Chapter

Engine Lightweighting: Use of Green Materials as Reinforcement in Aluminum Metal Matrix Composites

Akaehomen O. Akii Ibhadode

Abstract

Lightweighting of automobiles of which the IC engine is a part has become very important due to stringent emission regulations being imposed on vehicle manufacturers, and the need to have more fuel-efficient vehicles. The use of light weight materials such as aluminum metal matrix composites (AMMCs) made up of aluminum alloy and nonmetal reinforcements such as alumina and silicon carbide is one strategy used for lightweighting. Recently, there has been active research in the use of biodegradable green materials such as agricultural wastes as reinforcements for AMMCs. In this chapter, work done on the use of biodegradable green materials as reinforcements for AMMCs is reviewed. The potential for their use as engine parts materials is analyzed. The results show that they have the potential to provide significant weight and cost savings when used as engine parts materials.

Keywords: lightweighting, aluminum metal matrix composites, IC engine, green reinforcement materials

1. Introduction

Automobile lightweighting involves reducing the weight of an automobile in order to minimize fuel consumption and exhaust emissions. In electric vehicles (EV) however, the effect of lightweighting is to extend the range of each battery charge. The Vehicle Technologies Office of the United States Office of Energy Efficiency and Renewable Energy [1] states that "a 10% reduction in vehicle weight can result in a 6%-8% fuel economy improvement". Also, *Järvikivi* [2] reported in 2021 that each 100 kg reduction in a vehicle's weight cuts (on average) 8.5 g of CO_2 per 100 km. These figures tell us that a vehicle's performance with respect to fuel efficiency and cleaner operation is improved by lightweighting of the vehicle. The engine, which is the powerhouse of the vehicle can, on the average, weigh around 10% of vehicle curb weight. Thus, anything done to reduce the engine weight will impact the vehicle performance positively.

Strategies for lightweighting engines include the use of high specific strength materials (that is, high strength-to-weight ratios) such as high-strength aluminum alloys or aluminum metal composites, sheet metal fabrication of parts, innovative design of parts, additive manufacturing and friction reduction of moving parts [3–7].

Metal composites are engineered materials consisting of a metal matrix in which a nonmetal reinforcement is dispersed. The resulting material called a metal composite, combines the properties of the metal and the reinforcement material to produce better desirable properties than any of the two can provide individually. In this way, low-strength, lightweight engineering materials such as aluminum are converted to relatively high-strength materials suitable for use in fabrication of engine parts and others in the automobile. Common reinforcement materials include silicon carbide (SiC), aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), etc. [8–10].

With the advent of the Circular Economy [11, 12] and the necessity of going Green [13, 14], there has been a recent move to use green materials, especially biodegradables, essentially agricultural wastes, as reinforcement materials in metal matrix composites [15, 16]. Green materials are materials that have the following characteristics: are local and renewable, nontoxic, improve occupancy health, lowers cost, and conserve energy and water use and waste products, and have low embedded energy in their harvesting or collection, production, transportation, and use [17]. Examples of biodegradable green materials include palm kernel shells, periwinkle shells, coconut shells, corn cob, bagasse, rice husk, egg shell, etc. This has a number of potential benefits: more sustainable production, lower cost of reinforcement materials, optimal use of resources including waste materials, and cleaner environment in places where these biodegradable wastes are produced.

This chapter reviews the work done in using biodegradable green materials as reinforcements in aluminum metal matrix composites (AMMCs). It discusses their application to IC engine parts manufacture.

2. Review of green materials reinforced aluminum metal matrix composites (AMMCs)

In recent times there has been much interest in using renewable materials in the form of waste agricultural products as reinforcement materials in AMMCs, especially in developing countries. This is a result of a number of reasons: (i) they serve as a cheap alternative to conventional reinforcing materials such as silicon carbide and alumina, which are imported into these countries, and are expensive, (ii) enables the possibility of producing locally in these countries, lightweight high strength composites, and (iii) has the potential to create a cleaner environment due to the usage of these waste agricultural products for useful products.

The Appendix **Table A1** gives a summary of some of the research works carried out in using green materials for reinforcing AMMCs [18–85].

