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Research Article

Effect of Varied Cashew Nut Ash Reinforcement in Aluminum Matrix Composite

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In the present article, cashew nut biocarbon (CTB), an agricultural waste, is used as reinforcement in Al6061 by the heating process. The primary XRD study on CTB confirms the presence of SiO_2, Al_2O_3, iron-rich ferro-axinite, MgO, and Mn, which improve the material's properties when used as reinforcement. SiO_2 levels increase with annealing time. The extracted CTB is crushed into a ball mill for 24 hours, and the particle size is measured by SEM as 70–90 nm. An experimental study was performed with a variable percent weight of CTB with an increase of 5%–20% for structural stability applications. X-ray analysis tests the composite's elemental composition and intermetallic elements. It confirms that no such evidence exists. CTB's density, tensile, flexural, and impact tests measure CTB's impact. CTB has the lowest density variation and increases tensile and flexion bearing capacity by 30% and 47%, respectively. The lightweight brittle increment is impact-resistant. SEM fracture analysis shows transgranular and intergranular fractures with dimples, large craters, and peak areas.

1. Introduction

The fabrication of novel materials in the form of the addition of some foreign elements as reinforcement in the base matrix is of great interest among researchers. The disposal of agro-waste and allied products is always a challenging task for the nation [1]. To overcome these issues, several new technologies and pragmatism have been adopted. Several research activities utilized agricultural waste material as reinforcement in the base matrix, such as aluminum and magnesium [2, 3]. The systematic process of conversion of agro-waste material may result in the form of ceramic-rich elements in biochar [4]. Irrespective of its advantages, several foreign elements present in the ash may degrade the material properties [5]. Before the selection of any other agro-waste material as reinforcement in the metal matrix composites, proper investigation is required of the elemental composition [6]. The researchers had a unique way of converting the available elements into useful elements with varied heat and thermal processes. With the increase in the annealing temperature and the working condition, the elements present in the ash can be considerably converted, which could improve the material characterization rather than degrade its properties [7]. Studies have been conducted on agro-based byproducts such as rice husk ash, coconut shell ash, and coir ash and have concluded that the elements present in the ash may improve the mechanical properties and enhance the material used for various engineering applications [8, 9]. The presence of ceramic elements in biochar may improve the corrosion, wear, thermal, and hardness of the material. The adverse effects, such as low electrical conductivity and thermal insulation, become unavoidable [10]. As the shape of the biochar elements extracted from the agro-waste is irregular in shape and size, it progressively helps in the bonding phenomenon inside the matrix [11]. The particle shape may be modified to have effective stiffness and interfacial bonding within the matrix elements.

When burnt in proper condition, cashew nutshells will provide biochar with the major components of silicon dioxide and lime oxide [12]. Heating the biochar to some elevated temperature or increasing the annealing temperature/duration may result in the reduction of lime oxide content and progress to having an excess amount of silicon dioxide [13]. India is one of the major cashew nut cultivators in the world with an annual turnover of 810 million US dollars. Among them, Tamil Nadu alone contributes 710 kg/ha of cashew nut cultivation [14]. From these data, the disposal of the cashew nutshell is going to be a challenging task for the Tamil Nadu government and the Indian government as well. Generally, around 75% of the total cashew nutshell was sent to extract oil, and some portion was sent to extract gum for carbon composite substances [15]. However, the residues after the oil extraction are compressed to get cashew nutshell cake, which may contain a small quantity of oil. Usually, it is burned or put through the muffle furnace to become biochar and finally disposed of in the ground, which may cause severe environmental pollution, affecting soil fertility. On investigation of the ash, the presence of some elements is believed to improve the mechanical characterization and the material properties to a greater extent when it is used as reinforcement material. Aluminum is one of the base matrices, which suit the preparation of metal matrix composites [16]. Several metals, ceramics, and ash, such as rice husk ash and coconut shell ash, were utilized as reinforcement in the aluminum matrix with different weight percentages [17]. After proper investigation of fabricated composite, suitable weight percentages are being proposed and implemented for various engineering applications. The addition of 25% SiC in the aluminum matrix increased the strength of the composite by 100% [18]. The improvement in the density, strength, and hardness of the composite is recorded with the addition of this agro-waste reinforcement in the Al matrix [19]. The addition of aluminum oxide in the aluminum matrix shows no change in density, but strength has been considerably improved when compared to silicon carbide [20].

Agricultural waste is a very cheap form of reinforcement material that could be able to achieve similar strength and properties as the reinforcement of available ceramic reinforcements such as silicon oxide, silicon nitride, and aluminum oxide. The tensile strength and the harness were increased by up to 8% with the addition of agro-waste as filler elements in the Al matrix [21]. The addition of rice husk in the aluminum matrix can improve the stiffness property. However, the agglomeration with the increase in the filler percentage cannot be avoided irrespective of the advanced manufacturing process [22]. Comparative approaches with several agro-based filler elements were reported. Among them, rice husk ash has been given considerable attention in the research because of the presence of an actual amount of silicon oxide [23]. Proper sintering processes may be considerably involved in the change of elements that are available in the ash [24]. Among various manufacturing processes, the stir casting process has proven to be the simplest and easiest method of fabricating the composite. Recently, the ultrasonication casting process is preferred when adding nanoreinforcements [25]. The presence of ultrasonic vibration may enhance the particle distribution inside the matrix in a uniform manner. The selection of the proper ultrasonication frequency is another major task for the researcher [26]. Excess vibration causes the high-density sample to settle at the bottom of the molten mixture, which results in improper distribution of the particles inside the matrix [27]. In contrast to previous research, the current study employs agricultural waste of cashew nutshells, which has a higher SiO_2 content. It was collected in the Tamil Nadu region, and a systematic process was adopted to convert it into ash. The ball milling technique was used to convert the biochar into 80–90 nanosized particles. Adjusting the filler's weight percentage in aluminum matrix composites leads to a new material with improved properties. The composites have been subjected to some basic mechanical testing and characterization. This research helps pinpoint the optimal CTB concentration to use. A microcharacterization study conducted on the surface of the crack showed what happened when the matrix was strengthened from the inside.

