Recent Advancements in Sugarcane Bagasse-based Composites for Sustainable Waste Utilization

Md Mahadi Hassan Parvez, Md. Arifuzzaman*

Department of Mechanical Engineering, Khulna University of Engineering & Technology, Khulna, 9203, Bangladesh

Abstract: Sugarcane Bagasse (SB) composites have significant potential as a substitute for conventional materials due to their distinct properties, sustainability, and eco-friendly characteristics. This paper explores the utilization of SB waste in fabricating eco-friendly composite materials for sustainable industrial applications. Technological developments in the fabrication of composites using SB have led to significant enhancements in the mechanical performance, interfacial strength, and durability of these materials. Chemical treatments such as alkali treatment, silane treatment, and acetylation treatment of SB fibers play crucial role in bonding behavior of SB fiber with matrices. Nano- and micro-fillers have also been incorporated to improve the performance of SB-based composites through improved fiber-matrix interaction. Due to the unique properties, SB composites have gained attention in various industries, including construction industry, automobile industry, packaging industry, etc. The automotive sector could utilize SB bio-composites of interior parts contributing to energy reduced dependence on conventional plastic materials. SB-based bioplastics could serve as a substitute for traditional plastics that is biodegradable in the packaging industry to help solve problems related to waste plastic. The continuous development of SB composites indicates a promising future in which SB could become an excellent choice for producing sustainable materials, contributing to the circular economy. However, more systematic research is needed to properly integrate SB-based composites in various advanced applications.

Keywords: Sugarcane Bagasse-based Composites, Manufacturing Methods, Chemical Treatment, Mechanical Properties, Circular Economy.

1. INTRODUCTION

Sugarcane is a plant that grows well in tropical and subtropical regions and is used as a main ingredient in sugar and ethanol production (Huang *et al.* 2023; Meena *et al.* 2024). SB is a highly non-homogeneous substance composed of about 30–40 % pith fiber, originating from the center of the plant and mostly consisting of parenchyma material (Agarwal *et al.* 2023; Jaiswal and Devnani 2022). Due to their abundance and low-cost, cellulosic materials derived from SB are used in bio-composite engineering (Wibowo *et al.* 2024). Bagasse is a byproduct of agriculture that is very inexpensive and easily accessible. As the majority of bagasse is used as fuel in sugar plants (Guna *et al.* 2019). The processing each ton of sugarcane generates around 250-280 kg of bagasse, resulting in an annual production of nearly 54 million tons of bagasse (Le and Pham-Bao 2025; Ungureanu, Vlăduț, and Biriș 2022). A total of around 189 million metric tons of sugar were produced all over the world in the year 2025-26 and it is expected that the sugar market will increase at a compound annual growth rate of 1.36% by 2033 and produce around 223 million metric tons (Top 10 countries by sugar production n.d.). The substantial global availability and production of sugarcane, approximately 1.7×10^3 million tons per year, has led to increased research interest in SB as a lignocellulosic fiber in recent decades (Motaung *et al.* 2015). Natural fibers are being investigated by researchers throughout the world for potential use in various industrial fields due to their abundance, renewable nature, and biodegradability. There are many advantages in using natural fibers as a filler in composite materials. These include improved mechanical performance, reduced environmental impact, and biodegradability (Khalid *et al.* 2021). The recycling of agricultural waste would mitigate issues related to the buildup of such material (Kamel, Shafik, *et al.* 2024; Kamel, Wissa, and Abd-El-Messieh 2024). Sustainable urban development and the reduction of environmental degradation can only be achieved through the implementation of efficient waste management systems (Iwuozor *et al.* 2025). The elevated cellulose concentration in SB is particularly attractive to produce composite materials, due to the availability of sufficient raw materials and little processing expenses. Utilizing SB as a renewable composite material would facilitate different engineering applications derived from the process of converting SB waste into eco-friendly materials (Iwuozor *et al.* 2024; Kusuma *et al.* 2023).

The application of agricultural waste, especially SB, in the preparation of microwave absorbers, is a significant step (Tripathi and Sandha 2023). This performance was significantly enhanced by adding multi-walled carbon nanotubes to result in a maximum reflection loss value of -22.8 dB within the X-band