3. Discussion

3.1 Range of green reinforcement materials

Table 1 lists the green materials used by various researchers as reinforcement for AMMCs. It shows that green reinforcement materials cover a wide range of materials, mainly agricultural wastes. Twenty green reinforcement materials are shown.

Bagasse	Bamboo leaf	Bone	Breadfruit seed hull	Coconut shell
Corncob	Cow horn	Egg shell	Groundnut shell	Lemon grass
Maize stalk	Mango seed	Marula seed shell	Neem leaf	Palm kernel shell
Palm sprout	Periwinkle shell	Rice husk	Snail shell	Tamarind leaf

Table 1.
Green materials for reinforcing AMMCs as used by researchers.

3.2 Preparation of green reinforcement materials

Figure 1 shows the processing routes of biodegradable green materials for reinforcement of AMMCs derived from the review summary in the Appendix **Table A1**. The preparation starts with cleaning with water or distilled water to remove all impurities. This is followed by drying, usually in the sun for days or dried in an oven for a few hours. The dried material may be pulverized and then ashed; or ashed directly

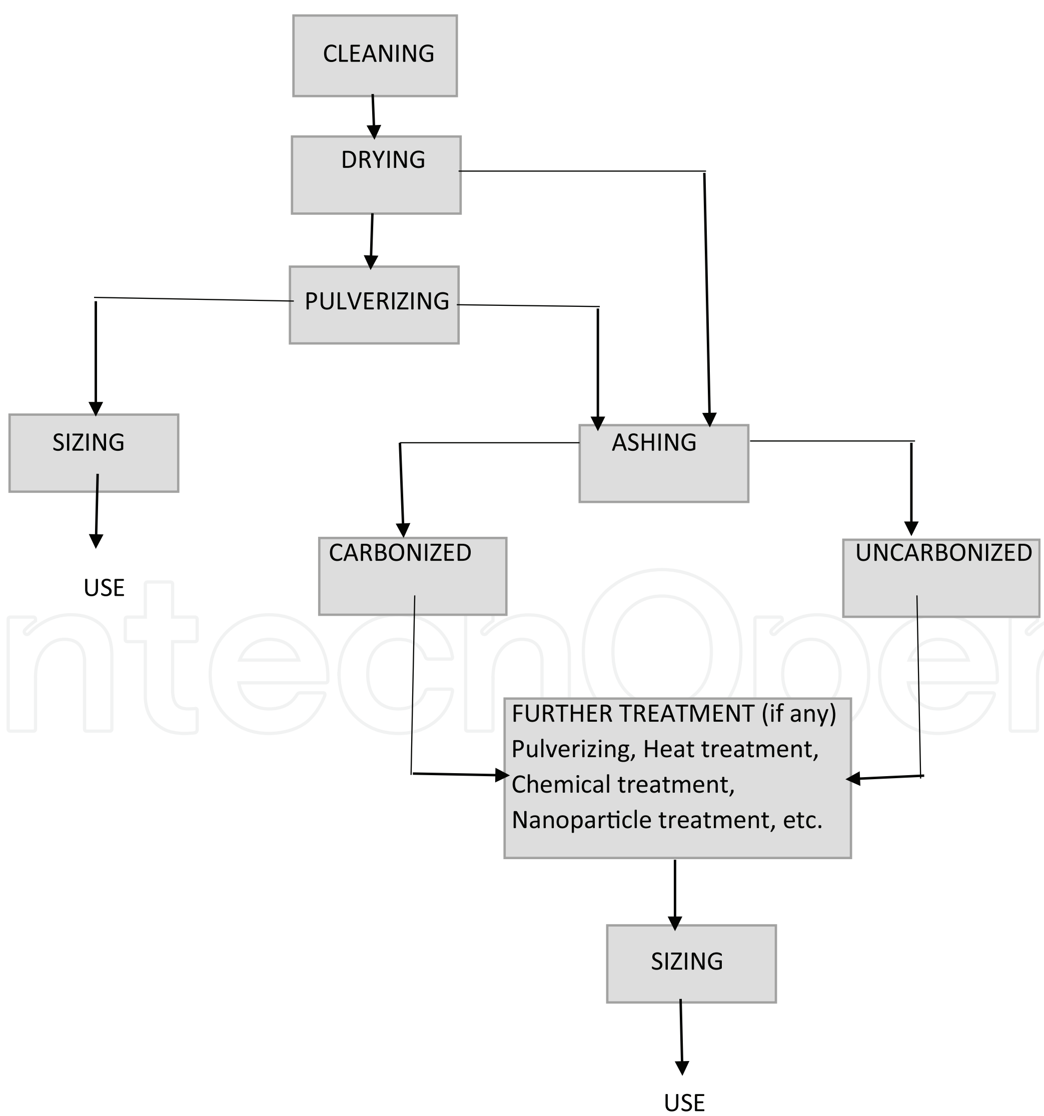

Figure 1.
Preparation routes for green reinforcement materials.

without pulverization. Depending on what is desired, the pulverized particles after sizing are used directly for reinforcement. Ashing can be done by heating in air or without air. When heated without air, carbonized ash is obtained. When heated with air, uncarbonized ash is obtained. The obtained ash may further be treated before sizing for use as a reinforcement material. Further treatment could include, pulverizing, conditioning by heat treatment in a furnace to reduce the carbonaceous and volatile constituents [77], chemical treatment and/or reduction to nanoparticle treatment [63]. Finally, the particles are sized by sieving and thereafter used as reinforcements.

The use of pulverized particles without ashing is a simpler route and most likely, less costly. There seems not to be any detailed work on the comparison of the performance of metal composites reinforced with straight particles, uncarbonized and carbonized ashes. However, Hassan and Aigbodion [44] showed that carbonized eggshell ash had better performance than uncarbonized ash.