2. Materials and Method

2.1. Cashew Nut Biochar Preparation. Cashew nutshell waste is a kind of agricultural waste that can be turned into biochar using a slow pyrolysis process. The cashew nutshell waste collected from Madurai, Tamil Nadu, was taken as raw material. The cashew nutshell waste is manually removed from the raw materials. After the cashew nuts are removed, the shell residue is collected and dried in direct sunlight to remove moisture. The collected garbage was then tightly packed into a tiny container that was completely sealed to prevent air from entering the container. The containers are then carefully placed inside the furnace, for 1 hour and heated constantly to become ash. The collection of cashew nutshell debris in these investigations is tested to temperatures of 400°, 500°, and 600°C. The container is then gently removed from the furnace after the completion of the pyrolysis process, and the prepared charcoal material is collected and ball-milled. The ball-to-mix weight ratio of 1 : 10 is achieved with consistent machining for 24 hours to get the nanosize particle. The biochar is collected and ready for reinforcement. The process involved in the preparation of the biochar is shown in Figure 1. The ball mill biochar particle size was measured through SEM analysis. From the report, it can be confirmed that the average particle size after the ball milling process is in the range of 70–90 nm, and it can be verified through Figures 1(a)–1(c).

The biochar is heated for 4 hours at 400°C, 500°C, and 600°C, respectively. The XRD analysis confirms the shift in the elemental composition. Table 1 displays the most common elements found in ash following heating. The four most abundant elements in this sample are arcanite, calcium carbonate, silicon dioxide, and carbon. Arcanite and gypsum levels have been falling while silicon dioxide and carbon have

(a) (b) (c)

Figure 1: Process of conversion of ash to CTB. (a) Furnace. (b) Ball milling machine. (c) SEM image for the CTB.

Table 1: Elemental composition of the CTB with change in annealing time.

Element name	% of main key elements in CTB		
	400°C	500°C	600°C
K_2SO_4	22–24	12-13	06-07
$CaCO_3$	21-22	13-14	04–09
SiO_2	41–46	67–62	74–76
C	06–10	12–14	21–24

been rising. Similar observations are noted by Suresh Kumar et al. [28]. Some of the content's calcium and potassium atoms have been transformed into carbon and silicon atoms. When used as a reinforcing particle in metal matrix composites, this transformation of the elements produces impressive results. Silicon dioxide was found to have an average percentage of 75% among the available elements at temperatures around 600°C. As shown in Figure 2, the XRD plot shifts as a function of annealing temperature. The advantages of silicon dioxide led the authors of this study to use preheated samples at 600°C as reinforcement in the aluminum metal matrix composite for the cases under consideration.

3. Stir Casting Process

CTB is successfully incorporated into the aluminum matrix at varying weight percentages of 5%, 10%, 15%, and 20% (specified as ALCTB-1, ALCTB-2, ALCTB-3, and ALCTB-4, respectively). We procured a rod of 99.9% pure aluminum from the Coimbatore Metal Mart in Coimbatore, India. After chopping them into small pieces, they are fed into the chamber of the ultrasonic stir casting apparatus shown in Figure 3. To incorporate the CTB as reinforcement into the molten metal, the ultrasonic stir casting machine spins at a steady 200 rpm while keeping the temperature at 780°C. Ultrasonication at a frequency of 2 kHz was used to introduce vibration into the mixture, which helped to improve the uniform dispersion of the reinforced particles. The OHNS cylindrical die with a 120 mm diameter is preheated to 200°C. After allowing the melt mixture to enter the preheated die, the die is compressed under a load of 80 kg/mm for one minute. This is done so that the material's microstructure and grain boundary are both uniform. Finally, the sample is ejected from the die and allowed to cool at room temperature. Furthermore, the fabricated samples were annealed at 200°C for 4 hours. The sample is then ground to a fine surface finish through an end milling process. Sufficient care has been taken to avoid the thermal effect during the polishing of the test sample. The fabricated samples are cut to the standard dimensions for the tensile (ASTM E08-8), flexural (ASTM A: 370), and impact (ASTM E23) tests to be contacted, as shown in Figure 4.

