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Review

Influence of agro-based reinforcements on the properties of aluminum matrix composites: a systematic review

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ABSTRACT

Aluminum matrix composites (AMCs) have been extensively studied primarily due to higher strength-to-weight ratio, lower cost, and higher wear resistance properties. However, increasing demand for economical and energy-efficient materials in the automotive, aerospace and other applications is tailoring research area in the agro-based composite materials. Therefore, the aim of this systematic review work is to study the influence of agro-based reinforcements on the tribological and mechanical properties of AMC's processed by various techniques. It was observed that the processing conditions can be designed to obtain uniform structures and better properties AMCs. The agro-waste reinforcement materials, such as rice husk ash, bamboo stem ash, coconut and shell ash can result in a reduction in the density of AMC's without compromising mechanical properties. Moreover, the efficient utilization of the agro-waste leads to a decrease in manufacturing cost and prevents environmental pollution, hence, can be considered as a sustainable material. The state-of-the-art revealed that the agro-based reinforcements do not form brittle composites, as in the case of ceramic reinforced composites. Hence, the study concludes that the agro-based AMCs have great potential to act as a replacement for costly and environmentally hazardous ceramic reinforced-AMCs which can especially be used in various automotive applications that demand higher strength-to-weight ratio, lower cost, and higher wear resistance.

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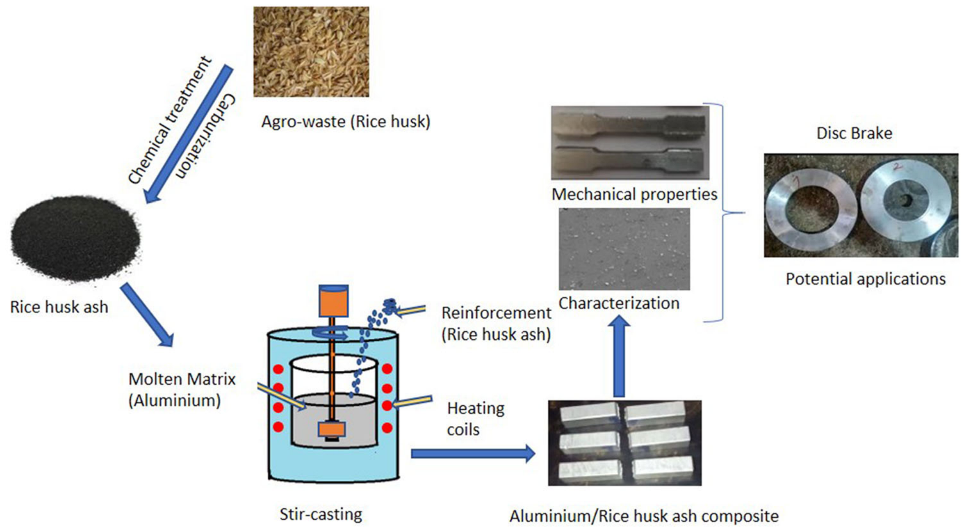
GRAPHICAL ABSTRACT



Introduction

Due to the increasing demand for economical and energy-efficient materials in the automotive, aerospace and numerous applications, the industrial sectors are concentrating on the development of lightweight, low cost and eco-friendly materials. Preceding work has conveyed that AMC's exhibit superior features such as lower density, higher stiffness, and low coefficient of thermal expansion, specific strength, and superior wear resistance [1–3]. Presently, researchers and scientists are paying more attention toward the development of discontinuously reinforced AMC's. This is due to the simpler production techniques that are economically feasible and result in the development of the homogeneous structure of particulate reinforced AMC's. The homogeneity of reinforcement particles and their interfacial bonding in the composites are further improved by subjecting them to several forming processes like forging, extrusion, and rolling [4]. Also, it has been reported that the type and fraction of reinforcement materials influence the characteristics of the Al composites. It has been reported that the significant improvement in the properties of Al composites can be achieved by the addition of even a small quantity of ceramic reinforcements [5–7]. These particulate materials are silicon carbide (SiC), boron carbide (B_4C), titanium carbide (TiC), Al_2O_3, and silica (SiO_2) particles. With the addition of ceramic reinforcements the physical and mechanical properties of materials can be improved, and such materials can be used as a replacement to the bulky cast iron in automobile applications such as brake rotor [8].

In addition, properties of these materials can be adjusted by the selection of suitable fabrication techniques such as coating reinforcements [9], precipitate strengthening [10], mechanical and thermal activation reactions [11] and varying percentage of reinforcements in AMC's.The addition of these hard particles into soft Al-matrices improve their hardness and wear resistance. However, the production of these ceramic materials is neither economical nor environmentally friendly. Taking these factors into consideration, researchers have found huge potential in agro-waste based reinforcements due to their economic viability and abundance availability [12, 13]. Furthermore, these materials are frequently disposed in an open land resulting in environmental contamination. Agro-waste materials such as rice husk ash (RHA) [14–16], groundnut shell ash (GSA)[17, 18], coconut shell ash (CSA) [18, 19], melon shell ash (MSA) [20] have been utilized by the researchers as reinforcing materials for improving the properties of AMC's. These AMC's can find application in automotive, aerospace, and construction materials [21, 22].

Thus, the utilization of agro-waste materials in the AMC industry can be beneficial in the reduction in environmental degradation resulting from their disposal [23, 24]. Although the addition of the ceramic particles improves stiffness, specific strength, and wear resistance of Al-alloys considerably, several drawbacks regarding the use of Al/ceramics composites have also been reported [23]. It has been observed that ceramic reinforcements increase the density of the developed composites. This can be attributed to a higher density of ceramic reinforcements such as SiC (3.22 g/cm^3) and Al_2O_3 (3.9 g/cm^3) in comparison to Al-matrices (2.7–2.8 g/cm^3). Also the ceramic particles have higher elastic modulus (400 GPa) in comparison to Al alloys (70 GPa). This degrades the aggregate properties leading to brittleness, poor machinability, and reduced fracture toughness of the AMC's [25, 26]. In addition to this, ceramic reinforcements in Al composites reduce the impact strength of the composites by reducing strain energy and forms regions of stress concentration [27]. Under these conditions, the development of agro-waste AMC's is quite beneficial. The use of agro-waste materials results in formation of low cost and lightweight composites without compromising their mechanical and tribological properties [28, 29]. However, there is a limited understanding of their service performance, thus restricts their utilization options for their wider use in applications. Consequently, it is important to review the morphological, mechanical, and tribological properties of these materials containing various agro-based reinforcements to conclude the advancements done so far and to look the way forward for the improvement of properties of AMC's by addition of such agro-based reinforcements.

Considering all these issues, this paper presents the overview of low-cost agro-based Al-composites using various processing technique i.e., stir casting, compocasting, powder metallurgy as well as additive manufacturing. The morphological, mechanical, and tribological analysis of fabricated agro-waste based materials have been extensively reviewed to find the best possible fabrication techniques for the development of agro-based AMC's. In general, this paper has been presented in six sections. The first section introduces the AMC's state-of-the-art and their strength improving efforts by the researchers. The second section describes briefly the various agro-based materials used by the researchers and their chemical compositions. In the third section, the properties of agro-based AMC's reinforced with agro-based materials have systematically been reviewed. The fourth section explains the various production techniques for the development of such agro-based AMC's. The fifth section includes the challenges and the way forward for the agro-based AMC's. In sixth section, the conclusion and remarks of the review have been elucidated.

Agro-waste reinforcement materials

Several agro-based materials are promising to be used as reinforcements in Al matrix composites development and some of them are mentioned in Table 1. The following are the agro-wastes recognized as potential reinforcing material:

Rice husk ash (RHA)

This agro-waste material is obtained from rice mills during the process of milling of the paddy. Usually, it is used as a fuel for generating electricity in the rice mills. However, it has been observed that about 25% of the total weight of rice husk forms ash during the steam generation process, thus not an efficient fuel [30]. Moreover, dumping it in an open land has resulted into a major impact on the environment.

