contaminants [6]. Drying is then done to reduce the moisture content to less than 10%, either in the sun or in ovens set to between 60°C and 80°C. To get a particle size of 50–300 µm, the shells are crushed using crushers or hammer mills after drying, and they are then finely processed, frequently with ball milling [11]. Depending on the need, the powder is sieved into various mesh sizes. Chemical treatments such as silane treatment or alkali (NaOH) washing are sometimes used to increase interfacial bonding and thereby compatibility with polymer matrices [11].

B. Availability and Cost

In areas that produce coconuts, particularly in South and Southeast Asia, CSP is easily accessible. It is a sustainable choice because it is made from agricultural waste [12]. Depending on purity, mesh size, and chemical treatment, CSP typically costs between $0.5 and $2 per kilogram. Manufacturers of biofillers and processors of agricultural byproducts in Thailand, Indonesia, and India provide bulk supplies. For enterprises looking for reasonably priced, environmentally friendly alternatives, its cost-effectiveness and accessibility make it a desirable reinforcement material[18].

C. Physical Properties

With a density of 1.2 to 1.5 g/cm³, CSP is a lightweight filler that is substantially less dense than mineral fillers like silica [6]. Its high porosity and particle size distribution range from 50 to 300 µm, supporting mechanical interlocking within polymer matrices. Because of its 5% to 10% moisture absorption, pre-drying is crucial before using it to create composites. Because of these physical properties, CSP can be used in construction and lightweight composite applications [5].

D. Chemical Composition

The natural polymer content of CSP is rich. The 25–35% cellulose component gives it structural rigidity. About 30–35% of it contains lignin, which adds stiffness and heat resistance. Twenty to twenty-five percent hemicellulose contributes biodegradability [6]. Because of the generally low ash level (0.5–2%), there is less inorganic residue, which is advantageous for cleaner applications. Because of its well-balanced chemical composition, CSP is a great environmentally friendly addition that possesses both strength and degradability (.

E. Thermal Properties

The thermal breakdown of CSP begins at approximately 200–250°C, making it appropriate for polymer processing at low to medium temperatures. CSP-based composites have the ability to self-extinguish because to the natural lignin in the shell, which offers a certain level of flame resistance (Ismail et al., 2020). These characteristics allow for its safe use in car panels, brake pads, and thermal insulation [9].

F. Mechanical Properties

CSP improves the tensile, flexural, and impact strength of composite materials. For example, CSP-epoxy composites have a flexural strength of 30 to 50 MPa and a tensile strength of 10 to 20 MPa [5]. CSP-HDPE composites exhibit impact strengths of up to 12 kJ/m^2 and tensile strengths of 15–25 MPa [16]. Strong particle-matrix bonding is responsible for these enhancements, particularly when CSP is chemically treated [10]. CSP is perfect for industrial and structural items since it increases stiffness and resilience to wear.

G. Applications

Applications for CSP are found in a variety of fields. CSP is utilized in epoxy and HDPE-based polymer composites for goods such circuit boards, lightweight panels, packaging, and automobile interiors [10]. To improve thermal insulation and lower material density, CSP is used in lightweight concrete, ceiling tiles, and eco-bricks in construction [5-18]. Because of its hardness (2–3 on the Mohs scale), CSP functions as a green abrasive in abrasive jet machining and can potentially replace silica or alumina. CSP is also utilized in automobile friction materials, such as clutch plates and brake pads [9]. CSP stabilizes clayey or black cotton soils by decreasing their plasticity and increasing their load-bearing ability [15].

H. Studies Conducted So Far

Several investigations have confirmed the potential of CSP. 20% CSP added to epoxy resulted in a 25% increase in flexural strength [5]. According to Vasu et al. (2017), CSP increased HDPE composites' hardness by 30%. CSP nanoparticles improve thermal stability. Many gaps still exist, though.