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*Address correspondence to this author at the Department of Mechanical Engineering, Khulna University of Engineering & Technology, Khulna, 9203, Bangladesh; E-mail: mahadihparvez@gmail.com, arif48@me.kuet.ac.bd frequency range. Optimal sound absorption performance was shown by hot press molding of sound absorption composites made utilizing SB as reinforcement and polycaprolactone as matrix (Pan *et al.* 2024). This finding provides theoretical support for the sustainable recycling of SB. By utilizing recycled newspaper and SB, the composite panels demonstrated promising properties for construction applications. This approach not only addressed waste management challenges but also created opportunities for more affordable and environmentally sustainable building materials (Etuk *et al.* 2023). Haghighat *et al.* (Haghighat *et al.* 2023) investigated fibers produced from SB waste to determine their influence on sound absorption performance, it was established that smaller fibers performed better in absorption performance and resistance to airflow but larger fibers had less acoustic efficiency. Kumar (Kumar 2026) used compression molding technology to manufacture SB fiber/polymer ABS biodegradable composites, obtaining an optimum tensile strength of about 40 MPa at a fiber content of 50% and a curing temperature of 125°C as sustainable alternatives to conventional polymer composites. Silva *et al.* (Silva *et al.* 2026) was developed formaldehyde-free-wood -inspired composite material using SB fibers and an adhesive made of natural rubber latex and alkali lignin, resulting in increased mechanical strength by up to 60%, greater wear resistance, lower porosity, and better interface compatibility for sustainable structural and coating applications. SB has shown potential as a lignocellulosic fiber in several fields, including biochar composites, microwave absorbers, and sound absorption materials. There is still a significant knowledge gap in understanding the mechanical, thermal, and environmental performance of SB-based composites for different industrial applications. It is also necessary to investigate the environmental impact of SB waste recycling processes.

Recent review papers in the field of SB-based composite materials have mostly focused on the specific issues including fiber extraction, mechanical properties, and chemical modification. This study aims to highlight the potential of SB-based composites as a replacement for conventional synthetic materials by investigating recent research outcomes. It focuses on the advancements in manufacturing techniques, in fiber treatment methods for property enhancement, effect of nano- and micro fillers and applications of SB-based composites. This review covers the environmental benefits and sustainability of SB recycling processes in relation to reduce the accumulation of agricultural wastes, and carbon footprint. This paper contributes to the advancement of eco-friendly composite materials while improving sustainable products in waste recycling by consolidating the existing literature and identifying future directions.

2. COMPOSITION AND PROPERTIES OF SB

SB, or sugarcane pulp, is a byproduct of sugarcane milling and juice extraction that is rich in lignocellulosic fibers. Sugarcane is a fibrous crop with an average of 65–75% water, 8-14% fibers, 11–18% sugars, and 12–23% soluble solids. Pure cane sugar and fiber make up the bulk of the crop (Santaella 2007). The waste SB has great promise as a source of these fibers (Phiri, Rangappa, and Siengchin 2024). The typical diameter of the fibers is 15 µm (Luz, Gonçalves, and Del'Arco 2007). The chemical compositions of the SB obtained from various sources are enlisted in Table **1**.

Table 1: Chemical Composition of SB.

Cellulose (%)	Hemi-Cellulose (%)	Lignin (%)	Pectin (%)	Reference
41.8	28.0	21.8	-	(Bilba, Arsene, and Ouensanga 2003)
45–55	20–25	18–24	0.6-0.8	(SachinYadav and Bhatnagar 2015)
50	25	25	-	(Huang et al. 2012; Xu et al. 2010)
32–34	19-24	25-32	-	(Sakdaronnarong and Jonglertjunya 2012)
39.53	25.63	30.36	-	(Chandel et al. 2014)
32–45	20–32	17–32	-	(Alokika et al. 2021)

Its morphological composition, rich in cellulose, hemicellulose, and lignin, enhances the compatibility for bio-composite applications. Figure **1** shows the flow diagram of the extraction process of bagasse. The plant is cut and the leaves are removed. Sometimes the skin is removed also. Then the plant goes through a pair of rollers to extract juice.

The mechanical and physical properties of the SB obtained from various literature are listed in Table **2.** Bagasse is a plant fiber mostly comprised of cellulose, with a relatively high modulus. SB has sufficient tensile strength and modulus, indicating its potential as reinforcement in composites.