Table 1 Various Al alloys matrices and agro-based reinforced composites

Matrix	Reinforcement	References
AA6063	Rice husk ash	[37]
AlSi10Mg	Rice husk ash	[38]
Al	Groundnut shell ash	[39]
Al6082	Coconut shell ash	[40]
AA6061	Palm sprout shell ash	[41]
Al6061	Sugarcane bagasse ash	[42]
Al	Palm shell activated carbon	[43]
Al0.3Si0.1 Mg	Horse eye bean seed shell ash	[44]
Al	Mustard husk ash	[45]
Al6063	Corn cob ash	[46]
Al6063	Palm kernel shell ash	[47]
Al356.2	Bamboo leaf ash	[48]

Table 2 Chemical composition of agro-based reinforcements

Agro-Waste	Composition							
	SiO_2 (wt%)	Al_2O_3 (wt%)	MgO (wt%)	Fe_2O_3 (wt%)	CaO (wt%)	K_2O (wt%)	SO_3 (wt%)	P_2O_5 (wt%)
RHA -Rice husk ash [57, 58]	97.09	1.135	0.825	0.31		–	–	–
CSA-Coconut Shell Ash [59]	45.05	15.6	16.2	12.4	–	–	–	–
BLA-Bamboo leaf ash[60]	75.9	3.5	–	1.22	7.47	–	–	–
POFA-Palm Oil Fuel Ash [61]	49.20	35.45	3.93	–	7.5	5.3	1.73	6.41
POC-Palm Oil Clinkers [62]	81.8	3.5	1.24	5.18	2.3	4.66	–	0.76

Therefore, researchers started utilizing this material most efficiently as reinforcement in high-performance AMC's as it offers lower density (0.3–1.9 gm/cm^3) and ease of availability [28, 31]. RHA consists of a higher percentage of SiO_2 along with other elements such as Al_2O_3, Fe_2O_3, and MgO, as shown in Table 2. Kumar [32] reinforced RHA and mica in Al7075 matrix composites and found an improvement in hardness, tensile strength as well as the toughness of the developed composites. Further some researches have extracted SiC from rice husk [33, 34] and used that as a reinforcing material due to their better properties as comparison to RHA [35]. Joharudin et al. [36], extracted silica from RHA through heat treatments and reinforced them in recycled Al7075 chip resulting into enhancement of the hardness of the developed composites.

Coconut Shell Ash (CSA)

This agro-waste material is mostly available in tropical regions in abundance and often used as fuel in boilers and furnaces [49]. But the combustion of CSA results in the release of CO_2 and methane in large quantities and hence, leads to significant environmental pollution [50]. It is preferred to use them as reinforcement in the production of Al-composites taking these considerations [51]. The density of CSA was found to be 2.05 gm/cm^3 and its constituents of elements are like SiO_2, MgO, Al_2O_3, and Fe_2O_3, as mentioned in Table 2.

The coconut shell when added as particles have proved to enhance the properties of Al composites. Kaladgi et al. [52] developed coconut shell micro particles (CMP) and Al_2O_3 reinforced Al6061 composites via stir casting technique. There was an increase in hardness and tensile strength with increasing reinforcement content. Also, Bello et al. [53] incorporated CMP in Al alloy developed by compo-casting technique and observed an increase in tensile properties as a result of good interfacial bonding between the matrix and reinforcement and due to formation of harder phases.

Bamboo leaf ash (BLA)

The bamboo trees are found in abundance in various sections of the world. These trees often litter their leaves in these regions; however, these can be used as BLA for economic purposes. It mainly constituents of ceramic oxides like SiO_2, Al_2O_3, CaO, K_2O, and Fe_2O_3, as shown in Table 2; thus, it can be used as reinforcements in the AMC's [54, 55]. Aleneme et al., [56] reinforced BLA in Al alloy and observed an improvement in the wear behavior of the resultant composites.

Palm Oil Fuel Ash (POFA)

This is agricultural waste abundantly found in Malaysia, and it contains a higher content of siliceous material. It is obtained on the combustion of oil palm fiber, mesocarp, and empty fruit brunch as boiler fuel to produce steam for palm oil mill, and the end product remaining after combustion is POFA [63]. This can be later used as reinforcing material [64]. Silica or silicon dioxide (SiO_2) is the main constituent found in POFA, mostly up to 40%, besides silica, other chemical components found in POFA are potassium oxide, magnesium oxide, calcium oxide, aluminum oxide, and iron oxide. The composition is shown in Table 2. The study of the effect of POFA on the mechanical and tribological properties revealed that addition of POFA improved the hardness, tensile strength, wear and coefficient of friction of the resultant composites [64].

Palm Oil Clinkers (POC)

The palm oil is primarily produced in Indonesia and Malaysia, contributes to 83% of total world production in 2015 [65]. The extraction process of this palm oil results in the production of waste in large quantities in the form of POC [66]. The disposal of these can be hazardous for the environment. Thus, it can find its usage as reinforcements in the Al composites [67]. Table 2 shows the chemical compositions of POC.

Sugarcane Bagasse ash (SCBA)

Bagasse is the waste product obtained after processing of sugarcane for extraction of juice. It is one of the largest agricultural wastes in the world. Many researchers have used this residue due to its versatility but not limited to feedstock, biofuel (ethanol), and paper [68]. The main elements of SCB are hemicellulose, cellulose, wax lignin, and ash [69]. Their presence makes SCB an ultimate material as a reinforcement fiber in the development of new material with exceptional physical and chemical properties [70, 71]. Chandla et al., [72] reinforced varying content of bagasse ash in Al6061/5wt% Al_2O_3 based composites via stir casting technique and observed an increase in hardness as well as the tensile strength of the composites with increasing bagasse ash content.

Properties of agro-waste reinforced composites

The structure, properties and processing analysis of various agro-wastes such as rice husk ash, breadfruit seed, corn cob ash, groundnut shell ash, bamboo leaf ash, coconut shell ash, maize stalk ash, lemongrass ash, aloe vera, and SiO_2 (agro-based)-reinforced Al composites are shown in Table 3. The effect of these agro-based reinforcements on the microstructure, mechanical and tribological properties of Al composites also discussed in the following sub-sections.

Microstructure of agro-waste reinforced composites

Oghenevweta et al. [89] carried out the microstructural analysis of the developed Al-Si–Mg-based composites reinforced with carbonized maize stalk waste by a stir casting technique. They claimed that a uniform distribution of reinforcements was obtained along the grain boundaries resulting grain refinement thereby forming better bonding. This in turn improved tensile strength and hardness value with the increased percentage of carbonized maize stalk. However, it was also mentioned that the impact energy, elongation and densities slightly decreased. Atuanya et al. [90] studied the influence of breadfruit seed hull ash as reinforcement on the microstructures and mechanical properties of Al–Si–Fe based composites fabricated via stir casting technique. The reduction in the grain size of the matrix and good interfacial bonding between the matrix and the reinforced particles was observed as evident from Fig. 1, leading to improvement in the hardness and strength; however, there was a slight decrease in impact energy.

Further, Saravanan and Kumar [91] observed good dispersibility of RHA in AlSi10Mg matrix causing improvement in the hardness, compressive strength, and tensile strength. The homogeneous dispersion of reinforced particles throughout the Al matrix and grain refinement is shown in Fig. 2. Gladston et al. [92] noticed that there was a unique distribution of RHA particles into AA6061 alloy matrix, developed through compo-casting technique leading to increased ultimate tensile strength and microhardness of the AMC's.This behavior can be attributed to the uniform distribution of RHA particles in the matrix material as shown in Fig. 3.

Jerin et al. [93] found a uniform dispersion of lemon grass ash (LGA) particles in the composite matrix manufactured via a compo-casting technique. The microhardness and the tensile properties of the composites were also improved. Furthermore, Kumar and Birru [94] observed that the Al composites reinforced with BLA exhibited superior properties due to their effective bonding with the matrix alloy and homogeneous distribution of BLA particles in composites. However there was reduction in the density and increased porosity values with increase in mass fraction of BLA particles. Also, Venkatesh et al. [95] studied microstructural characteristics of GSA and

Table 3 Agro-waste reinforced Al composites

Reinforcement	Matrix	Study (Properties)	Characterization and testing	Fabrication technique	Reference year
Palm kernel shell	AA 6063	-Microstructure -Physical -Mechanical	-XRF -XRD -Density, -Porosity -SEM -EDX	Stir-casting	[73] 2020
Rice husk (Si-compound)	AA 6063	-Tribological	-Coefficient of friction (CoF) -Wear rate	Two-step stir-casting	[74] 2020
Aloe vera ash	AA7075-T6	-Mechanical -Tribological	-CoF -Wear rate -UTS	Friction stir processing	[75] 2020
RHA	AA7075	-Physical and -Morphological	-SEM -Density -Porosity - Hardness	Powder metallurgy	[76] 2020
Rice husk (silica)	AA7075	-Physical	-Density -Porosity -Hardness	Powder metallurgy	[77] 2020
BLA–SiC	AA 6063	-Mechanical	-Stress–strain	Stir-casting	[78] 2020
Rice husk(silica) and graphite	Al	-Physical - Mechanical - Thermal	-FESEM -FTIR -XRD -Hardness -Density	Powder metallurgy	[79] 2020
RHA	AA6061	-Tribological	-Wear rate	Friction stir processing	[80] 2020
RHA	AA6061	-Physical - Mechanical	-SEM -Density -Hardness	Two-step casting	[81] 2020
Pine leaf ash	Al	-Tribological	-SEM -Hardness -Wear rate	Friction stir processing	[82] 2020
RHA	Al6061	-Mechanical	-Hardness	Stir-casting	[83] 2019
Bagasse ash and graphite	AA7075	-Physical -Mechanical	-Density -Hardness - tensile	Squeeze casting	[84] 2020
CSA and SiC	LM24	-Microstructure -Tribological	-XRD -Wear rate	Squeeze casting	[85] 2019
RHA –fly ash	A356	-Tribological	-Wear rate -Wear mechanism	Double stir-casting	[86] 2019
Bagasse ash and SiC	Al 5056	-Tribological	-Wear rate -Hardness	Stir-casting	[87] 2019
RHA	AA7075	-Microstructure -Mechanical	-SEM -EDX, -Microhardness	Friction stir processing	[88] 2018