For example, little research has been done on the performance of CSP under UV light and its application in abrasive jet machining. The potential of CSP in cutting-edge applications may be further unlocked by research on nanoscale CSP and surface changes like plasma treatment [3].

IV. METHODLOGY

The research that has been done on Coconut Shell Powder (CSP) as a reinforcing filler in composite materials is reviewed and analyzed in this part. Finding the applicability of CSP for applications based on abrasive jet machining (AJM) and extracting methodological patterns are the objectives.

A. Preparation and Processing of CSP Composites

Coconut shells are gathered, cleansed of organic waste and dust, and then allowed to dry in the sun before being ground by a machine. In order to manage the particle size, which is normally between 75 and 150 µm, the fine powder is first produced in a ball mill or high-speed grinder and then sieved [6-11]. To enhance surface roughness and interaction with polymer matrices, CSP is occasionally chemically treated with a NaOH solution (5–10%) [5-14].

The most popular matrix materials are epoxy, polyester, and HDPE; these materials are selected due to their superior mechanical strength, bonding, and resistance to deterioration [5-16]. To ensure equal distribution of CSP, fabrication is usually carried out by hand lay-up, compression molding, or extrusion molding [13-19].

B. Characterization Techniques Used

1) Mechanical, physical, chemical, and morphological analysis are all part of characterization.
2) Surface roughness and particle bonding are investigated by SEM (Scanning Electron Microscopy) [11].
3) Elements such as SiO_2, CaO, and K_2O are identified using EDX and XRF techniques [12].
4) ASTM guidelines are followed for performing tensile, flexural, and impact testing [5-8].
5) Tests for density and water absorption aid in assessing durability [16].
6) The enhanced mechanical and barrier qualities with ideal CSP loading up to 15%–20% are confirmed by each test.

C. Use and Relevance in Abrasive Jet Machining

Despite its limited utility as an abrasive, CSP exhibits great promise in AJM applications. This is because of its sustainability, hardness, carbon content, and resistance to abrasion. CSP-filled composites can be used in:

1) Components subjected to abrasive wear, such as nozzle linings.
2) Fixtures or substrates for jet impingement experiments.
3) With additional modification, they might be treated as abrasive particles (albeit tested not yet).

By using comparable composites that have been investigated at different pressures, standoff distances, and abrasive sizes, AJM experiments can be planned [7]. Response Surface Methodology (RSM) and Taguchi are two popular optimization strategies [17].

D. Comparative Overview of Fabrication Approaches

1) Compression molding to fabricate epoxy composites with 5–20% CSP. They observed that mechanical strength improved up to 15% filler content but declined beyond that due to poor dispersion [5].
2) CSP-filled HDPE composites using extrusion molding. The composites showed increased hardness but reduced ductility at higher CSP levels [16].
3) Hand lay-up to fabricate epoxy composites with CSP and tamarind shell powder. Hybrid fillers resulted in better tensile and flexural strength than CSP alone [8].
4) Combined CSP with coir fibre in a polyester matrix via hand lay-up. Their composites exhibited improved wear resistance and surface hardness [19].
5) The epoxy composites created using rice husk and CSP shown improved machining performance and increased erosion resistance, making them appropriate for AJM applications [7].

E. CSP and Sustainability's Role

Dimensional stability, hardness, and mechanical strength are all improved by CSP. It promotes waste valorization and lowers the cost of polymers. Studies also demonstrate its benefits in:

1) Stabilizing soil [15].
2) Lightweight concrete [18].
3) Polymer composites and brake pads [9].
4) Hybrid reinforcement made of natural fibers [19].

As a bio-based filler, it promotes the objectives of the circular economy and green production.

F. Methodology Conclusion

According to the researched literature, CSP is a very versatile and environmentally friendly filler material. It is appropriate for abrasion-sensitive situations like AJM due to its reliable reinforcing behavior in epoxy and thermoplastic composites, as well as its affordability and wide availability. Although there aren't many direct investigations on CSP in AJM, this review offers a foundation for investigating it in composite fixtures, nozzle design, and possibly as a green abrasive.