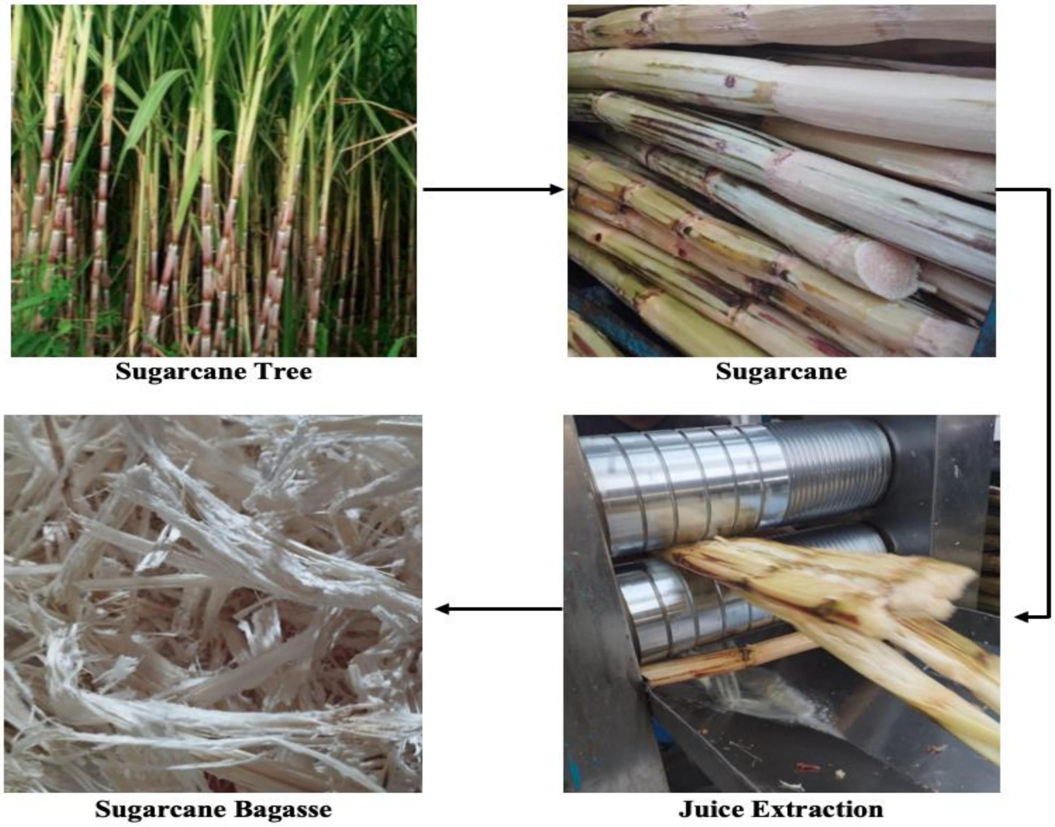

Figure 1: SB from juice extraction process.

Table 2: **Mechanical and Physical Properties of SB.**

Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Failure (%)	Density (g/cm^3)	Ref.
20–290	19.7–27.1	1.1	1.2	(Jayamaui *et al.* 2020)
170–290	15-19	-	-	(Wirawan *et al.* 2011)
222	-	1.1	-	(Satyanarayana, Guimarães, and Wypych 2007)
222–290	17–27.1	1.1	1.25	(Misnon *et al.* 2013)

3. ADVANCEMENTS IN SB-BASED COMPOSITE MANUFACTURING PROCESSES

The composite manufacturing methods using SB have advanced significantly, facilitating the production of environmentally sustainable, high-performance materials appropriate for construction and interior uses. Methods such as press molding and vacuum infusion have enhanced the characteristics of SB-based composite panels by optimizing fiber distribution and matrix adhesion, thus minimizing voids and obtaining superior interfacial bonding and surface finishes. By selecting resins, including epoxy and polyester, and adjusting fiber dimensions, researchers have attained enhanced tensile and bending properties. The feasibility study of recycling waste newspaper and SB to produce composite panels for construction showed their suitability for ceilings or partitions, where higher SB fiber content improved water absorption and thermal characteristics (Etuk *et al.* 2023). The effects of manufacturing methodologies on SB composite fiberboard were investigated, and it was shown that the optimal tensile and bending strengths were obtained with fine fibers, an epoxy matrix, and vacuum infusion technique (Madgule *et al.* 2023). Particleboards, cross-bonded with self-binding and bone glue, were produced using SB by several particle pre-treatments, improving physical and mechanical properties without the use of formaldehyde (Islam *et al.* 2024).

Table 3: Different manufacturing techniques of SB composites.

Manufacturing Process	Matrix	Fiber Length & Quantity	Findings	Impact	Ref.
Injection molding	PLA	SB nanocellulose; 1, 2, 3, 4, 5 wt.%	Improved tensile strength, flexural strength, fracture toughness, and impact strength by 41.44%, 26.21%, 89.79%, and 16.38% respectively, for a 2 wt. %	Positive	(Gond *et al.* 2022)
Hot press molding	Polycaprolactone	1 mm; mass fraction 35%	Enhanced sound absorption	Positive	(Pan *et al.* 2024)
Hand lay-up	Epoxy	10 cm, 40% volume fraction	Achieved maximum tensile strength and impact energy for 2 hours soaked in 5% NaOH-treated SB composite, respectively, compared to the 1 hr. and 3 hr. soaked in 5% NaOH-treated SB composites.	Positive	(Laksono *et al.* 2021)
Hand lay-up	Epoxy	Powder form used (sieves no. 70 and openings 210 microns); 5, 10, 15, 20, 25, and 30 wt.%	Achieved maximum tensile strength for 20 wt.% NaOH treated SB powder and maximum impact energy for 30 wt.% NaOH treated SB powder.	Positive	(Faruqui *et al.* 2024)
Hand lay-up	Epoxy	SB powder (200–300 micron); 10, 15, 20 wt.% powder used with banana fiber (total fiber 30 wt.%)	Increased tensile strength, impact strength, and hardness values for 20 wt.% SB powder-filled by 44.78%, 55.84%, and 11.03%, respectively, compared to the 10 wt.% SB-filled composite.	Positive	(Madgule *et al.* 2023)
Compression molding	Epoxy and Natural resin (Dammar resin, pine resin, and Cashew nut shell liquid resin)	Fine grade SB; 1 to 10 mm	Obtained maximum flexural and tensile strength for Cashew nut shell liquid resin-incorporated SB composite boards.	Positive	(Patil *et al.* 2023)
Hot press molding	Urea-formaldehyde	SB crushed to different particle sizes; sorghum stalk, SB, and matrix ratio was 25:50:75	Increased internal bonding, modulus of elasticity, flexural strength, and moisture content with high resin content and pressing pressure.	Positive	(Adefris Legesse *et al.* 2022)
Compression molding	Polyester	SB powder (70μm); 0, 9, 18, 27, 36, 45, and 54 wt.% of SB	Achieved optimal tensile and flexural strengths with NaOH treated 36 wt.% SB fillers in comparison to 0 wt.% SB fillers. Tensile strength and flexural strength increased by 92.81% and 63.86%, respectively.	Positive	(Obiukwu *et al.* 2024)