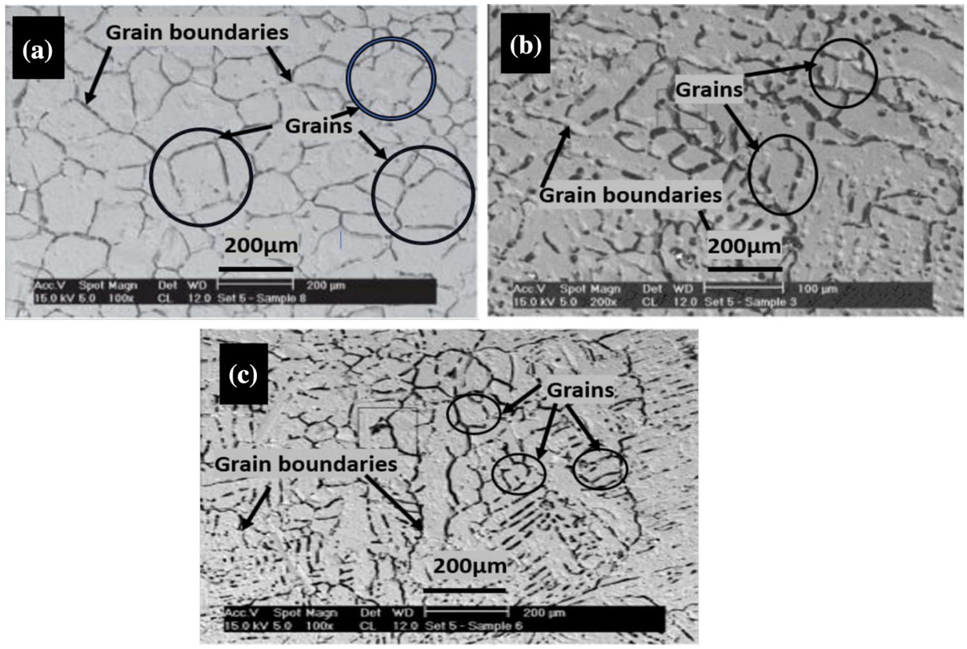


Figure 1 The microstructure of aluminum alloy reinforced with, **a** 2 wt%, **b** 6 wt% and **c** 8 wt%, breadfruit seed hull ash. Reproduced with permission from [90].

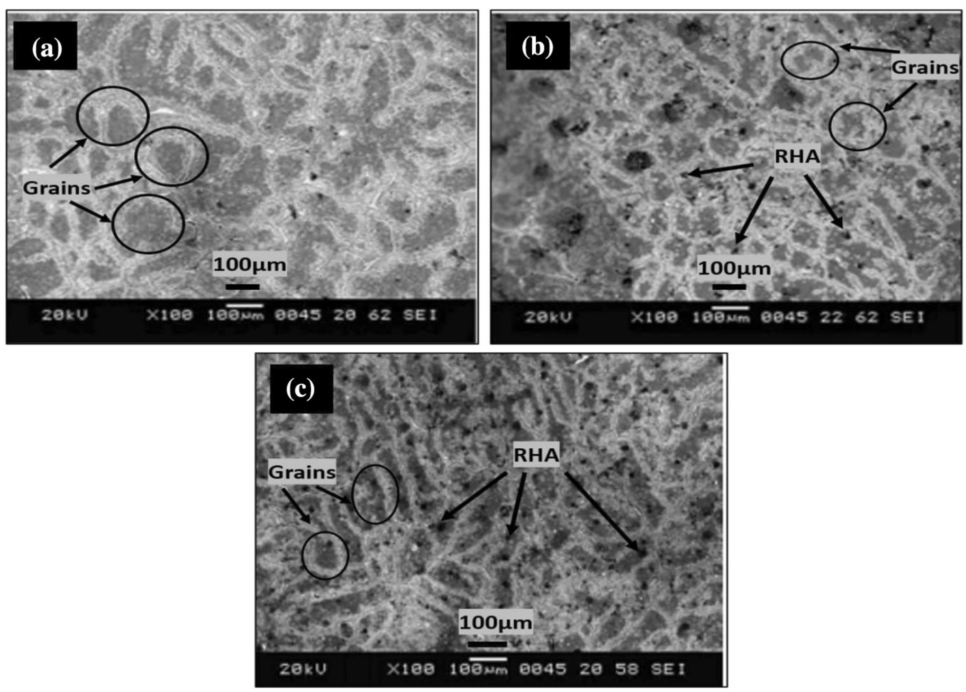


Figure 2 SEM images showing microstructure of **a** $AlSi_{10}Mg$, **b** $AlSi_{10}Mg$ + 6% RHA **c** $AlSi_{10}Mg$ + 12% RHA composites. Reproduced with permission from [91].

boron carbide reinforced Al composites developed via squeeze casting technique and revealed the uniform distribution and better bonding of reinforcements with the matrix materials forming clear interfaces in the reinforced composite, however, agglomeration and cluster formation takes place with increased GSA particles.

Mechanical properties of agro-waste reinforced composites

Many researchers studied the influence of these agro-waste reinforcements on the mechanical properties of Al based composites. Ahamed et al. [96] observed the decrease in densities of Al composites reinforced with RHA fabricated by stir casting technique;

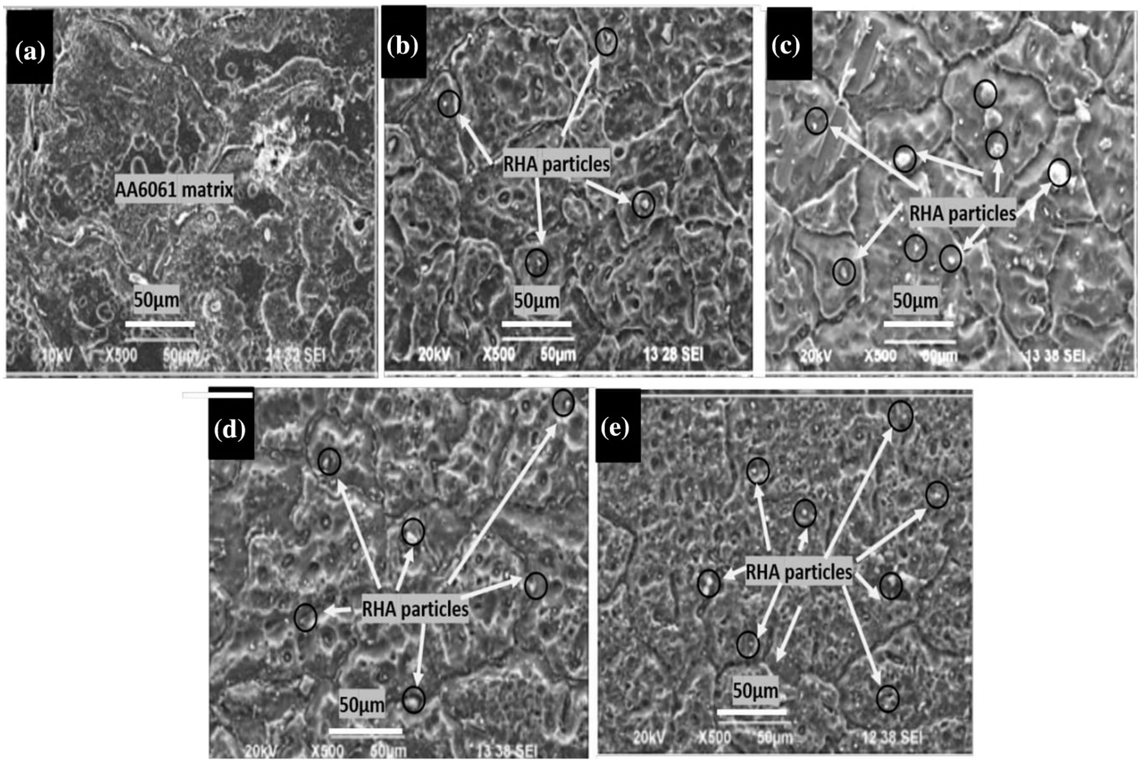


Figure 3 SEM images of AA6061 composites with varying RHA content, **a** 0wt%,**b** 2wt%,**c** 4wt%,**d** 6wt%, and **e** 8wt%. Reproduced with permission from [92].

however, yield strength, ultimate strength, and hardness of the composites increased, as shown in Fig. 4. Agro-waste reinforcements are found to reduce densities of composites without conceding the mechanical properties of composites. Varalakshmi and Kumar [97] fabricated Al 6061-coconut shell ash metal matrix composites using a stir casting technique. There was an increase in the ultimate tensile strength and hardness of the composites even though the density of the CSA reinforced composites decreased. It has been observed by the researchers that small percentages of ceramic reinforcements when replaced by agro-waste particles in the Al composites there was a significant improvement in properties.