A Microtek-made densitometer instrument is used to measure the density of the fabricated composite using the traditional Archimedes principle. The dimension of the sample used for the test is $10 \times 10 \times 10\ mm^3$. Mitatyo makes a micro-Vickers hardness tester used to examine the hardness of the fabricated composite, and the data are recorded in terms of VHN. A deadweight of 500 grams is applied for 10 seconds. The experiment is conducted at an ambient temperature of 28°C. Five indentation observations are conducted, and the average is calculated and reported. The tensile test is conducted using the equipment model INSTRON UTM-DIRC/ME-01, which has a head velocity of 0.5 mm/min. The elongation percentage for the applied load condition is recorded for four experimental runs, and the average is recorded. The flexural test is conducted using a three-point bending tester model INSTRON UTM-DIRC/ME-01 that has a traverse head speed of 0.5 mm/min. Four experimental runs were conducted, and the average was recorded. The computer-integrated Charpy impact tester is used to conduct an impact test on the V-notch test samples. The root radius of the V notch is 0.25 mm to a depth of 2 mm and an inclination angle of 45°. Four experimental trial runs were conducted, and the average value is reported.

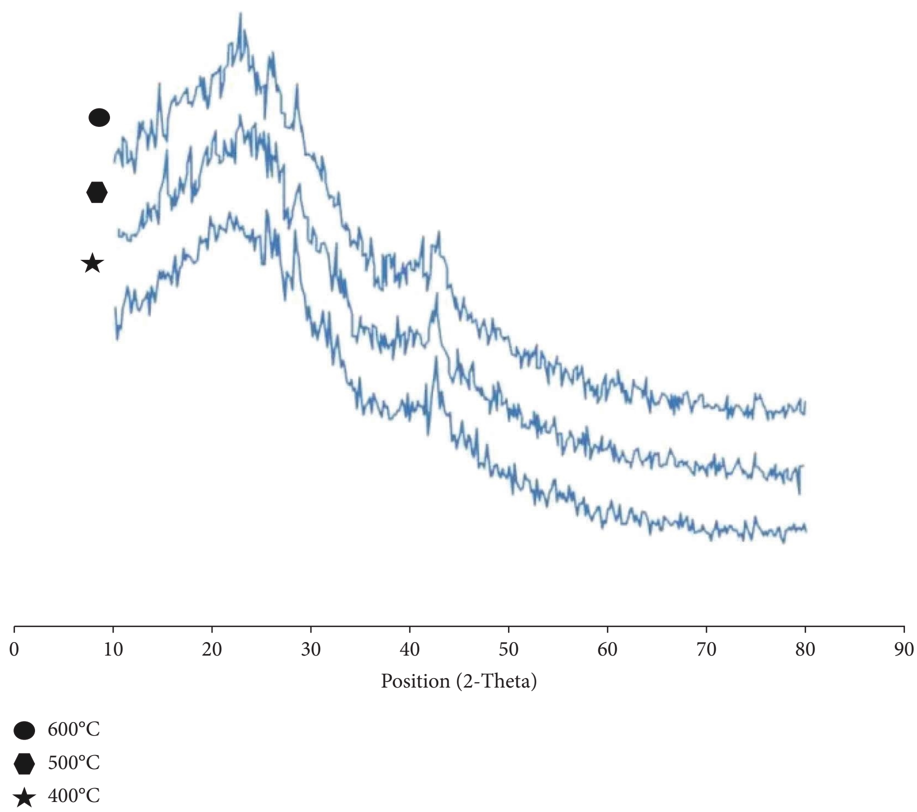


Figure 2: XRD of CTB.

4. Results and Discussions

4.1. Density and Microstructural Analysis. The density of a sample is drastically affected by the incorporation of a reinforcement matrix [29]. ALCTB samples that have just been made are tested for a secure density. Density is determined by modifying the classic Archimedes principle [30]. Researchers find that the reinforced CTB has a density very close to that of pure aluminum. Incorporating this nanoreinforcement resulted in a negligible change in density [31]. However, the porosity significantly affects the quality of the end material. The external load applied at the time of fabrication of this composite material influences the microstructure of properties of the material to a greater extent. Proper sintering condition with ultrasonication has resulted in the even distribution of reinforcement in the matrix. The applied load tends to squeeze the grain particles and further the annealing process helps relieve internal stress that is introduced inside the grain particle during the fabrication of ALCTB. This action almost always provides better results in getting void-free test samples. To examine the significance of CTB in the matrix, microstructural examinations (Mag: 50x) were carried out for all four combinations. The microstructure available for the various weight percentages of CTB reinforced metal matrix composite is shown in Figure 5. With the increase in the reinforcement in the base, the matrix improves the formation of the grain boundary. The even distribution of the reinforcement is confirmed. It is believed that CTB has occupied the grain boundaries of the aluminum elements in the matrix, and small particle distribution along the grain as well is visible in the microstructure image. The ultrasonication casting process exhibits the uniform distribution of the particles. However, with the increase in reinforcement, the agglomeration of the CTB particles along the grain boundary is noted and can be verified in Figure 5(d).

To measure elemental distribution in the matrix, ALCTB-4 (20% weight ratio sample) underwent EDAX. The distribution of the elemental peak is shown in Figure 6. The elemental composition of aluminum is witnessed in the image along with foreign elements like Fe, Ca, SiO_2, and oxygen.

With the increase of reinforcement in the base aluminum matrix, a slight improvement in the density of the composite is noted. As the density of CTB is slightly greater than the base metric element, as a result, a gradual improvement in the density of the composite sample is recorded with the increase in the weight ratio of the reinforcement. The rate of change of density concerning the nascent sample is considered negligible, and hence the significance of the addition of reinforcement is of the least importance in the density studies. The variation of the density with an increase in the weight percentage of reinforcement is shown in Figure 7.