V. RESULTS

According to the reviewed research, the exceptional mechanical, wear-resistant, and biodegradable qualities of coconut shell powder (CSP) make it a promising reinforcement material for polymer composites. Up to an ideal filler proportion (usually 10–15%), CSP improves tensile and flexural strength, according to studies like those [5-13]. CSP-filled composites are appropriate for parts subjected to abrasive conditions, like in abrasive jet machining (AJM) systems, since other studies have confirmed enhanced surface hardness and impact resistance [8-19].

Although no research has used CSP as an abrasive material in AJM directly, its application in AJM-related components like nozzles or fixture surfaces is supported by its capacity to tolerate mechanical stress and enhance erosion resistance [7]. Furthermore, CSP is inexpensive, widely accessible, and environmentally benign, providing a sustainable substitute for synthetic fillers. Thus, CSP-reinforced composites, particularly those made with epoxy or thermoplastics, have a lot of potential for usage in AJM setups that prioritize material performance and green manufacturing in the future.

VI. CONCLUSION

According to this review, coconut shell powder (CSP) is a very efficient and environmentally friendly reinforcing ingredient for polymer matrix composites. According to several studies, CSP can greatly increase hardness, impact resistance, tensile strength, and flexural strength, particularly when applied in the range of 10% to 15% by weight [5-13]. It is a good choice for high-performance applications because of its natural composition, which is rich in cellulose and lignin, as well as its comparatively high hardness and abrasion resistance. CSP's potential for long-term and structural applications is further enhanced by its capacity to decrease water absorption and enhance dimensional stability [16].

Existing research indicates that CSP-based composites perform well under erosion and surface wear, which are crucial in AJM environments, despite the fact that CSP has not yet been extensively investigated in direct abrasive jet machining (AJM) applications [7-19]. Because of this, they could be helpful in AJM setups for producing nozzles, workpiece holders, shields, or even protective layers. Additionally, CSP is an environmentally benign substitute for synthetic fillers due to its low cost, widespread availability, and biodegradable nature, which supports the objectives of green and sustainable manufacturing.

In conclusion, there are economic, ecological, and mechanical benefits to using coconut shell powder. Its effectiveness in enhancing composite qualities and its potential for erosion-based applications provide compelling evidence for its application in AJM-related domains. CSP has the potential to be a key element of future sustainable machining systems, lowering environmental impact while preserving functional performance, with more focused study and testing.

VII. FUTURE SCOPE

There is a lot of need to expand this research specifically toward abrasive jet machining (AJM) applications, even though the reviewed studies offer a solid basis for the mechanical and structural benefits of Coconut Shell Powder (CSP) in composite materials. Real-time machining experiments employing CSP-reinforced composites under abrasive jet conditions are yet mainly unexplored, while the majority of current research concentrates on static mechanical properties. To assess material removal rate (MRR), surface roughness, kerf breadth, and wear resistance under various conditions such as pressure, nozzle diameter, and abrasive flow rate, future research should fabricate CSP-filled composites and expose them to controlled AJM operations.

Following appropriate processing, such as surface treatment and particle size reduction, CSP itself may also be studied as a possible environmentally benign abrasive material. Because of its inherent hardness and abrasive properties, it could be a sustainable alternative to artificial abrasives like silicon carbide or alumina. Additionally, to produce sophisticated green composites with specific qualities for machining and structural applications, hybridization of CSP with various bio-fillers such rice husk, tamarind shell, or coir fiber could be investigated [9-17]. In general, CSP has the potential to make a substantial contribution to the development of eco-composite materials, sustainable machining, and green manufacturing, particularly in precision industries that aim to lessen their environmental effect.