3.3 Chemical compositions of green reinforcement materials

Table 2 shows the chemical compositions of most of the green reinforcement materials listed in **Table 1**. We could classify the reinforcements whose oxide analyses are given into (i) silica-based, (ii) calcium oxide-based, and (iii) alumina/ferric oxide-based reinforcements. These are shown in **Table 3**. Eight of the materials are silica based having at least 41% SiO_2 as their highest oxide contents, three are calcium oxide based having at least 40% CaO as their highest oxide contents, and only one is alumina/ferric oxide based having at least 35% Al_2O_3 and at least 30% Fe_2O_3. When these green materials are used as reinforcements in AMMCs, they release their oxides into the matrix to affect the properties of the metal matrix.

Table 2 also lists the densities of these biodegradable green materials, which shows that most of the materials have much lower densities than aluminum which is commonly used as matrix of metal composites.

3.4 Fabrication of green materials reinforced AMMCs

There are a number of methods used for the fabrication of AMMCs [8]. However, the stir casting process is frequently used because it promotes the casting of uniformly reinforced metal composites as stirring transfers particles into the liquid metal and maintains the particles in a state of suspension [33]. The two-step stir-casting process involves the following steps [99]:

i. Preheating of the reinforcement particles to improve wettability with the metal matrix

ii. Heating the metal matrix above the liquidus temperature

iii. Cooling the liquid metal matrix in the furnace to a semi-solid state

iv. Adding the preheated reinforcement particles to the semi-solid metal matrix and stirring continuously for a short period, say 5 min

v. Superheating the composite slurry while stirring at a specified speed and time