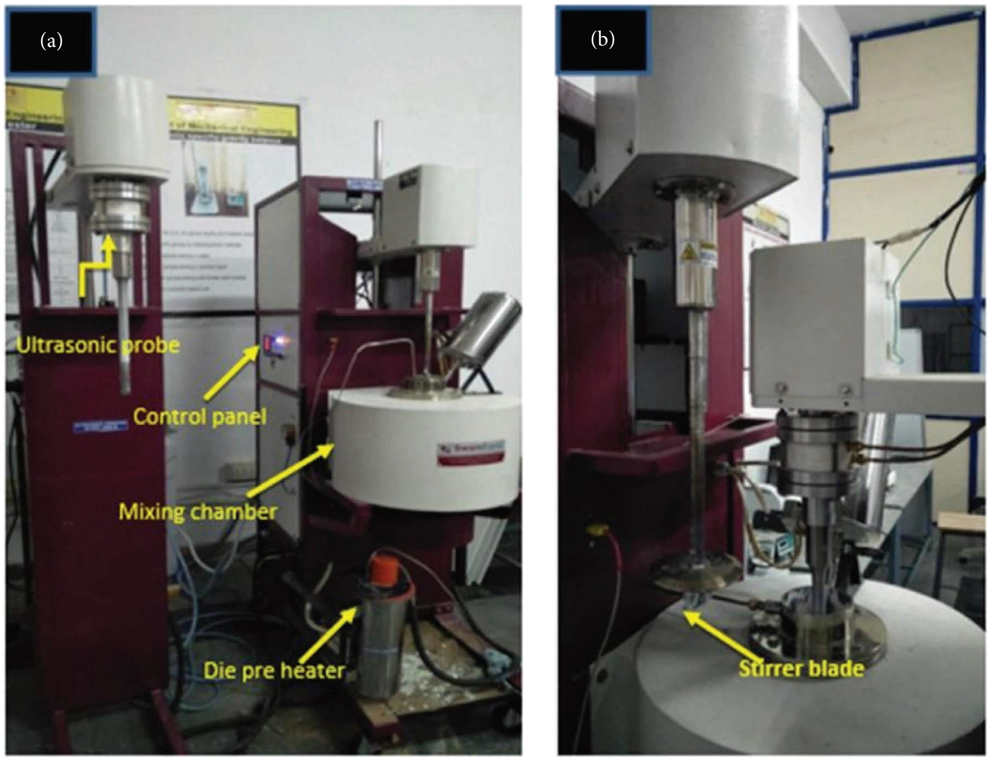
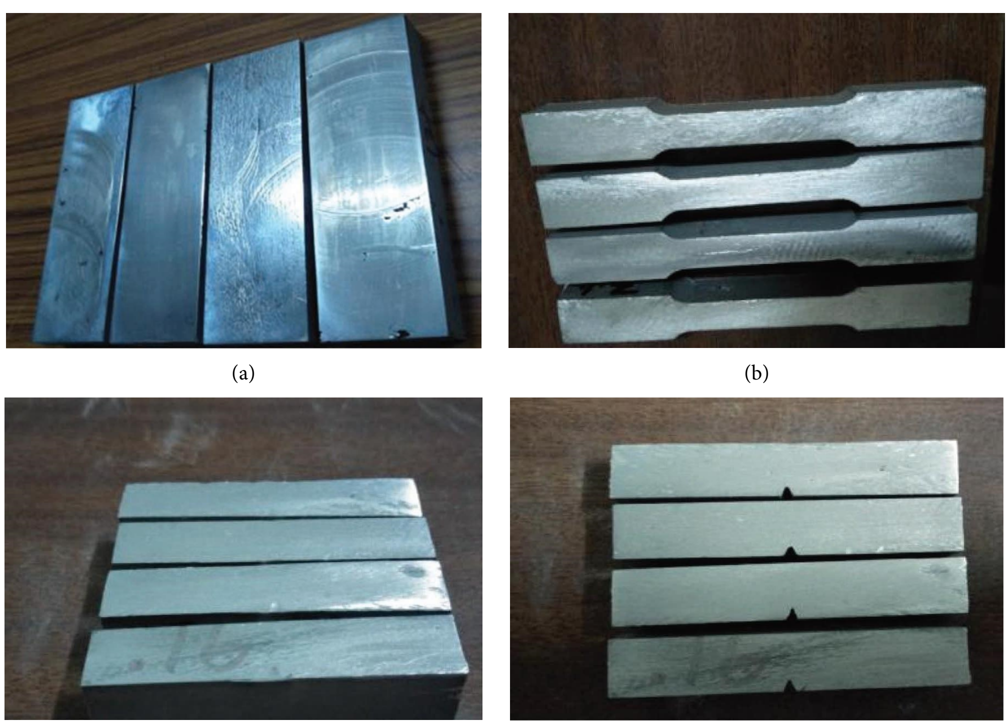
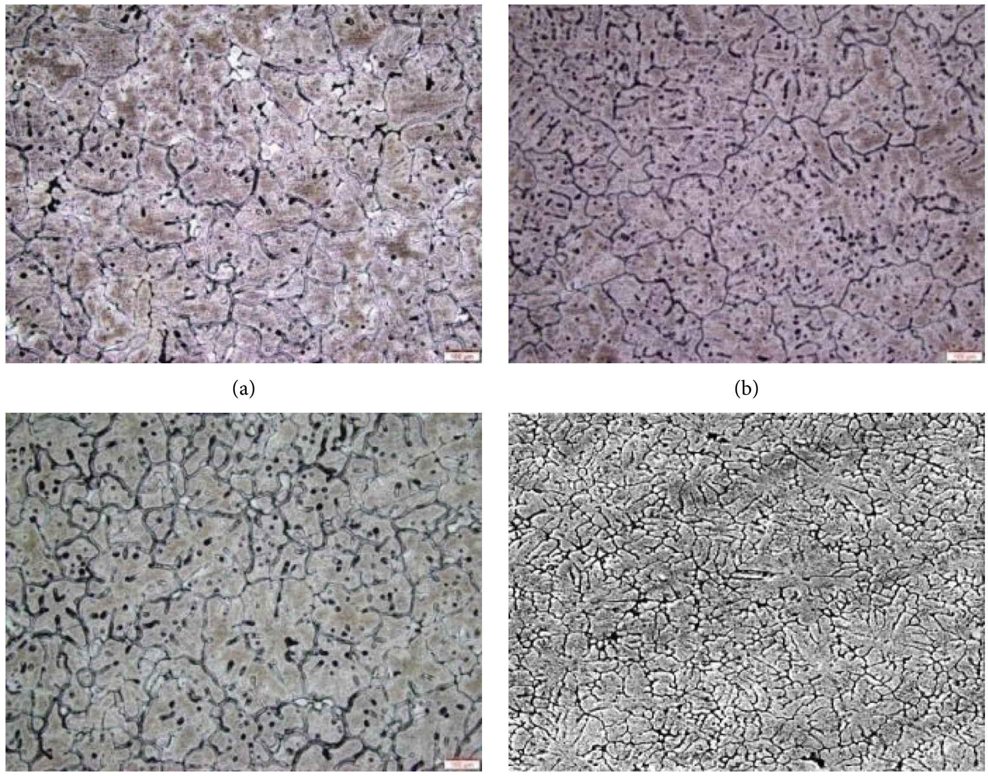