Prasad et al. [98] employed two step stir casting technique for the fabrication of Al composites reinforced with RHA and SiC particulates and reported an increase in hardness, ultimate tensile strength, and yield strength with an increase in weight fraction however the densities decreased. Although double stir casting techniques allow improvement in

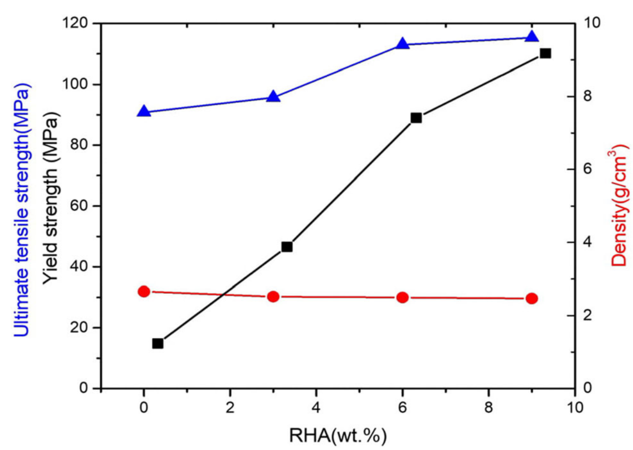


Figure 4 Variation of yield strength, ultimate tensile strength, and density with the wt % of RHA in Al composite. Reproduced with permission from [96].

wettability, eventhough it remains still a challenge to overcome. However, this problem can be solved by using the vortex method for the development of AMC's. Gireesh et al. [99] developed aloe vera, and

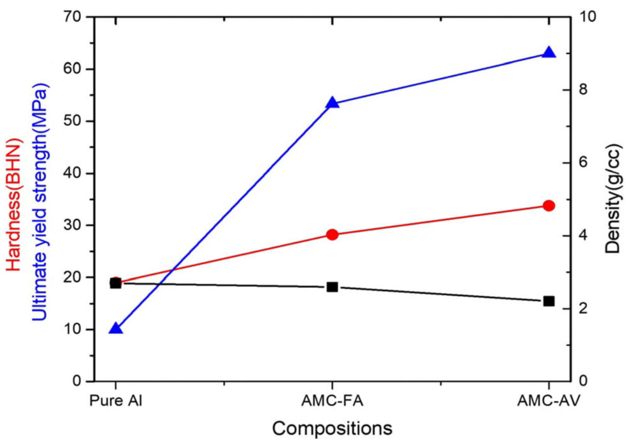


Figure 5 Comparison of mechanical properties, ultimate yield strength (MPa), hardness (BHN), and density(g/cc) of AMC's on the addition of fly ash (FA) and aloe vera (AV). Reproduced with permission from [99].

fly ash reinforced AMC's and compared their mechanical properties. They concluded that the mechanical properties improved more by the addition of aloe vera as compared to fly ash, as evident from Fig. 5. Devanathan et al. [100] fabricated AMC's reinforced with CSA and FA via stir casting technique and observed an improved hardness, tensile strength and percentage elongation of the composites with increase in weight percentage of CSA.

Gupta et al. [101] studied mechanical properties of RHA and Al_2O_3 reinforced Al/Si12 composites and observed an improvement in the microhardness, tensile strength, and flexural strength of the composites. Moreover, Shankar et al. [102] fabricated AlSi10Mg composites reinforced with SCBA particles via stir casting process and observed an increase in their hardness, tensile, and impact strength, however, their ductility decreased with increase in the weight percentage of SCBA. Table 4 showed the effect of agro-based reinforcements on the mechanical properties of Al composites. The hardness, tensile strength,yield strength, impact strength and compressive properties were found to increase in the agro-based content however only upto certain limit.

Tribological properties of agro-waste reinforced composites

An attempt has been made by Gupta et al. [101] to develop Al-Si12 matrix composites reinforced with RHA and Al_2O_3 and evaluate their tribological performance. There was an improvement in the weight loss with increase in weight percentages of reinforcements as shown in Fig. 6. Also, Shaikh et al. [112] fabricated Al-based composites reinforced with SiC and RHAusing the powder metallurgy technique. The study revealed the decrease in hardness and wear loss of the composites with an increase in RHAcontents up to 10%. However, the corrosion and wear study by Kanayo and Olubambi [113] revealed that there was an increment in both the corrosion as well as wear rate by increasing the percentage of RHA and alumina reinforced Al–Mg–Si composites. The wear behavior was observed changing from abrasive wear to both the adhesive and abrasive wear with increase in RHA content.

Bodunrin et al. [114] developed silica sand, and BLA reinforced Al composites via stir casting technique. The porosity measurement and study of wear performance concluded that the composites became lesser denser with increasing BLA content. There was also a reduction in hardness; however, composite with silica sand and BLA reinforcements had higher wear resistance than single reinforced Al6063-silica sand composite. In addition, Alaneme et al. [115] also fabricated Al–Mg–Si alloy matrix composites with RHA and SiC as reinforcements by double stir casting technique and observed improvement in corrosion resistance, coefficient of friction and wear behavior of composites. Prasad and Shoba [116] investigated the dry sliding wear behavior of AMC's reinforced with RHA and SiC particulates fabricated via vortex method. The study revealed that the reinforced composites exhibited higher wear resistance as compared to unreinforced composites. Deshmukh and Pathak [117] studied the influence of varying wt% of rice husk based SiO_2 on the mechanical and wear properties of AMC developed by stir casting technique. It was concluded that the wettability of the matrix with reinforcement was improved due to the addition of Mg during the stir casting process, and better wear resistance was achieved due to the higher Vickers hardness.

Kumar and Birru [118] studied the tribological properties of BLA reinforced Al composites and observed decreased wear rate values with increased BLA content in the composites. Similarly, Bodourin et al. [119] reinforced BLA in Al6063 alloy matrix and found an improvement in the hardness and the wear resistance of the material. Furthermore, Shankar et al. [102] evaluated the tribological properties of SCBA

Table 4 Properties of agro-waste reinforced aluminum composites

Compositions	Hardness	Tensile strength (MPa)	Compressive strength (MPa)	References (Year)
	Brinell hardness (BHN)			
A-356.2/2wt.%RHA	77	175	233	
A-356.2/4wt.%RHA	83	239	261	[103] (2016)
A-356.2/8wt.%RHA	84	278	268	
	(VHN)			
Al6063	58	135	154	[104]
Al6063/3GSA	60	138	188	(2015)
Al6063/6GSA	65	152	200	
Al6063/9GSA	67	156	212	
Al6063/12GSA	68	147	240	
			Yield strength (MPa)	
Al–Si–Mg/10SiC	93	185	144	
Al–Si–Mg/9SiC/1CCA	91	182	142	
Al–Si–Mg/8SiC/2CCA	90	174	136	[105] (2014)
Al–Si–Mg/7SiC/3CCA	86	170	133	
Al–Si–Mg/6SiC/4CCA	81	162	126	
			Impact Energy (j)	
Al	38	55	13	
Al + 3CSA + 5 SiC	40	120	11.5	[106] (2017)
Al + 5CSA + 5 SiC	43	122	9.5	
Al + 10CSA + 5 SiC	45	125	8.5	
			Yield strength (MPa)	
AA6061	130	120	98	
AA6061/1.5SiC	140	132	102	
AA6061/0.75SiC/BLA	185	154	128	[107] (2018)
AA6061/0.75SiC/NLA	158	140	115	
AA6061/0.75SiC/TLA	170	137	120	
	Rockwell Hardness (HRA)		Yield strength (MPa)	
Al–Si–Mg	50	100	78	
Al–Si–Mg/6SiC	57	135	115	
Al–Si–Mg/4.5SiC/1.5GSA	55	130	105	
Al–Si–Mg/3SiC/3GSA	53	125	100	[18] (2018)
Al–Si–Mg/1.5SiC/7.5GSA	52	120	90	
Al–Si–Mg//6GSA	51	115	86	
Al–Si–Mg/10SiC	64	160	130	
Al–Si–Mg/7.5SiC/2.5GSA	63	150	120	
Al–Si–Mg/5SiC/5GSA	58	147	118	
Al–Si–Mg/2.5SiC/7.5GSA	56	140	117	
AlSiMg10GSA	5	136	115	
			Energy absorbed(j)	
Al7075	127	114	0.6	
Al7075/3CSFA	134	121	1.3	