vi. Casting the molten composite into molds

Green material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	MnO	ZnO	TiO_2	Cr_2O_3 or (Cl)	P_2O_5	Mn_2O_3 Or (NiO)	SrO	LOI	Density, g/cm^3
Rice Husk Ash [22]	97.095	1.135	0.316	0.073	0.825	0.146	0.181	0.092	—	—						0.965	1.8–2.1 [86]
Bamboo Leaf Ash [25]	75.9	4.13	1.22	7.47	1.85		5.62				0.20						2.64 [87]
Bagasse Ash [22]	77.286	10.951	3.660	2.088	1.489	0.487	3.159	0.381	—	—						3.277	0.238 [22]
Breadfruit Seed Hull Ash [33]	15.45	35.80	30.34		1.20		0.52	0.45	0.22	0.05		5.06					1.98 [33]
Coconut Shell Ash [29]	46	16	14		18	.	1.2	0.9	0.5	0.6							2.05 [37]
Corncob Ash [88]	66.34	7.48	4.44	11.57	2.06	1.07	4.92	0.41									0.8–1.2 [89]
Egg Shell [90]	0.09	0.03	0.02	50.70	0.01	0.57		0.19				(0.219)	0.24	(0.001)	0.13	47.8	2.49 (uncarbonized) 1.98 (carbonized) [90]
Mango Seed Shell Ash [56]	43.574	13.847	6.211	14.895	3.173	1.797	4.559	2.302		2.653	2.129	0.005	4.173	0.130	2.653		0.4–0.425 [91]
Groundnut Shell Ash [50]	41.42	11.75	12.60	11.23	3.51	0.44	11.89	1.02	0.23	—	0.63	—	1.71			3.57	0.23 [92]
Palm Kernel Shell (unashed) particle [61]	55.69	9.43	3.32	11.21	4.85	0.67	9.71	1.76	0.72	—	—	0.27	2.39				1.70–2.05 [93]
Periwinkle Shell [31]	32.84	10.20	7.02	40.84	1.47	0.26	0.14	0.24			1.07		(P_2O = 0.01)	0.78			2.3 [70]
Snail Shell Ash [94]	0.55	1.35	0.4	74.30	0.62		0.21	0.25		0.01	0.01	0.001	0.22				2.55–2.81 [95]
	Ca	Mg	K	P	CO	Organic carbon	S	N									
Cow bone [31]	36.05	0.74	0.85	16.43	4.58												1.24–1.71 [96]
Cow hone [97]	0.396	0.014	0.09	0.165		39.97	0.049	15.54									1.283 [98]

Table 2.
Chemical compositions of green reinforcement materials.

	Rice husk	Bagasse	Bamboo leaf	Corncob	Palm kernel shell	Coconut shell	Mango seed shell	Groundnut shell	Snail shell	Egg shell	Periwinkle shell	Breadfruit seed shell
Silica based	>97% SiO_2	>77% SiO_2	>75% SiO_2	>66% SiO_2	>55% SiO_2	>46% SiO_2	>43% SiO_2	>41% SiO_2				
Calcium oxide based									>74% CaO	>50% CaO	>40% CaO	
Alumina/Ferric oxide based												>35% Al_2O_3/ >30% Fe_2O_3

Table 3.
Classification of green reinforcement materials according to their prominent oxide content.

3.5 Microstructure of green materials reinforced AMMCs

The large body of knowledge on metal matrix composites as exemplified by the references on green materials reinforced AMMCs in the Appendix **Table A1** shows that when the metal composite is well fabricated, the microstructure of the composites shows the uniform distribution of green materials particles in the aluminum matrix. The uniform distribution of the reinforcement particles in the microstructure of the composites is the main reason for the enhancement of the mechanical properties of AMMCs [33, 44, 100]. Also, Atuanya et al. [33] showed that the increase in reinforcement weight fraction gives rise to decrease in matrix grain size in the composites as shown in **Figure 2**. This decrease in matrix grain size further improves the mechanical properties of the composites as reinforcement content increases.

3.6 Physical and mechanical properties of green materials reinforced AMMCs

Figure 3 shows the plots of relative density ρ_r, relative tensile strength σ_r, relative hardness H_r, and relative impact energy E_r of aluminum metal matrix composites (AMMCs) against weight percent of reinforcement particles, for egg shell ash [44] and breadfruit seed hull ash [33].

The relative density, relative tensile strength, relative hardness, and relative impact energy are defined respectively as

$$\rho_r = \rho_c/\rho_m \quad (1)$$

where ρ_m = density of reference metal matrix, ρ_c = density of composite.