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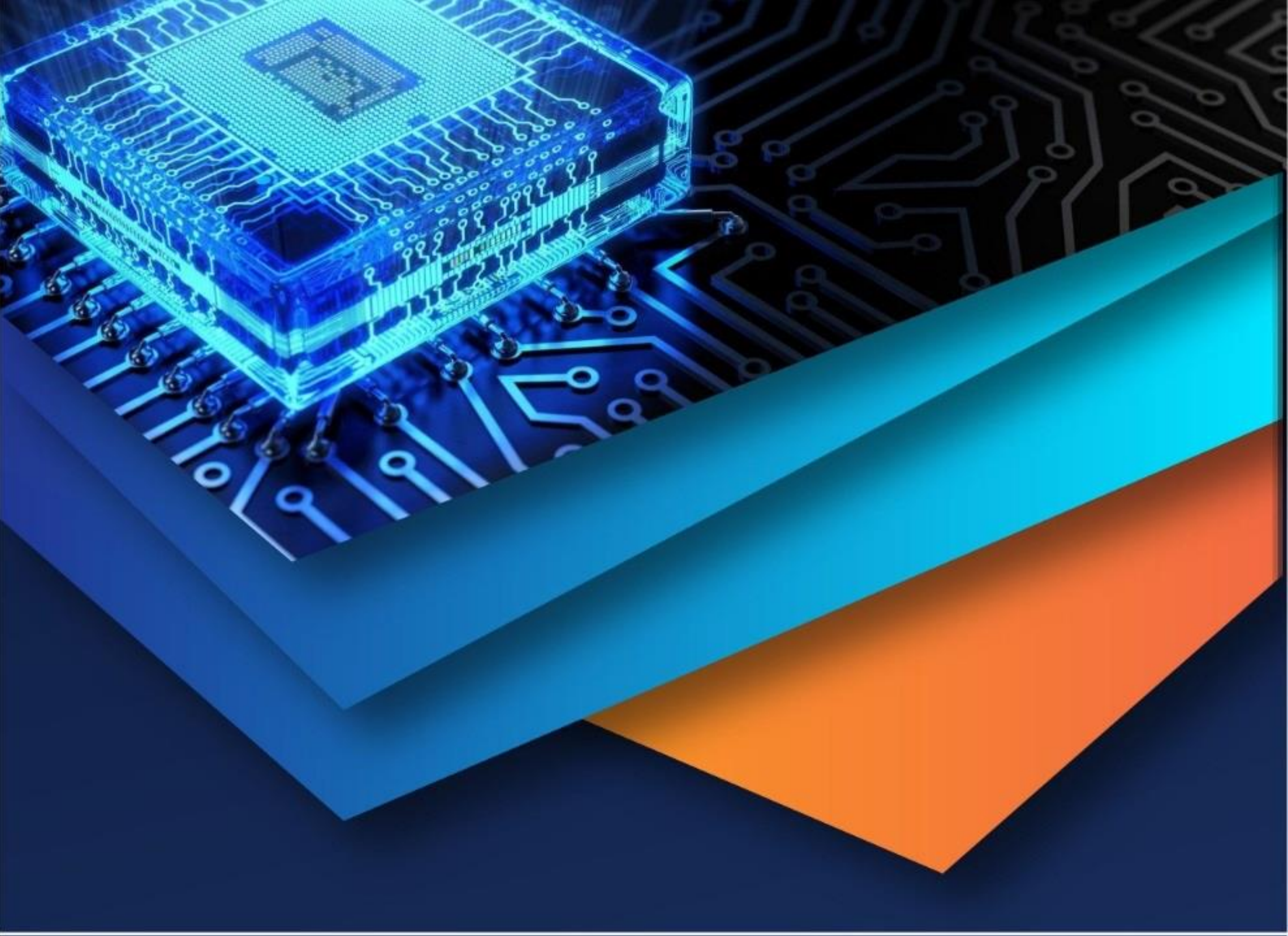

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