Table 4 continued

Compositions	Hardness	Tensile strength (MPa)	Compressive strength (MPa)	References (Year)
Al7075/3B_4C/ 3CSFA	142	135	1.8	
Al7075/6B_4C/ 3CSFA	149	155	2.1	[108] (2018)
Al7075/9B_4C/ 3CSFA	155	189	2.3	
Al7075/12B_4C/ 3CSFA	169	177	2	
	(HRA)		Young's modulus (GPa)	
Al 6063 Alloy	62	110	15	
Al6063/2 SiO_2 (rice husk derived)	65	130	25	
Al6063/4 SiO_2 (rice husk derived)	67	150	37	[109] (2018)
Al6063/6 SiO_2 (rice husk derived)	69	160	43	
Al6063/8 SiO_2 (rice husk derived)	72	200	50	
	(BHN)		Elongation%	
A6061	152	6	2	
A6061/2RHA	170	6.03	2.4	[110]
A6061/4RHA	175	613	2.5	(2020)
A6061/6RHA	178	6.23	2.7	
A6061/8RHA	188	6.34	2.9	
	(HV)		Impact strength(J)	
Al/1.6RHA(150 µm)	92	100	2.5	
Al/1.6RHA(300 µm)	88	80	5.2	
Al/1.6RHA(600 µm)	85	90	6.8	[111]
Al/0.4graphite/1.6RHA(150 µm)	115	130	5.5	(2020)
Al/0.4graphite/1.6RHA(300 µm)	96	120	7	
Al/0.4graphite/1.6RHA(600 µm)	105	125	8.2	
	(BHN)		Impact strength(J)	
Al7075/3mica	107	244	8.2	
Al7075/3mica/5RHA	128	260	9	[32]
Al7075/3mica/10RHA	139	268	8.5	(2020)
Al7075/3mica/15RHA	146	262	7.8	
BLA: Bamboo leaf ash	CCA: Corn cob ash		TLA: Tamarind leaf ash	FA: Fly ash
RHA: Rice husk ash	NLA: Neem leaf ash		GSA: Groundnut shell ash	AV: Aloe vera
CSFA: Coconut shell fly ash				

particles reinforced AlSi10Mg alloy matrix composites. The wear rate and coefficient of friction(COF) of the developed composites decreased with increase in the weight percentage of ash content, however, it increased on increasing applied load. Also, Lakshmikanthan and Prabu [120] developed Al(6061) alloy composites reinforced with CSA by stir casting technique and observed that the wear rate decreases upto 6wt % of CSA, on futher addition their values increased, however, COF increased on addition of CSA as evident from Fig. 7.

Prasad and Krishna [121] observed an increase in the wear rate and the COF of A356.2 matrix composites on addition of RHA. Furthermore, Panda et al., [122] investigated the COF and wear rate of AMC reinforced with CSA. The COF as well as wear rate decreased with increased CSA content. Therefore, these agro-waste AMC's also influence the

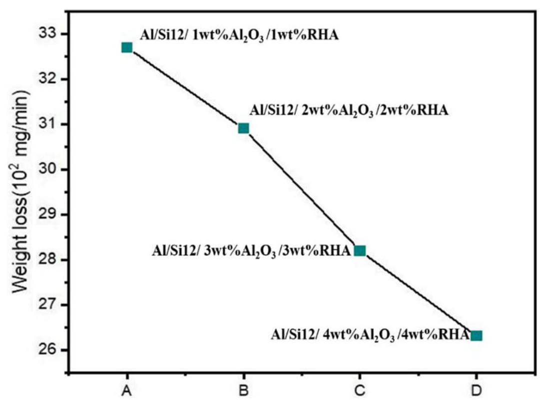


Figure 6 Weight loss of RHA and Al_2O_3 reinforced Al/Si12matrix composites at a velocity of 1.5 m/s at a load of 9.8 N and sliding distance of 1000 m. Reproduced with permission from [101].

tribological properties of the composites[123, 124]. From the literature review, it can be seen that the researchers have used agro-waste ash as reinforcements in the Al matrix. This ash has low strength, thus improves the mechanical properties of Al matrix insignificantly. There is a need to improvise the characteristics of agro-waste materials by carrying out various processing techniques in order to get better reinforcing material out of them. Table 5 shows the effect of agro-waste reinforcements on the tribological properties of AMC's developed by various techniques. It reveals that the hardness of composites increase while as their wear rates decreases on addition of agro-based reinforcement, however, COF increases in certain cases. These properties are favorable for several applications. Since agro-wastes have potential in providing high strength, cost-effective, and environmental-friendly material, their improvement can enhance properties of Al composites to greater degrees; therefore, these cannot be ignored and need further investigation.

Limitation of agro-based AMC's

The issue of wettability and the interfacial bonding between the reinforcement and Al matrix is a matter of concern in case of agro-based reinforcements that forms solid liquid interface during fabrication process, especially when liquid state or semi-liquid state manufacturing process is employed. The dispersion of agro-wastes particles with Al matrix material is another important issue. The strength of the reinforced composites depends upon the wetting action between the agro-based reinforcements and Al matrix. Many researchers have used various techniques to improve this, but still requires more extensive research to overcome this problem. Although agro-based reinforcements have proven to

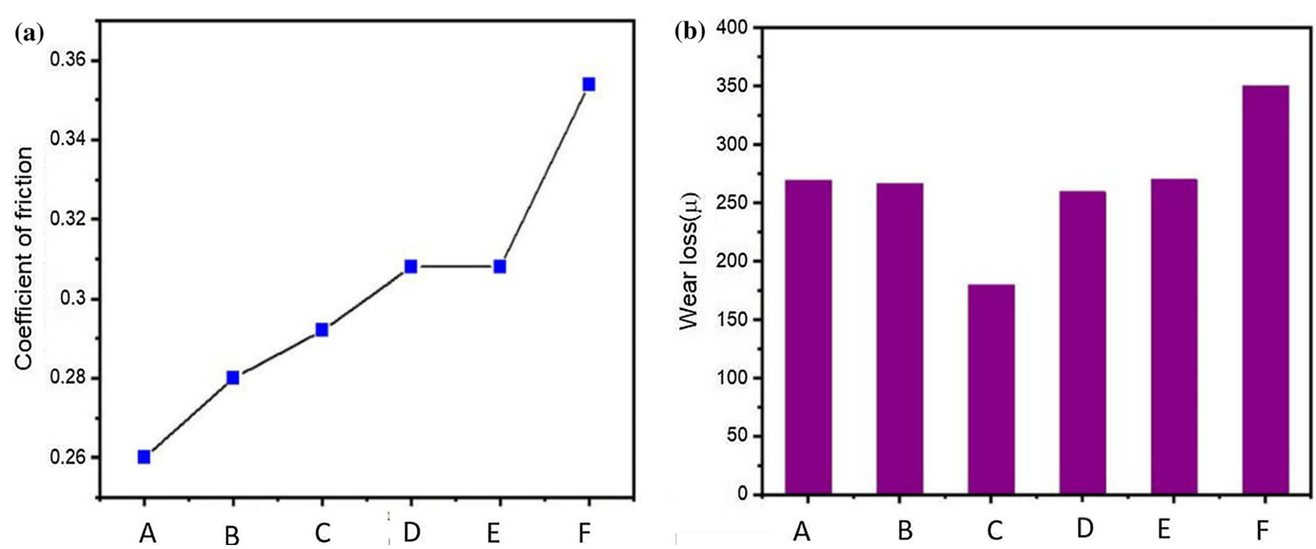


Figure 7 Effect of CSA content on the **a** Coefficient of friction, and **b** wear loss of composites at under constant sliding distance, sliding velocity and load of 1000 m, 1.5 m/s, 10 N, respectively(A,B,C,D,E,and F indicate 0,3,6,9,12 and 15wt.% CSA, respectively). Reproduced with permission from [120].