$$\sigma_r = \sigma_c/\sigma_m \quad (2)$$

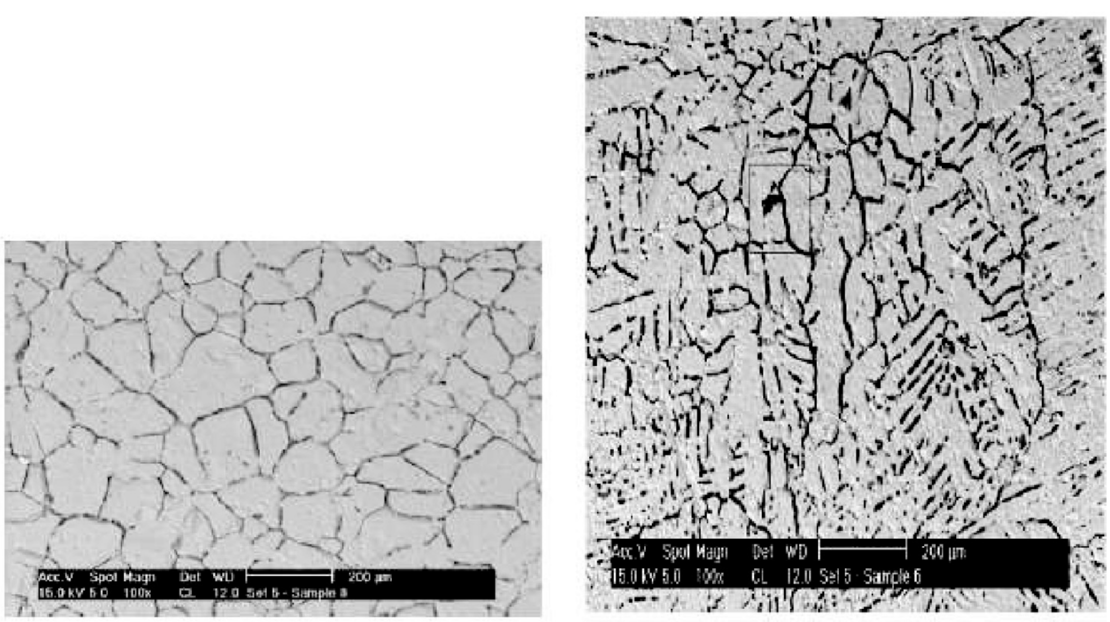

Figure 2.
SEM of aluminum alloy reinforced with (a) 2 wt.% and (b) 10 wt.% of breadfruit seed hull ash (mag. ×100) [33].