Figure 3: Ultrasonic stir casting machine.



(a) (b) (c) (d)

Figure 4: Test samples. (a) Stir cast samples. (b) Tensile samples with ASTM E08-8. (c) Flexural test with ASTM A 370. (d) Charpy impact testing machine with ASTM E23.



(a) (b) (c) (d)

Figure 5: Microstructure of (a) ALCTB-1; (b) ALCTB-2; (c) ALCTB-3; (d) ALCTB-4.

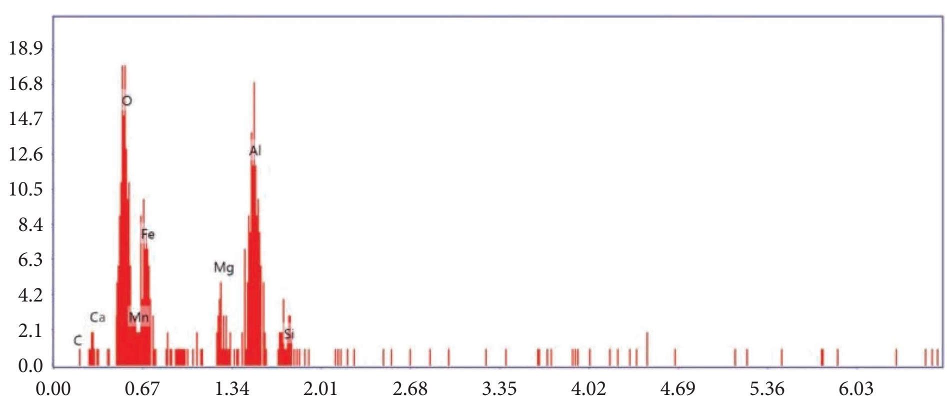


Figure 6: EDs spectra of the fabricated composite.

4.2. Hardness. The presence of silicon dioxide in the CTB significantly improves composite hardness. The resulting 15% weight ratio provides a significant improvement of 11% compared to the nascent sample. On closer examination of the microstructure of 15 wt% composites, it clearly shows a uniform grain boundary, and the even distribution of CTB particles along the grain has significantly improved the hardness of the material to a greater extent. The increase of more than 15 wt% results in the excess accumulation of reinforcement along the grain boundary (confirmed through microstructural study). It is believed that the interaction effect among the CTB particles is significantly less when compared to metal ash interaction. The adhesive bond effect is significantly higher when compared to the cohesive bond. The effect of the improvement in the harness can be further revealed in the mechanical test section. The variation in the harness with the change in CTB is shown in Figure 8.