Table 5 Tribological properties of agro-based aluminum composites

Compositions	Hardness (HV)	Wear rate (gms)	Coefficient of friction	Processing technique	Ref. (Year)
Al	48	0.0531	0.34		
Al + 3.4wt.%SiC	66	0.0115	0.298	Stir- casting	[125]
Al + 0.9 wt.%JA	59	0.015	0.313		2020
Al + 3.4wt.%SiC + 0.9 wt.%JA	57	0.0165	0.326		
		μm			
AA7075	115	38	0.24		
AA7075 + 5 wt.%CSA	136	42	0.19		
AA7075 + 10wt.%CSA	162	32	0.20		
AA7075	115	45	0.27		[126]
AA7075 + 5 wt.%CSA	136	48	0.28	Stir- casting	2019
AA7075 + 10wt.%CSA	162	38	0.29		
AA7075	115	55	0.30		
AA7075 + 5 wt.%CSA	136	50	0.36		
AA7075 + 10wt.%CSA	162	49	0.37		
		Mm^3/N-m			
A7075	60	1.8×10^{-4}	–		
A7075 + 2wt.%B_4C/RHA	70	1.9×10^{-4}	–	High vacuum	
A7075 + 4wt.%B_4C/RHA	90	2×10^{-4}	–	casting	[127]
A7075 + 6wt.%B_4C/RHA	110	2.3×10^{-4}	–		2019
A7075 + 8wt.%B_4C/RHA	127	2.4×10^{-4}	–		
	HRF				
A356 + 2wt.%LBWA	8.8	0.13	–		
A356 + 4wt.%LBWA	10.9	0.12	–	Stir-casting	[128]
A356 + 6wt.%LBWA	11	0.166	–		2020
A356 + 8wt.%LBWA	14.2	0.11	–		
A356 + 10wt.%LBWA	15.3	0.034	–		
AA7075-T651(20 N)	–	0.832	0.4680		
FSPed AA7075- T651(20 N)	–	0.7052	0.4568	Stir casting	
AA7075- T651/WFA (20 N)	–	0.646	0.4181	and	[129]
AA7075-T651(50 N)	–	0.113	0.1969	Friction stir	2019
FSPed AA7075- T651(50 N)	–	0.0575	0.1320	processing	
AA7075- T651/WFA (50 N)	–	0.0403	0.1119		
AA7075-T651/PKSA(20 N)	–	0.7051	0.4507	Friction stir	[130]
AA7075-T651/PKSA(50 N)	-	0.0277	0.1158	processing	2019
Al6061(RT)	–	0.2×10^{-3}	–		
Al6061 + RHA(RT)	–	0.15×10^{-3}	–		
Al6061 + FA(RT)	–	0.09×10^{-3}	–	Casting	
Al6061(150°)	–	0.14×10^{-3}	–	And	
Al6061 + RHA (150°)	–	0.064×10^{-3}	–	Forging	[131]
Al6061 + FA (150°)	–	0.048×10^{-3}	–		2019
Al6061(Forged)	–	0.139×10^{-3}	–		
Al6061 + RHA(Forged)	–	0.130×10^{-3}	–		
Al6061 + FA(Forged)	–	0.09×10^{-3}	–		
JA-Jute ash	RHA-Rice husk ash		LBWA-Locust bean waste ash		
RT -room temperature		WFA-Wood fly ash			FA-fly ash

improve the morphology, mechanical and tribological properties of AMC's as mentioned in the previous sections however, limitations with respect to some properties are also observed. Arora and Sharma [132] developed RHA and SiC reinforced Al composites via stir casting technique and observed that with the increasing of RHA content, hardness and tensile strength decreased with the increment in wear rate. Similar trends were observed with the addition of BLA [133] and CCA [105] in Al–Mg-Si matrix material.

The incorporation of agro-based reinforcements also reduces the elongation at break thus affecting the elasticity of material. Hossain et al., [134] noticed decrease in elongation at break with increase in RHA content in Al alloy. Also, Sarkar et al., [135] found that the increasing RHA content in Al composites reduces their hardness, tensile strength as well as elongation at break. The limitations were not only specific to mechanical properties but were also observed for tribological properties of the resultant agro-based Al composites. Kamal and Siddiqui [45] reported that there was a decline in the hardness, and increment in the wear rate of the mustard husk ash (MSH) reinforced Al composites developed by powder metallurgy technique, with increase in MHS content. The coefficient of friction was found to be higher with higher content of CSA in Al matrix composite due to more CSA particles at the interface causing abrasive wear as a result of more rubbing action [122]. However, agro-wastes aluminum composites have very limited data on the utilization of additive manufacturing (AM) approach for the development of new composite that poise other challenges thus, it stresses importance of such amazing technique in verifying new set of results for advanced and wider applications of this material.

Fabrication of agro-based AMC's

AMC's are generally developed through two routes, liquid and solid route. The liquid route involves stir casting, friction stir processing, and compo-casting techniques, while solid route includes powder metallurgy technique. The brief idea about these techniques are described as follows:

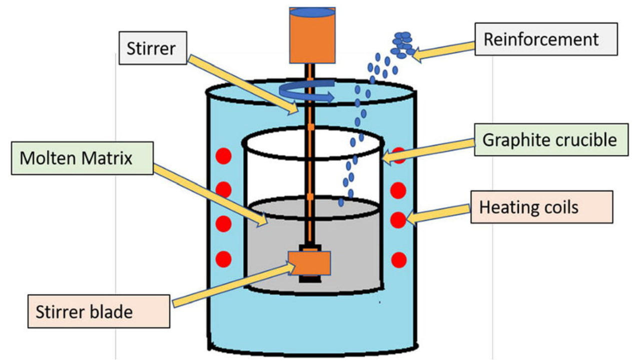


Figure 8 Schematic diagram of stir casting technique.

Stir casting technique

Owing to the flexibility, simplicity, and economic viability of the technique, it is mostly considered for fabricating AMC's [37, 136]. Figure 8 shows the stir casting technique that is commonly used for aluminum-composite fabrication. Even though concerns of uniform distribution of reinforcing particles, wettability, porosity, interfacial reactions particle agglomeration, isolation, and formation of unwanted secondary phases have been observed, however, the methods to overcome them have also been reported [136, 137]. The optimization of mixing parameters such as stirring speed, rotation of stirrer, blade angle to stirrer axis can lead to reduced particle clustering and segregation [138, 139], and also can be further reduced by employing a two-step stir casting technique [140, 141].

In stir casting technique, it is hard to get proper dispersion of reinforced particles due to the specific gravity of reinforcements that allow them to settle at the bottom during the process of fabrication. Numerious researchers have employed stir casting method for developing Al composites reinforced with agro-waste as mentioned in Table 6. The two-step stir casting technique was employed by researchers to improve the wettability of agro-based reinforcement in Al matrix thereby improving the properties of composites[142]. Also, wettability between the Al matrix and reinforcing materials was improved by coatings the reinforcing materials [143] or by using wetting agents such as magnesium and borax [144]. Another problem of interfacial reaction and formation of unwanted secondary phases that deteriorate the properties of the composites can be avoided by choosing reinforcing materials that inhibit the

Table 6 Agro-waste reinforced aluminum composites and their fabrication techniques

Agro-based reinforcement	Composition	Fabrication technique	References
Rice husk ash (RHA)	Al-6061/SiC/RHA	Stir casting process	[135]
	AA6351/SiC /RHA	Stir casting technique	[147]
	AA6082/ B4C/RHA	Stir casting technique	[148]
	Al64430/SiC/RHA	Stir casting technique	[149]
	Al6061/TiC/RHA	Stir casting technique	[150]
Coconut shell ash(CSA)	Al-Si-Fe/ CSA	Double stir-casting technique	[151]
	Al-Si-Fe alloy/CSA	Double stir-casting technique	[152]
	Al7079/CSA	Stir casting technique	[153]
Bamboo char(BC)	Al-6061/ B4C/BC	Stir casting technique	[154]
Groundnut shell ash	A356/ GSA	Stir casting technique	[155]
Sugarcane bagasse ash(SCBA)	AlSI10Mg/SCBA	Stir casting technique	[156]
	Al-7%Si/BA	Stir casting technique	[157]
	Al-7075/ graphite/SCBA	Stir casting technique	[158]
Melon shell ash(MSA)	Al-12%Si/MSA	Stir casting technique	[159]
Bean pod ash(BPA)	Al/BPA	Stir casting technique	[160]
Palm Kernel shells (PKS)	Al6063/PKS	Stir casting technique	[161]
Bagasse ash (BA)	Al/ Graphite/ BA	Friction stir processing	[162]
	Al/Boron nitride/BA	Friction stir processing	[163]

interfacial reaction, such as boron carbide and alumina [145, 146]. The porosity can be controlled by optimizing several process parameters during casting process of AMC's. Various researchers have developed Al composites with agro-based reinforcements via stir casting techniques and the fabricated composites exhibiting improved microstructure as well as better properties as evident in Table 6.