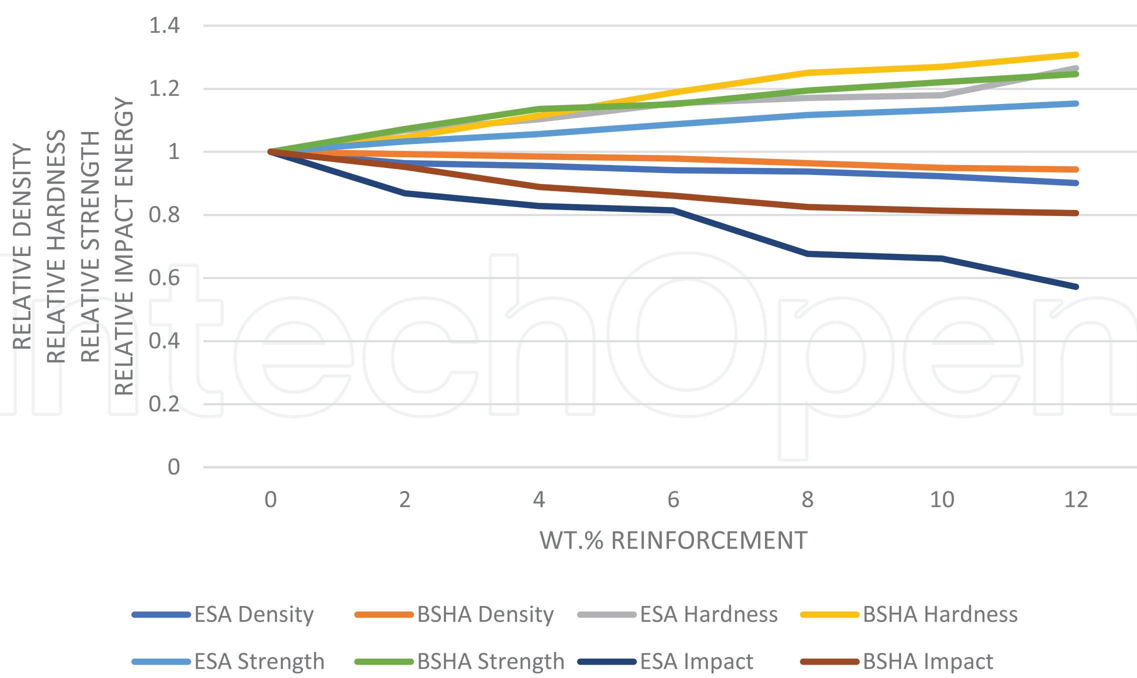

Figure 3.
Density, hardness, strength and impact energy of aluminum metal matrix composites reinforced with egg shell ash and breadfruit seed hull ash.

where σ_m = tensile strength of reference metal matrix, σ_c = tensile strength of composite.

$$H_r = H_c/H_m \tag{3}$$

where H_m = hardness of reference metal matrix, H_c = hardness of composite.

$$E_r = E_c/E_m \tag{4}$$

where E_m = impact energy of reference metal matrix, E_c = impact strength of composite.

The figure shows that as the weight percent of reinforcement materials increases, density and impact strength decrease, while tensile strength and hardness increase for both reinforcement materials.

The density of composites decreased as the percent addition of reinforcement materials increased because the green materials, egg shell ash (ρ = 1.98 g/cm^3), breadfruit seed hull ash ((ρ = 1.98 g/cm^3) (see **Table 2**) are light materials compared to the densities of the aluminum metal matrices used (2.775 g/cm^3 in both cases). This is in contrast to the use of conventional reinforcement materials such as alumina and silicon carbide. **Figure 4** shows that as the addition of alumina ($\rho_{alumina}$ = 3.95 g/cm^3) and silicon carbide (ρ_{SiC} = 3.21 g/cm^3) increased, the density of the composites increased because of their higher densities than the reference aluminum alloy matrix. This shows that use of biodegradable green materials as reinforcement materials for AMMCs will produce lighter composites suitable for lightweighting of IC engines and other automobile parts, and industrial parts where lightweighting is important.

Figure 3 shows that the hardness of the composites increased, above the reference metal matrix, as percent reinforcement content increased. This is attributed to an increase in the volume of precipitated phases or a high dislocation density. The

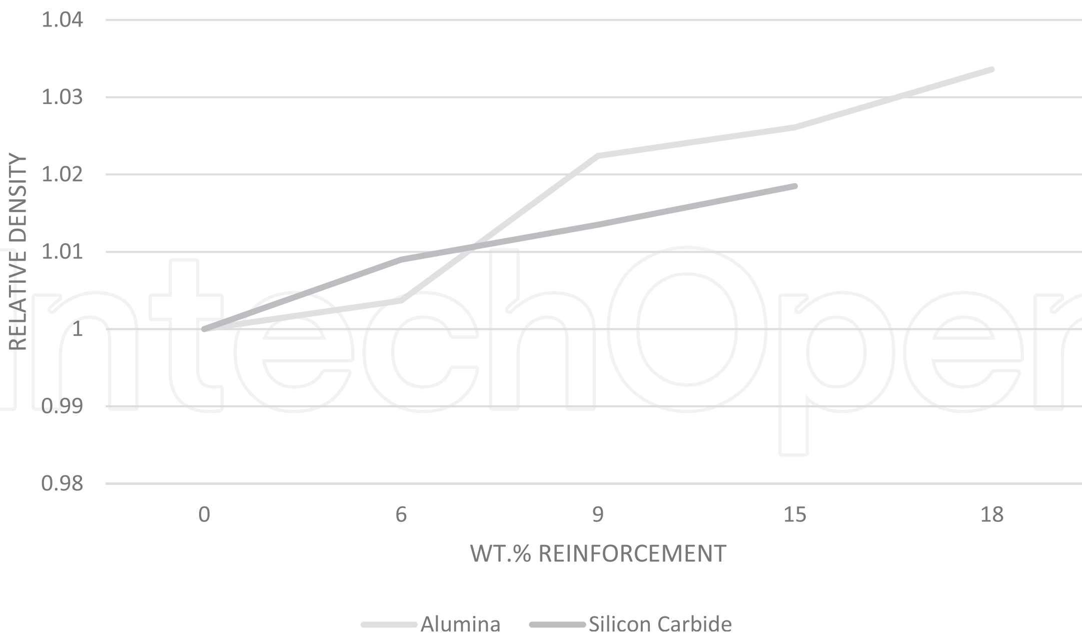

Figure 4.
Relative densities of AMMCs reinforced with alumina [99] and silicon carbide [101].