Palletization and injection molding at controlled temperatures and pressures were the subsequent steps in the production of bio-composites made from chemically treated SB fibers and polypropylene using a twin-screw extruder (Hidalgo-Salazar *et al.* 2018). The Palsule method comprises twin screw extrusion and injection molding processes in order to come up with an environmentally friendly SB reinforced functionalized styrene ethylene butylene styrene composites (Dinesh and Palsule 2022). Research on the recycling of SB and waste newspaper into composite materials for building purposes revealed significant improvements in thermal characteristics, water absorption, and mechanical strength using several manufacturing methods. Manufacturing techniques such as twin-screw extrusion, vacuum infusion, and injection molding improved material performance, offering sustainable alternatives for environmentally friendly construction materials. Different types of manufacturing process associated with SB and their findings are enlisted in Table **3**.

It is observed that the injection molding showed improved mechanical and energy absorption properties at low filler content (2 wt.%) when used in PLA (Gond *et al.* 2022). Hot press molding was effective for improving sound absorption and bonding properties with higher pressure and resin content (Adefris Legesse *et al.* 2022; Pan *et al.* 2024). Hand lay-up was a widely used method of manufacturing SB-base composites. Composites produced using this method showed good results in strength and impact properties, particularly when fibers or powders were chemically treated and used in proper proportions (Faruqui *et al.* 2024; Laksono *et al.* 2021; Madgule *et al.* 2023). Compression molding improved the mechanical properties significantly with treated fillers and suitable resin proportions. All manufacturing processes resulted in positive improvements, but the performance depended on choosing the right process conditions, filler size, and composition. It is difficult to compare the properties based on the manufacturing processes because of variations in processing parameters and resin system. It may be a potential research topic to compare the properties of SB-based composites resulting from utilization of various manufacturing processes fixing the constituents proportion and treatment process.

An analysis of various manufacturing processes reveals that vacuum infusion and compression molding are capable of offering superior interfacing and lesser voids in comparison to traditional hand lay-up processes. Injection molding is an effective technique when dimensional accuracy and scalability are concerned. Hand lay-up techniques are cost-effective for low-cost applications, though they lack uniformity and repeatability. Extrusion-based approaches are beneficial in terms of better filler dispersion and scaling.