4.3. Tensile Test. To examine the tensile behavior of the composite material, fabricated specimens were subjected to a tensile test in the UTM machine as per the ASTM standard. The addition of reinforcement shows its influence on tensile behavior. With the addition of reinforcement, an increment

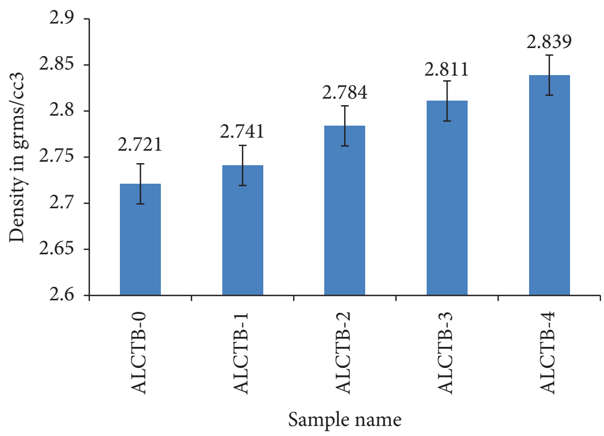


Figure 7: Density results.

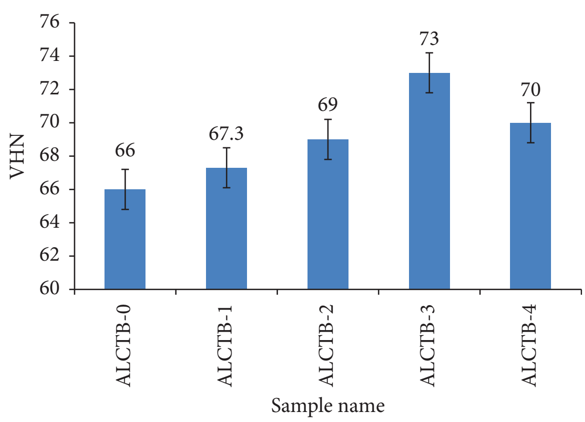


Figure 8: Vickers hardness for the fabricated samples.

in the load withstanding capacity has been observed. Among the considered composition, ALCTB (15% of CTB) provides significant improvement in tensile behavior. The load-bearing capacity increased to 30% with a decrement of 20% displacement. Additions of reinforcement in the Al matrix consistently improve the load standing capacity. Hard silicon oxide elements in the CTB signify its importance. Increase in the density and the hardness of the sample import a slight increase in brittle nature. Figure 9 shows the load-displacement curves of the fabricated composite as well as the nascent sample.

To explore more, the fracture mechanics behind the addition of this reinforcement is examined on the ALCTB-3 fracture surface. The top end under the bottom end of the fractured sample has undergone an SEM image, and it is shown in Figures 10(a) and 10(b). Figure 10(a) is taken on the top portion of the fracture surface. Squeezed and crushed grains are seen all over the images with both transgranular and intergranular fractures. Dimple regions also noted indicating the deformation of reinforcement from the surface. A smooth cleavage surface confirms the slippery nature of the reinforcement. Unlike other ceramic materials, which are being used as reinforcement in the metal matrix composites, the proposed CTB allows the slippery of particles and it behaves as a smooth and soft

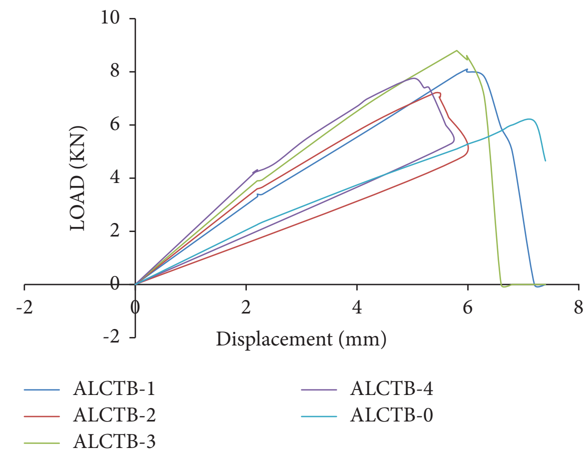


Figure 9: Tensile test for a different sample of reinforcement.

reinforcement. Figure 10(b) captures the bottom portion of the test sample. The presence of the excess amount of peak regions and small burrs-like arrangement is due to the effect of the pulling force. Specifically, a shallow hole structure seen on the factor surface may be due to the bulk of the formation of CTB particles. In this region, CTB agglomeration may happen and may cause the removal of the excess material.

4.4. Flexural Test. The 3-point bending test load-displacement curve is shown in Figure 11. A similar trend like the tensile test is observed for all the test conditions. Most likely ALCTB-3, i.e., aluminum with 15 percent of CTB provides an acceptable range of observation over the given test condition. In comparison with the nascent sample, almost the load withstanding capacity is increased, and typically for ALCTB-3, it is doubled with the addition of this reinforcement by 47%. A slight increase in the brittleness reduces the displacement value by 14%.

In the study on the fracture mechanism behind the failure of the ALCTB-3 sample, the same process followed for the tensile test is also adopted for the flexural test. Figures 12(a) and 12(b) are taken from the top end of the fractured surface as well as the bottom end. The red circle clearly shows the compressive nature of the elements, which creates a big crater-like structure on the fractures of the surface. The slippery nature of the particle is observed and noted in Figure 12(a). The presence of excess cracks and their propagation along the grain boundary is visible in Figure 12(b) which implies the effect of the pulling force exerted by the sample during the test condition. Small dimples with the peak and valley regions are noted on the fractured surface. The addition of this reinforcement has nowhere affected the material properties as all the fracture surfaces are in plastic deformation in nature.