increase in the weight percentage of hard and brittle phases of the reinforcing materials in the aluminum alloy is responsible for the increments in hardness as reinforcement materials increase [33].

Also, **Figure 3** shows that as the percent weight of reinforcement increased, the tensile strength increases over the reference metal matrix. This may be a result of several factors such as good particle/matrix interfacial bonding, fine reinforcement particle size, and the strengthening effect of the reinforcing materials [33, 102–104].

The figure also shows that as the percent reinforcing material increased, the impact strength of the composites decreases. This is due to the brittle nature of the reinforcing materials which degrades the impact strength as the reinforcement material increases [33].

3.7 Application of green materials reinforcements to IC engine parts

Table 4 shows IC engine parts in which aluminum alloys are used. The table shows the permissible stresses specified for the parts. The strengths of some biodegradable green reinforcement materials are also shown to see if they measure up with strength requirements of the engine parts. These strength figures indicate that there is promise for use of these biodegradable green materials for reinforcement of AMMCs as IC engine parts materials. We note that their strength values are increased when high aluminum alloys are used as reference metal matrix. These results indicate that these biodegradable reinforcement materials have the latitude of being able to generate high-strength AMMCs by choice of type of aluminum alloy, type of biodegradable material, and amount of reinforcement. By this statement, it follows that all the IC engine parts shown in **Table 4**, and possibly, other parts not shown, could readily be made with biodegradable green materials reinforced AMMCs. We note that factor of safety values which could be as high as 6 in certain cases, such as in connecting rod design, are required to reduce the strength values of the green biodegradables shown in **Table 4**. Despite this, biodegradables show great promise as reinforcing materials in AMMCs.

Engine part	Permissible stress, MPa [105]	Tensile strength of biodegradable reinforced AMMC, MPa				
		Rice husk [74]	Palm kernel shell [63]	Periwinkle shell [70]	Breadfruit seed hull [33]	Egg shell [44]
Engine block	35–100	312.5	263.4	132.5	215	113
Cylinder head	30–50					
Piston	50–90					
Connecting rod	60–100					

Key: Rice Husk (A356.2/8wt.%RHA) [74], Palm Kernel Shell (A356/4wt.%PKSA) [63], Periwinkle Shell (Al6063/15wt.%PSA) [70], Breadfruit Seed Hull (Al–Si–Fe/12wt.%BSH) [33], Egg Shell (Al-Cu-Mg/12wt.%EG) [44].

Table 4.
Potential application of biodegradable materials reinforced AMMC to IC engine parts.

3.8 Engine lightweighting by biodegradable green materials reinforced AMMCs

From previous work [5], in which a gasoline engine rated at 7.1 kW at 5500 rpm generating a maximum torque of 18.0 Nm at 3500 rpm was used to calculate engine weight reduction, we use this same engine to calculate potential weight reductions when using is made of these biodegradable green materials reinforced AMMCs to replace the materials used to make some parts namely, engine block, cylinder head, piston, and connecting rod. **Table 5** shows the engine weight reduction analysis. The engine block was made of cast iron, and cylinder head, piston, and connecting rod made of aluminum alloys were replaced in the analysis with AMMCs reinforced with rice husk (RH) ash, palm kernel shell (PKS) nanoparticles, and periwinkle shell (PS) ash. The table shows that:

i. Total parts (engine block, cylinder head, piston, and connecting rod) weight reductions are 54.63%, 61.54%, and 63.01% when PS, RH, and PKS reinforced AMMCs are used respectively in descending order of reinforcement density.

ii. Total engine weight reductions are 28.64%, 32.26%, and 33.04% when PS, RH, and PKS-reinforced AMMCs are used respectively.