4. EFFECTS OF CHEMICAL TREATMENTS ON SB-COMPOSITES

Surface treatment of SB composites comprises chemical modifications through alkali treatment or silane coupling to improve interfacial adhesion between bagasse fibers and the matrix. Table **4** highlights the impact of chemical treatment on SB composites. The improvement in mechanical strength, water resistance, and durability of the composite makes it more suitable for structural applications. Vaneewari *et al.* (Vaneewari and Saranya 2023) investigated the influence of the silane binding agent on the mechanical characteristics of SB and polypropylene composites, with different silane concentrations (10% and 20%) utilizing compression molding. The investigation showed that silane-treated fiber composites exhibit significant improvement in properties due to enhanced fiber–matrix bonding. A 20% silane treatment yielding maximum tensile and impact strength, while increasing silane content beyond this level leads to reduced flexural strength. Zainal *et al.* (Zainal *et al.* 2017) evaluated the mechanical and chemical characteristics of SB treated with 3-aminopropyltriethoxysilane (3-APS) in polypropylene (PP)/recycled acrylonitrile butadiene rubber (NBRr) composites. The use of silane treatment using 3-APS on SB improved adhesion and interfacial bonding in polypropylene/recycled acrylonitrile butadiene rubber composites. Bam *et al.* (Bam, Gundu, and Onu 2019) studied the impact of the weight percentage of SB filler on the tensile strength for the four different treatments of SB (i.e., non-treated, stearic acid treated, acetylation treated, and alkali treated). Across all the treatments, the tensile strength increased with the increase in filler content up to 30% and subsequently decreased upon further addition of SB fillers. Acetylation-treated SB showed the highest tensile strength at 30% filler content and continued to show higher strength even at higher filler contents. Alkali-treated SB followed closely, with a peak just below the acetylation curve at 30%. Stearic acid-treated SB showed moderate tensile strength at 30%, whereas untreated SB always shows the lowest tensile strength. Above 30%, all the treatments tended to decrease the tensile strength, with acetylation-treated SB still maintaining the best strength at 50% filler and non-treated SB dropping to the lowest value (almost 2 MPa). Boontima *et al.* (Boontima *et al.* 2015) processed SB chopping into 10 mm fragments and immersed for alkaline treatment in 1%, 2%, or 3% (wt/v) NaOH solution for a duration of 2 hours. The fibers were washed to a pH of 7.0, dried at 80°C for 15 hours, and thereafter kept in sealed bags. The 2% (wt/v) NaOH-treated fiber at 15 wt% in the composites exhibited the highest enhancement in impact strength compared to the non-treated fiber sample. The tensile and flexural characteristics of the composites were not improved. Hamin *et al.* (Hamin *et al.* 2023) implemented an alkaline treatment with a 5 wt.% sodium hydroxide (NaOH) solution to improve the surface properties of sugarcane bagasse. Alkaline treatment enhanced surface roughness and reduced surface impurities. The addition of sugarcane bagasse into potato starch significantly improved thermal stability and mechanical properties, attaining the highest tensile strength (5.30 MPa) and Young's modulus (28.72 MPa) at 6% SB loading. The additional SB incorporation decreased the strength of the composite. Acetone treatment was found to enhance fiber properties by dissolving hemicellulose and partially removing surface lignin, thereby promoting superior fiber–matrix bonding and resulting in significantly lower swelling in washed treated samples (Acharya, Mishra, and Mehar 2009). In acetylation, 90 g of cellulose was reacted with 456 g of glacial acetic acid at 35 °C for 45 minutes, followed by the addition of 150 g of acid and 0.6 mL of concentrated H_2SO_4 for 1 hour, before introducing 264 g of acetic anhydride and 3.6 mL of H_2SO_4 over a period of 3 hours. The acetylation showed negative impact on the mechanical properties of SB composite for polypropylene matrix (Luz *et al.* 2008).

Table 4: Effect of chemical treatment on SB composite materials.

0	Chemical Quantity	Matrix	Outcome	Impact	Ref.
Alkaline (NaOH)	5% NaOH (Soaked for 1 hr.)	Starch, Glycerol	Improved surface roughness, tensile strength and thermal stability	Positive	(Hamin *et al.* 2023)
Alkaline (NaOH)	1, 2, and 3 % NaOH (wt/v) for 2 hr.	Polylactic acid	Achieved maximum improvement in impact strength of treated fiber at 15 wt.% but the tensile and flexural properties were not improved.	Mixed	(Boontima *et al.* 2015)
Alkaline (NaOH)	5% of NaOH (agitated for 30 min. at 30 °C)	Epoxy	Improved tensile, flexural, impact strength, and hardness by 25%, 30%, 33%, and 20% respectively compared to untreated composites.	Positive	(Marichelvam *et al.* 2021)
Alkaline (NaOH)	5% NaOH (stirred for 2 hr.)	Polypropylene	Enhanced tensile strength and Young's modulus by 4–20% and 0.3–25% respectively compared to untreated composites.	Positive	(Zainal *et al.* 2020)
Alkaline (NaOH)	3% NaOH (8 hr. at 30 °C)	LDPE	Tensile strength and tensile modulus were improved significantly by about 13% and 196% respectively, for 30 wt.% fiber	Positive	(El-Meniawy *et al.* 2021)
Sulfuric Acid	10% sulfuric acid solution (reactor of 350 L at 120 ºC, 10 min)	Polypropylene	Increased tensile and flexural strength by 16% and 45% respectively.	Positive	(Cerqueira, Baptista, and Mulinari 2011)
Sulfuric Acid	10% sulfuric acid solution (reactor of 350 L at 120 ºC, 10 min)	HDPE	Increased tensile strength with increasing fiber content.	Positive	(Mulinari *et al.* 2010)
Acetylation and Alkaline	Acetic acid and anhydrides (Acetylation), 5% NaOH (Alkaline) for 5 hr.	LDPE	Increased tensile strength, impact strength by 10- 40% and 10-50%. Acetylation-treated composites showed better result.	Positive	(Bam *et al.* 2019)
Acetylation	456 g of glacial acetic acid for 90g of cellulose	Polypropylene	Decreased mechanical properties.	Negative	(Luz *et al.* 2008)
Silane	5 g of fiber in an emulsion of 0.5% to 8% (by volume) silane for 2 hr.	Cementitious	Improved water resistance of the fibers.	Positive	(Bilba and Arsene 2008)
Silane	5% 3-APS and ethanol (100 g of SB was added and stirred for 1.5 hr.)	Polypropylene	Increased tensile strength and Young's modulus by 30% and 32% respectively.	Positive	(Zainal *et al.* 2020)
Alkaline and Acrylation	1% NaOH for 30 min and 1% acrylic acid for 1 hr.	Epoxy	Improved 3% thermal stability in alkaline- and acrylic acid- treated composites at 10% SB content.	Positive	(Mittal and Sinha 2017)