4.5. Impact Test. The sudden load withstanding capacity of the fabricated composite is measured through the impact test and the observations, as shown in Figure 13. The hard reinforcement particles significantly improve the density of

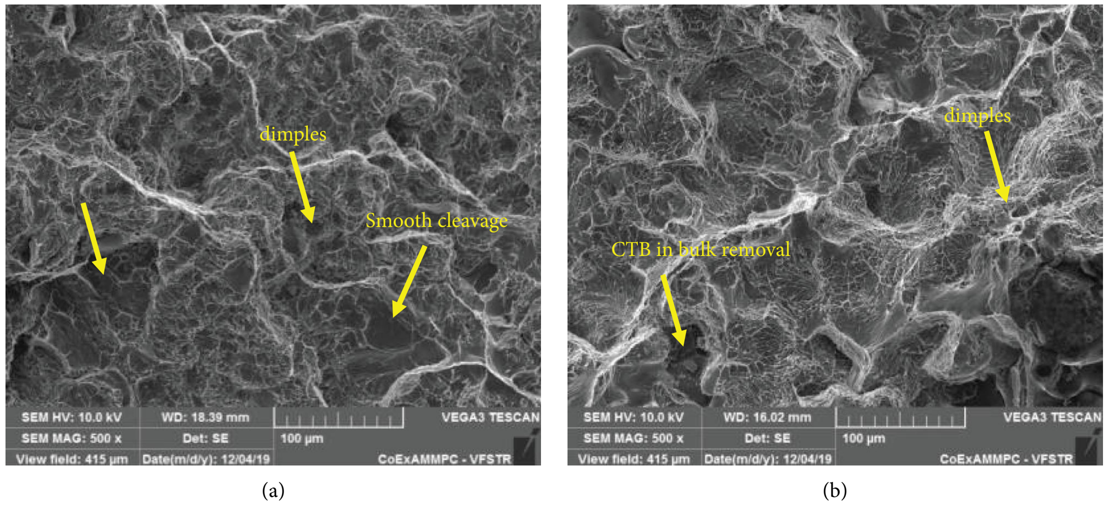


Figure 10: Fractured surface of tensile test samples.

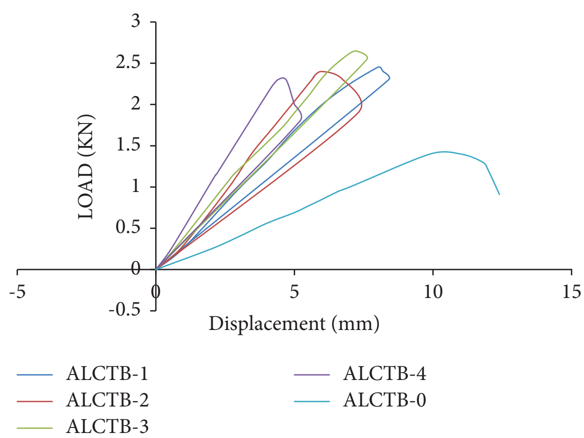


Figure 11: Flexural test for a different sample of reinforcement.

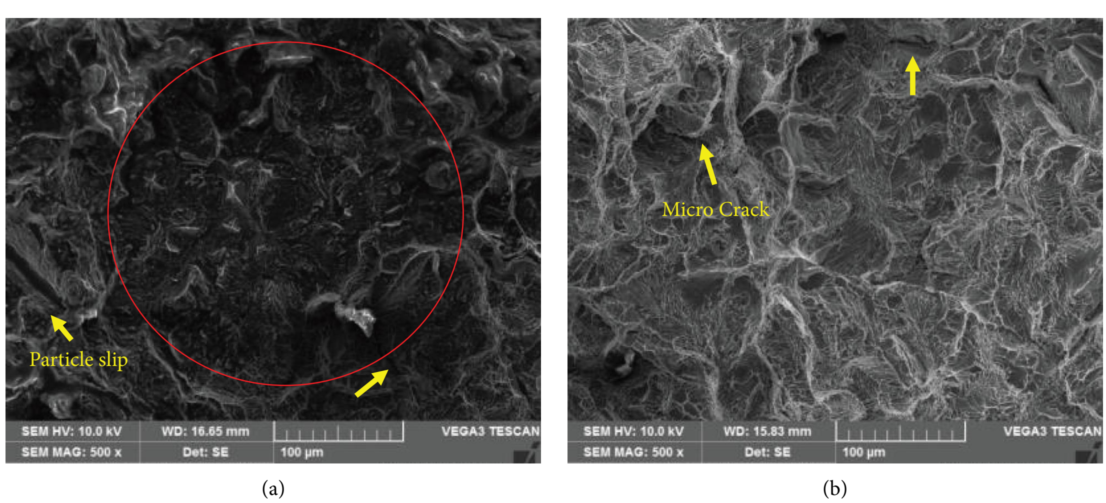


Figure 12: Fractured surface of flexural test samples.