Compo-casting technique

Although fabrication of composites by stir casting is highly discouraged owing to poor wettability of ceramic particles during the fabrication process [164]. Numerous methods were anticipated to improve the wettability by the addition of wettability agents [165], by preheating [166], oxidation [167], and coating [168] of ceramic reinforcements. However, such methods result in an increase in the overall production cost. Thus, a technique in which casting temperature is lowered and ceramic particles are added when the aluminum is in a semi-solid state. This is the most economically viable technique for enhancing wettability and is called as compo-casting or slurry casting [169] as demonstrated in Fig. 9. Compo-casting is widely employed for the fabrication of composites due to its low cost, easiness, close to net shape, and large-scale production [170]. In addition, this technique has been successively employed for the fabrication of various agro-based AMC's [171]. Several investigations have revealed improved wettability and uniform distribution of ceramic particles in the AMC's produced through compo-casting compared to stir casting. Therefore, compo-casting is regarded

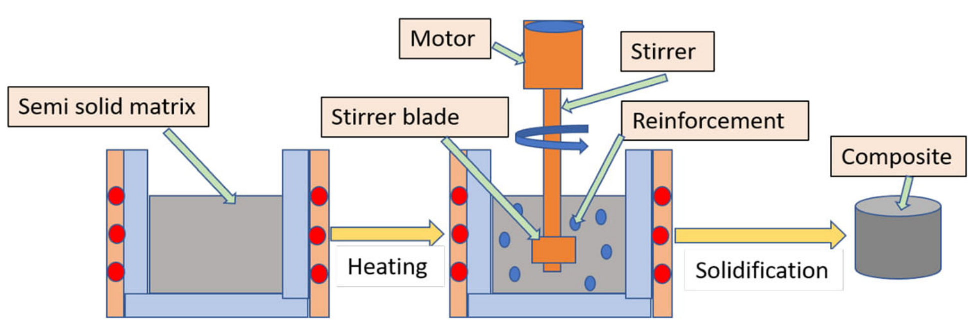
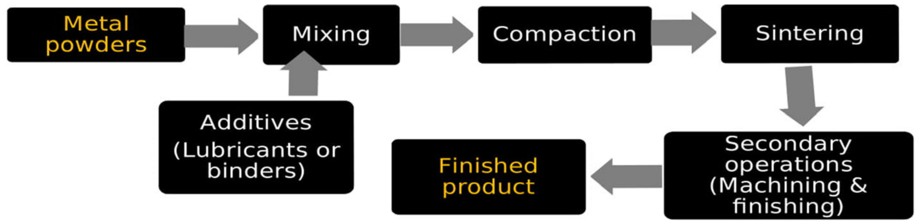


Figure 9 Schematic diagram of compocasting technique.

Figure 10 Powder metallurgy process.



as the most appropriate method for the development of low-cost composites efficiently. Some researchers have used this technique in the fabrication of aluminum-based agro-waste composites to overcome the issue of wettability encountered in the stir casting technique.

Powder metallurgy technique

Powder metallurgy technique is a recent preferred technology due to its various benefit of fabricating composites to near net shape characteristics, controlled homogeneity of structure, highly efficient use of the initial metals (95–98%), high productivity, a unique capability of producing porous materials, minimum consumption of energy and raw materials. Powder metallurgy is a recently growing technique advantageous for composites with ceramic and other reinforcement [172]. In this process, powders are transformed into materials through various methods, as shown in Fig. 10. It enables uniform distribution of reinforcements throughout the composite substrate. Powder metallurgy involves multiple steps such as mixing of powders, compaction, and sintering, as shown in Fig. 10. The process is not confined to any material, and it can be used to fabricate composites of a wide range of materials [173]. This technique results in the development of products of near-net-shape that does not require machining after fabrication. This technique is mostly preferred due to its advantages over other techniques as particle agglomeration, low wettability, and formation of detrimental phases, which are some of the complications linked with liquid metallurgy route are easily evaded [174]. Yusoff et al., [175] developed Palm shell activated carbon-reinforced aluminum composites via powder metallurgy technique and investigated the effect of factors such as applied load, sliding distance and reinforcement content (wt.%) on the wear properties analysis of variance (ANOVA). The improvement of wear resistance was found to be strongly dependent on the reinforcement content.

Additive manufacturing (AM) can be considered as an advanced powder metallurgy process if powder is used as input raw material. It is the process of making objects from 3D model data by joining materials mostly layer upon layer [176]. This technology can be applied to develop agro-wastes reinforced composite parts. The two basic parameters of metal AM process are the input raw material and energy source used to form the part [177]. Input raw material includes metal powder, whereas wire and

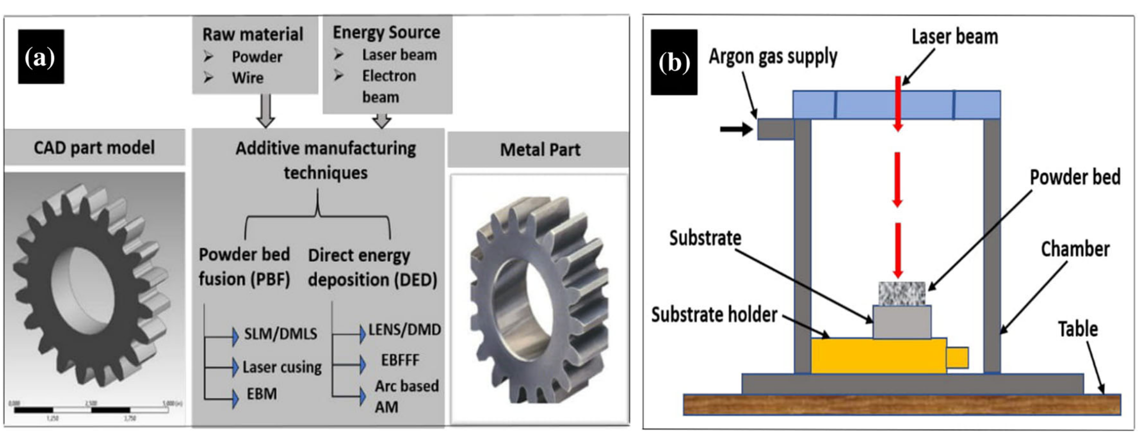


Figure 11 **a** Additive manufacturing processes, **b** Schematic diagram of apparatus for power fusion technology proposed for agro-based AMC's fabrication.

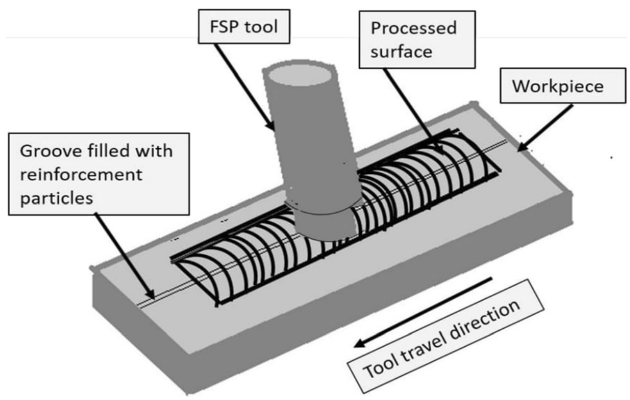


Figure 12 Schematic diagram of friction stir casting technique.

laser or electron beam can be utilized as energy source as shown in Fig. 11(a). AM machine requires CAD model of the part in the stereo lithography file format. Specialized slicing software then slices this model into number of cross-sectional layers. AM machine builds these layers one by one to manufacture complete part [178]. Thickness of these layers depends on the type of raw material and the AM process used to manufacture the finished part. Metal AM processes can be developed by two catagories: Powder-bed fusion (PBF) and Directed energy deposition (DED) AM. In PBF as illustrated by Fig. 11(b), the thermal energy selectively fuses regions of powder bed to form the final composite part [176]. The PBF approach involves processes selective laser sintering/melting (SLS/SLM), laser curing and electron beam melting (EBM), etc. In DED, thermal energy is used to fuse materials (powder or wire form) by melting as they are being deposited [176]. Although this technology has been applied by the researchers for the development of the Al alloys (SLM and DMLS) [179, 180] and AMC's (DMLS process) and studied their microstructure, properties and wear behavior [181–183] but it is yet not utilized for the development of agro-based AMC's. This technology can find huge potential in this area thus, needs to be explored further.