The 3% and 5% NaOH concentrations generally yielded positive improvements in surface roughness and interfacial adhesion in most thermoplastic and thermosetting matrices, especially epoxy, LDPE, polypropylene, and starch. However, under optimal conditions, excessive treatment, as applied to PLA, showed low or even adverse mechanical properties (Boontima *et al.* 2015). Sulfuric acid treatment continually improved tensile and flexural strength in polyolefin matrices by promoting cellulose exposure. Combined treatment methods, which enhance fiber cleanliness and chemical affinity, generally yielded better results than individual treatment methods. Acetylation treatment was more successful than other treatment methods in LDPE, whereas it was not found suitable in polypropylene. This indicates the importance of chemical affinity between the matrix and fibers even after treatment. Silane treatment was found to be effective in increasing stiffness and hydrophobicity for cement and polypropylene matrices. Therefore, the applicability of silane treatment would be successful in situations where water resistance is critical.

Chemical treatment of SB enhances the mechanical properties due to better adhesion between the fibers and reduces moisture absorption, hence increasing the strength and durability of the composite applications. Therefore, the suitable chemical treatment and

Table 5: Effect of nanofiller on properties improvement of SB composite.

Nanoparticle	Nanoparticle Quantity	Outcome	Impact	Ref.
Nano silica	1, 3, 5 and 10 phr	Increased the cure rate index and enhanced modulus and hardness of natural rubber composites incorporating silica nanoparticles due to increased composite stiffness, while tensile strength improved up to 5 phr and declined at 10 phr as a result of silica nanoparticle aggregation.	Positive	(Boonmee and Jarukumjorn 2020)
Nano silica	1 wt.%	Enhanced the mechanical performance of alkali-treated SB particulate composites by incorporating nano-silica particles, which reduce micro-voids, resulting in improvements in tensile strength (3.5–15.9%) and tensile modulus (3–9%) when ultrasonic mixing is employed.	Positive	(Fong, Khandoker, and Debnath 2018)
Nano graphene (NG)	0.10, 0.25, 0.50, 0.75 and 1.00 wt.%	Enhanced tensile and flexural properties with NG addition due to its high aspect ratio and large surface area, with 0.1 wt.% NG and 30 wt.% SB yielding increases of 22.5% in tensile strength, 29% in tensile modulus, 6.8% in flexural strength, and 30% in flexural modulus, while higher NG loadings caused nanoparticle agglomeration and reduced mechanical performance.	Positive	(Chaharmahali *et al.* 2014)
Cellulose nanocrystals	1% nanocrystal	Cellulose nanocrystals inclusion did not significantly improve the mechanical and physical properties of SB particleboards, due to reduced adhesive interaction and increased adhesive viscosity.	Negative	(Mesquita *et al.* 2019)
Nano clay	1, 2, 3, and 4 wt.%	Increased tensile modulus and yield of composites by approximately 26% and 15%, respectively, with 3 wt.% nanoclay, then slightly decreased at 4 wt.%, while the impact strength was reduced progressively from 1 to 4 wt.% nanoclay, and water absorption was decreased with increasing nanoclay content.	Positive	(Nourbakhsh and Ashori 2009)

optimized SB loading significantly improve the performance of SB composites. As alkali and acetylation treatments enhance interfacial bonding and surface properties, resulting in optimal mechanical attributes at moderate filler concentrations, beyond which filler agglomeration and inadequate stress transfer lead to a reduction in strength. The chemical affinity between the matrix and treated fiber also plays important role on bonding behavior between fiber and matrix which in turn results in degradation in mechanical properties. The enhancement of mechanical properties using chemical treatment can be explained by the removal of hemicellulose, lignin, wax, and other surface contaminants from the SB fibers. Excess chemical treatment may alter the structure of cellulose and hence weaken the fiber.

5. EFFECTS OF NANO- AND MICRO-FILLERS IN SB-COMPOSITES

The incorporation of nano- and micro-fillers in composites is a well-known technique for enhancing the mechanical properties of composites. The certain properties of the SB composites can also be improved using nanofillers. Table **5** highlights the effect of nanofiller on properties enhancement of SB composites. Hybrid composites produced from SB fiber, rice husk, and wood powder have stronger mechanical properties than single fiber composites, with values of 16–20 MPa compared to 14–18 MPa (Velmurugan *et al.* 2023). Egg and snail shells combined with SB improved the mechanical properties of hybrid reinforced epoxy composites more than eggshell powder only, with optimal performance at 12–20 wt.% particulate reinforcement (Oladele *et al.* 2024). An evaluation of the physical and mechanical properties of bio-composites revealed that an increase in SB composition leads to a decrease in density, an increase in water absorption, and a reduction in flexural strength and modulus (Ismail I, Ikram M, and Zulfalina Z 2024). According to the American National Standards Institute (ANSI) guidelines for particleboard applications, these properties improved as particle size decreased.