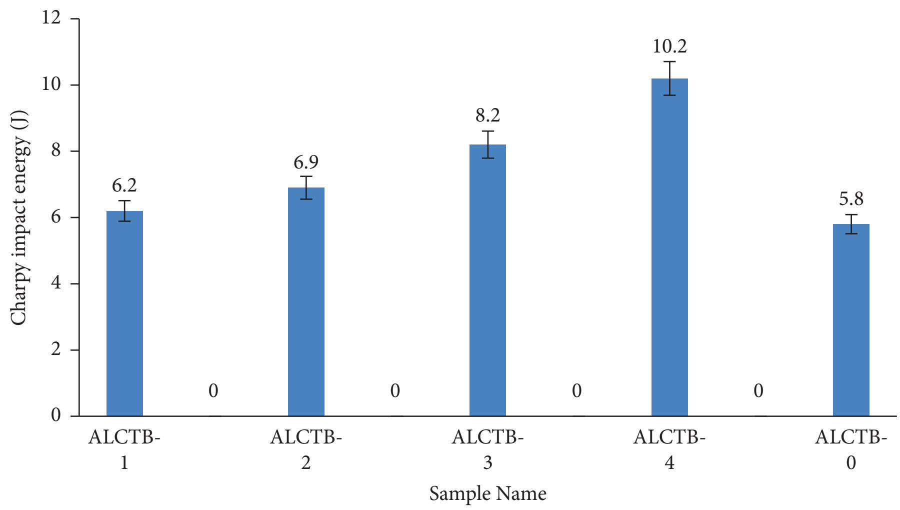
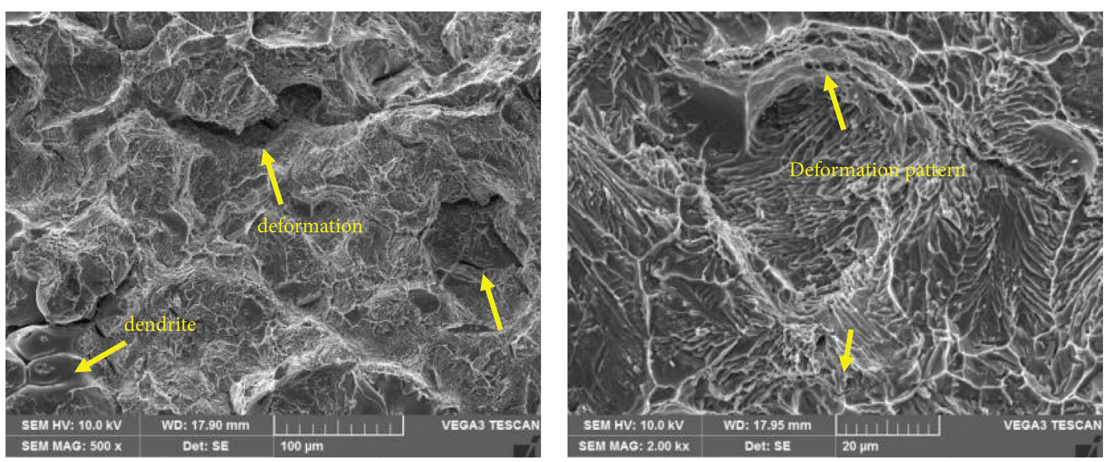


FIGURE 13: Impact test for observations.



(a) (b)

FIGURE 14: Fractured surface of impact test samples.

the material as well as the hardness. The hardest material can hold sudden loads to a greater extent. The AICTB-4 (20% of CTB) composition shows the highest observations with an increment of 43%.

To understand the mechanism behind the sudden impact load, the same study procedure applied for the tensile and flexural test is conducted for the impact test. Figures 14(a) and 14(b) are taken from the sample AlCTB-4 near and another end of the notch area. The surface nearer to the notch area suffers severe deformation, and it can be confirmed through the presence of macrocracks and the dislocation of the particles. Besides the presence of dendritic structure, the effect of the sudden load has caused serious damage to the test sample. On the other end, the removal of CTB from the matrix is visible and it is shown as dendritic pattern in Figure 14(b).

5. Conclusions

The cashew nutshell is processed methodically so that its silicon dioxide-rich elements can be extracted and used to make CTB. The ultrasonication-aided casting process was used to incorporate the different CTB weight percentages into the aluminum Matrix composite. The XRD peak verifies that the biochar contains an excessive amount of silicon dioxide. There was no discernible change in sample density after the reinforcement was added. Microstructural characterization verifies the accumulation of nano CTB particles along the grain boundary of an aluminum element with uniform dispersion. An excessive amount of CTB in the matrix will lead to particle agglomeration and clustering regardless of the manufacturing process, which will have far-reaching consequences for the material's properties. With an increase in CTB at the fracture surface, a deformation in the grain boundaries was observed. When reinforcement was added to ALCTB-3, the load increased by 30% while the displacement decreased by 20%. The same thing happens when the load or displacement is increased by 47 and 14 percent, respectively, in the flexural test, which is used in the ALCTB-3. Both tensile and flexural tests have revealed a minor decrease in the material's ductile behavior. The impact test showed that the specimen had a remarkable ability to withstand a sudden load. Results from the impact test on ALCTB-4 are up 43 percent. The failure is plastic deformation in nature, with transgranular and intergranular failure modes, as shown by microscopic analysis of the surface of the sample. Dimples, wear marks, and a flat fracture plane all speak to the reinforcement's (CTB) behavior. According to the results of all mechanical tests and characterization, ALCTB-3 (15% CTB in the Al matrix) is the best possible composition.

Data Availability

No data were used to support the findings of this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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