Friction stir processing

Friction stir processing is a unique technique that modifies the surfaces and effects the surface of the composites by transforming them into a more homogeneous microstructure and thus improves their properties. This technique as shown in Fig. 12 has benefits over stir casting, and powder metallurgy techniques as these techniques result in an increase in stiffness and strength at the expense of toughness and ductility. Friction stir processing results in the development of surface metal matrix composites (SMMC's) with higher surface hardness[184, 185] and enhanced creep resistance while retaining the toughness and ductility of the metallic substrates [186]. This technique improves the reinforcing particulate distribution in the composites. It has been employed as a post-fabrication process on the AMC's fabricated by powder metallurgy route in order to improve their properties [187]. This technique was also used to develop nanocomposites surfaces on metallic substrates [188].

This technique has made fabrication of bulk MMC's possible [189, 190], but it requires further research work in order to get adequate information for commercializing the process. FSP technique was adopted by Dinaharan et al. [191] to fabricate rice husk reinforced Al6061 composites. The morphological characterization revealed the absences of agglomerations or segregations. Moreover, increment in tensile strength from 220 to 285 MPa was also reported. Also, Fatchurrohman et al. [192] studied the effect of parameters of FSP on the microstructure and mircrohardness of Al6061 based RHA-reinforced composites and thus, found the optimum process parameters at which the composites exhibited better properties. Abdulmalik and Ahmad [193] fabricated RHA-reinforced Al 6061 based composite by FSP technique, and the composites exhibited homogeneous distribution of reinforcements with increased hardness values.

Research Gap

From the above literatures we have found the following gaps:

1. There is a scope on improvement of agro-based reinforcements by chemical and heat treatments to replace costly reinforcements like SiC, Al_2O_3 etc., as the agro-based reinforcements such as rice husk ash, coconut shell ash consists of such elements.
2. More research need to focus on the fabrication techniques that can overcome the challenges of improving the interfacial bonding between the Al matrix and agro-based reinforcements.

3. Optimization of process parameters for the development of agro-based reinforced Al composites with their optimum property attainment have not been studied so far.
4. Study on optimization of wear resistance property for agro-based AMC's at elevated temperature have not been explored yet.
5. Work needs to be focused on the production of high-quality and low-production-cost agro-based AMC's. Technologies such as additive manufacturing need to be explored for the development of components for various applications.

Challenges and way forward

Presently, the low cost and high-performance engineering components are getting much consideration from material scientists. The replacement of harzardous reinforcement to agro-based has played an important role in improving the sustainability and environmental degradation. Thus, material scientists are paying more attention toward improvement of such reinforcements. In addition, the disposal of such materials otherwise cause environmental issues; thus, their usage as reinforcements can solve this problem. As such, agro-waste based AMC's are potential candidate materials but advancements are still challenging for their efficient utilization as a reinforcement for composite. Some of them are:

1. The microstructure studies of agro-based AMC's fabricated via stir casting route revealed non-homogeneous distribution of reinforcing particles and face the issue of wettability. Accordingly, the agro-based AMC's fabricated by using different techniques can overcome this issue and help in achieving uniform distribution of reinforced particles as well as good bonding between matrix and reinforcing particles. These techniques are compo-casting, vortex method, powder metallurgy, friction stir processing, etc. Additionally, agro-based AMC's and their techniques can be tailored to get the required morphology of the composites with better wettability and bonding strength thereby leading to enhancement of properties.
2. These agro-based reinforcements insignificantly improve the properties of composites thus there arises a need of improving their strength either by their surface modification or by further processing them into better quality reinforcements, such as silica derived from rice husk as compared to rice husk ash can be considered as a better reinforcement.
3. Their potential in improving the wear rates have not been yet explored extensively. Thus, the study of wear properties of these composites requires further investigation at different operating conditions. For e.g., to replace the hazardous lead and asbestos, fiber is used as a friction material in automobile brakes and clutches. In addition, these agro-wastes due to their availability in abundance can also reduce the production cost and thus can led to a reduction in component cost; therefore, we can get a low-cost technology.
4. The reuse and recycle of of the agro-waste material is an issue to be dealt with, thus an appropriate processing route would be the focus of immediate future work. Their remarkable advantages are that they are comparatively cheaper, lightweight, and possess higher strength to weight ratio as compared to ceramic reinforced composites.
5. Lightweight and high strength agro-based AMC's can be used as a replacement of the conventional materials in various applications. However, more investigation of the potential of agro-waste is crucial, focusing on optimizing the production process for obtaining better reinforcing materials and determining the optimum processing parameters. This can encourage the production of agro-based AMC's on a large-scale using agro-waste.
6. Additive manufacturing techniques can be used for the fabrication of agro-based AMC's. It is a novel method of developing parts to near net shape using layer by layer addition of materials which reduces: fly ratio (input material weight to final part weight) up to 1:1 [194, 195] as compared to 10:1 or 20:1 in case of conventional manufacturing processes. It provides freedom in part designing and can produce complex parts with low density, high strength, good thermal properties, and good energy absorption for applications like heat exchangers in automobile, computer, and aerospace industries [196]. It can allow mass production as it eliminates the processes like casting, forging, rolling, drilling, machining and welding, etc. and produces part in single

processing step. In addition, it reduces assembly requirements by combining number of parts into a single part. This technology has not been yet applied to develop agro-based AMC's. However, it has great potential to be used for the fabrication of low cost and high strength agro-based AMC's. For the fabrication of agro-based AMC's, powder bed fusion process will be preferred. Initially, the homogeneous mixture of Al powder and agro-based reinforcement will be prepared. Then this powdered mixture will be layered on the substrate as shown in Fig. 11(b) and laser pulse or electron beam will be fired at the particular location depending upon the cross section to be formed from the CAD model. An energy source either in the form of laser beam or electron beam melts the powder by scanning powder layer in an inert atmosphere. After scanning one layer another layer will be deposited on the formed layer which will be again scanned by an energy source. Repeating this cycle layer by layer the complete part will be formed. It can reduce the overall cost and leads to material conservation and sustainability. In combination with the utilization of agro-based materials this technology has a huge prospect in lightweight and low-cost manufacturing.

To sum up, it can be said that due to energy efficiency, cost-effectiveness, and environmental friendliness, these materials can find application as a reinforcing material in the composites and have vast potential, scope, and prospects for the researchers in the field of expectation and enrichment of characteristics of the agro-based AMC's. However, there is still the need to characterize the potentials of agro-waste by converting them into better reinforcing particles that can enhance the properties of AMC's.

Conclusion

This review has systematically discussed various agro-based reinforcements and their influence on the microstructural, mechanical, and tribological properties and the processing techniques involved. Some of the key findings are:

1. Addition of various combinations of reinforcements in the composites are developed to attain desirable mechanical properties that are difficult to achieve in ceramic reinforced composites.
2. The agro-based AMC's reinforced with agro-waste products have revealed that the better performance of AMC's can be reached at lower production cost even though replacement of about 50% synthetic reinforcement by the agro-waste is possible without compromising any property. As revealed by the literature that replacing SiC or alumina by the agro-waste in small quantity results in an improvement in properties of the composite.
3. The agro-based reinforcements like, maize stalk ash, coconut shell ash, rice husk ash, etc. reduce the density of AMC's on their addition to composites. However, acceptable porosity levels are obtained in these composites.
4. The mechanical properties of agro-based AMC's revealed that the mechanical properties can be controlled by varying composition and reinforcements.
5. Various research works include agro-based materials as reinforcements and have studied influence, characteristics and properties of the AMC's; however, these also depend on the production technique employed.
6. Among all the techniques stir casting has been used extensively, however, it has various limitations associated, such as wettability and nonuniform dispersion of reinforcements. Thus, other techniques are now considered such as friction stir casting, compocasting and powder metallurgy.
7. These agro-waste materials have the potential to replace the hazardous reinforcements such as asbestos fiber used as a friction material in automobiles; coir fiber, when reinforced in the aluminum composite, has proved to be better candidate material as filler materials in brake pad applications and thus expand their scope of applications.

Acknowledgements

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Declarations

Conflict of Interest We have no objection to share research data with other researchers who can evaluate our findings, and increase trust in our article. Here, mainly the research data are taken from different sources with appropriate citation for elaborating the review article.

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