The incorporation of different nanoparticles, such as nano-silica, nano-graphene, cellulose nanocrystals, and nano-clay, has shown diverse effects on the mechanical properties of the polymer composites. Nano-silica at any concentration tends to increase tensile strength, modulus, and hardness but decrease elongation at break with increasing content (Boonmee and Jarukumjorn 2020). Specifically, at 1 wt.% of nano-silica, a significant improvement in mechanical performance was observed (Fong *et al.* 2018), which also suggested that moderate loading provides the best outcomes. A significant reinforcement effects of nano-graphene were observed in SB/polypropylene composites, with the most improvement at 0.1 wt.% (Chaharmahali *et al.* 2014). Even low graphene inclusion can greatly improve mechanical properties because of its high surface area and strength, whereas 1 wt.% cellulose nanocrystal loading did not improve the mechanical or physical properties of SB particleboards (Mesquita *et al.* 2019). Poor adhesive interaction and increased viscosity highlight the need for compatibility between nanoparticles and matrix materials. Nano clay at 1–4 wt.% improved the tensile strength and water absorption of SB composites, with optimum performance at 1–3 wt.% (Nourbakhsh and Ashori 2009). This confirms that nano clay not only increases the strength of the composite but also improves its durability by decreasing the moisture content. The nano-graphene and nano-silica showed the highest improvement in mechanical properties at lower filler concentrations, while the cellulose nanocrystals show a negative effect.

6. APPLICATIONS OF SB COMPOSITES

SB is used in construction materials due to its mechanical properties, affordability, and ecological advantages, hence improving the strength and sustainability of composites across many applications. For use in construction applications, an investigation was conducted to find a thermal insulation and sound-absorbing material that was found to be both cost-effective and environmentally friendly (Mehrzad *et al.* 2022). SB can serve as a sustainable building material when combined with cement to produce eco-friendly composites that improve mechanical properties (Iqbal *et al.* 2024). SB ash may replace up to 50% of cement in construction materials, enhancing strength, reducing weight, and promoting sustainable building materials. These materials can be used as fiberboard for interior cladding (Freitas *et al.* 2023; Gbadeyan *et al.* 2023; Guirguis, Farahat, and Micheal 2023). An analysis was conducted on the effects of SB ash in cement composites on the environment (Liu *et al.* 2024). The results showed that this material may be a sustainable option due to its capacity to use waste and produce less carbon dioxide. SB ash may replace up to 50% of cement, increase strength, reduce weight, and reduce carbon emissions. This eco-friendly composite enhances mechanical properties and provides sustainable building solutions, especially fiberboard for interior cladding.

SB fiber ash serves as a reactive silica source in alkali-activated binders, improving strength and sustainability in building materials (Murugesan, Vidjeapriya, and Bahurudeen 2020). SB may serve as an addition in concrete blocks, improving compressive strength, especially at 5% and 15% proportions of bagasse ash (Nasruddin *et al.* 2022). SB ash serves as an excellent pozzolan in blended cement manufacturing, improving compressive and tensile strengths while decreasing permeability in concrete (Murugesan *et al.* 2021). By reducing waste, increasing thermal insulation, and providing an environmentally acceptable alternative to traditional materials, using SB in composites as building blocks improves sustainability (Souza, Eires, and Malheiro 2022). As a reactive silica source in alkali-activated binders, SB ash improves compressive and tensile strengths, reduces permeability, and increases thermal insulation in concrete, making it an eco-friendly alternative that reduces waste and resource use.

Automotive bio-composites employ SB to make eco-friendly package trays and sustainable acoustic materials with better sound absorption. SB is used in automobile bio-composites for interior components such as parcel trays, providing a sustainable substitute for traditional materials (Juliana *et al.* 2018). SB may be used in the automotive sector to produce sustainable acoustic materials, improving sound absorption characteristics (V *et al.* 2023). Graphene extracted from SB might improve automobile materials due to its remarkable strength, electrical conductivity, and thermal characteristics, possibly substituting traditional components (Varshney, Guliani, and Jeyaseelan 2022).

SB has been gaining applications in the packaging industry to substitute the conventional products made from plastics because of its green characteristics. SB can be recycled and integrated with microbial cellulose to produce sustainable, biodegradable packaging materials that exhibit improved strength and flexibility, making them appropriate for food packaging applications (da Silva Junior *et al.* 2024). Bioplastics made from bagasse have several potential applications in many different sectors, including food packaging, and contribute to reducing the plastic pollution issue (Elkayaly, Hazem, and Fahim 2022). The cost-effectiveness of SB-based packaging materials must also be evaluated in comparison with conventional plastic alternatives. The development of bio-composite materials that may be used for packaging (Mahmud, Belal, and Gafur 2023).

The integration of SB into alternative materials improves their durability and flexibility, rendering them appropriate for diverse packaging applications (Janika *et al.* 2024). The use of bagasse minimizes dependence on non-biodegradable polymers, thereby tackling the escalating waste crisis in the packaging industry (Singh, Sharma, and Sambyal 2022). Packaging based on SB is said to be degradable; formulated material has decomposed significantly even within weeks of testing. The integration of SB enhanced the durability and flexibility of alternative materials, rendering them appropriate for diverse packaging applications.

7. SUSTAINABILITY AND ENVIRONMENTAL IMPACT

SB composites have significant impacts on the environment. It has a substantial impact on sustainability since they provide environmentally friendly alternatives to conventional materials. SB composites enhance sustainability through the utilization of agricultural waste, and mitigation of environmental pollution within the brown sugar industry (Hiranobe *et al.* 2024). A sustainable geomaterial composite, made from SB ash, glass fiber, and blast furnace slag, was developed to enhance load-bearing capacity and reduce environmental impact (Nikhade *et al.* 2023). SB and low-density polyethylene were used to make eco-friendly composites with improved thermal degradation and ultraviolet resistance resulting from maleic anhydride and carbon black reinforcement and environmental durability (Saber, Abdelnaby, and Abdelhaleim 2023). Composites made of SB fiber and polyester resin have shown excellent mechanical properties for treated fibers (Obiukwu *et al.* 2024).

SB composites demonstrate reduced energy consumption and lower global warming potential in comparison to carbon composites (Ramachandran and Gnanasagaran 2024). The composite of SB and microbial cellulose presents a biodegradable alternative to nonbiodegradable polymers (da Silva Junior *et al.* 2024). Composite fiberboard made from SB improves thermal insulation, encourages sustainable construction methods, and recycles agro-waste, all of which contribute to a significant decrease in carbon emissions and environmental impact (Guirguis *et al.* 2023). Sustainable and environmentally acceptable alternatives to carbon-based materials include SB composites.

SB composites are good for the environment and help spread sustainable products by reducing plastic waste and making use of a renewable resource (Hossam and Fahim 2023). Biodegradable, long-lasting, and very efficient at water purification, SB composite membranes have a negligible influence on the environment and may be recycled into carbon (Aditya *et al.* 2024). SB composites help to keep the planet habitable by developing the concepts of the waste recycling and producing biodegradable products.

8. CONCLUSION

SB composites have great potential in many industries due to their unique properties, economic feasibility, and environmental sustainability to fabricate sustainable engineering products. This paper reviews the recent developments in the field of SB-based composite materials for waste recycling, with emphasis on the impact of composition, manufacturing technology, chemical treatments, nano-/micro-filler addition, applications in industry, and environmental sustainability. The presence of lignin and cellulose in the lignocellulosic structure of SB allows reinforcing various polymeric and cementitious materials for wide engineering applications.

Modern manufacturing technologies such as vacuum infusion, extrusion, and injection molding affect the mechanical and thermal properties of SB-based composites positively due to proper fiber distribution and interfacial bonding. Chemical treatments, including alkali, silane, sulfuric acid, and acetylation treatments, improve fiber-matrix adhesion and water-resistant properties. The effectiveness of the treatment depends on the matrix compatibility and optimal processing conditions. The addition of nano- and micro-fillers such as nano-silica, nano-graphene, and nano-clay contributes to increasing tensile strength, stiffness, hardness, and water-resistant properties at optimal filler amounts. SB-based composite materials can be applied in various industries, including construction, automobile industry, food packaging, thermal insulation, and acoustic material.

SB-based composites can be used in various engineering fields such as in building materials, automotive interior applications, acoustic panels, thermal insulation systems, packaging materials, etc. due to their low weight, biodegradable properties, cost-efficiency, and good mechanical behavior. There are a number of drawbacks that include variability in quality of fibers, moisture effect on fibers, absence of standard procedures for processing, and inconsistent experimental procedures. Future research into these materials should focus on creating multifunctional hybrid composites, using surface modification, optimizing the use of fillers and nano- or micro-fillers, conducting life cycle assessment, studying biodegradation, and scaling up production.

The development of SB-based composite materials results in waste valorization, and advancement of a circular economy in the industry. Further improvement in technology widens the applicability of SB and further support positive transformation toward a more sustainable and circular economy.

AUTHORS' CONTRIBUTIONS STATEMENT

Md Mahadi Hassan Parvez: Conceptualization, Writing original draft, Methodology, Formal analysis. Md. Arifuzzaman: Conceptualization, Writing review & editing, Supervision.

DATA AVAILABILITY STATEMENT

Not applicable.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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