The table also shows when it is assumed that aluminum alloy A356 is used to originally make the engine block. With this scenario, the total parts weight reductions are 13.94%, 27.03%, and 29.83% when PS-, RH-, and PKS-reinforced AMMCs are used, respectively. Also, in this case, the total engine weight reductions are 5.12%, 9.93% and 10.96% when PS-, RH-, and PKS-reinforced AMMCs are used, respectively.

These results show the massive engine lightweighting achieved when only a single cast iron part is replaced with AMMC. When the engine block was assumed to have been made originally from aluminum alloy A356, the weight reductions achieved by replacement with the biodegradable green materials reinforced AMMCs, are also appreciable: the total weight reductions on parts are 13.94%, 27.03%, and 29.83%, and on whole engine are 5.12%, 9.93%, and 10.96% when reinforced with PS, RH, and PKS, respectively.

These results follow the trend of density reduction. The percent weight reduction depends on the percent reduction of densities from original engine material to the biodegradable green reinforcement material. For example, the density reduction from

Engine part	Material	Density, kg/m^3 [Ref?]	Weight, kg	Volume, m^3	Weight Equivalent of Biodegradable Reinforced AMMC, kg			Weight Reduction, kg/(% on individual parts)		
					RH, (ρ_c = 1.95 g/cm^3)	PS (ρ_c = 2.3 g/cm^3)	PKS, (ρ_c = 1.875 g/cm^3)	RH	PS	PKS
Engine Block	Cast Iron	7079	10.25	0.001448 (1448 cm^3)	2.824	3.330	2.715	7.426/ (72.45%)	6.92/ (67.51%)	7.535 (73.51%)
Cylinder Head	Aluminum Alloy (A356)	2670	3	0.001124 (1124 cm^3)	2.192	2.585	2.108	0.808/ (26.93%)	0.415/ (13.83%)	0.892/ (29.73%)
Piston	Aluminum Alloy (A4032)	2690	0.094	0.000035 (35 cm^3)	0.068	0.081	0.066	0.026/ (27.66%)	0.013/ (13.83%)	0.028/ (29.79%)
Connecting Rod	Aluminum Alloy (A7075)	2803	0.157	0.000056 (56 cm^3)	0.109	0.129	0.105	0.048/ (30.57%)	0.028/ (17.83%)	0.052/ (33.12%)
Total			13.501	0.002663 (2663 cm^3)	5.193	6.125	4.994	8.308/(−)	7.376/(−)	8.507/(−)
Weight reduction on total parts of 13.501 kg								61.54%	54.63%	63.01%
Weight reduction on total parts of 7.117 kg if engine block was originally made from A356 (details not shown)								27.03%	13.94%	29.83%
Weight reduction on total engine weight of 25.75 kg								32.26%	28.647%	33.04%
Weight reduction on total engine weight of 19.366 kg if engine block was originally made from A356 (details not shown)								9.93%	5.12%	10.96%

Table 5.
Engine weight reductions by biodegradable materials reinforced AMMCs.

aluminum alloy A356 to palm kernel shell (PKS) is about 30% which is the same percent reduction in weight. Thus, finding a low-density reinforcing material with high reinforcement performance is the key to weight reduction.

3.9 Cost analysis of biodegradable materials reinforced AMMCs production

A cost analysis of the production of one of the biodegradable reinforcement materials discussed above, specifically, PKS is presented. This is done to quantify the financial benefit that may accrue to the deployment of waste biodegradables as reinforcing materials in AMMCs.

Refer to **Figure 1** which shows the processing steps for obtaining reinforcement particles for AMMCs. For the analysis, we assume PKS particles, unashed and uncarbonized. Unashed and uncarbonized PKS particles have been used directly to reinforce AMMCs successfully by Edoziuno et al. [61], Ibhadode and Ebhojiaye [8].

In manufacturing, the material cost C_m is usually a fraction of the production cost, C_p. That is:

$$C_m/C_p = x_m < 1 \tag{5}$$

To simplify the analysis, we make the following assumptions:

i. we take a moderately low value of x_m = 0.2, due to uncertainties that may be associated with the manufacturing process such that four-fifths of the production cost is attributed to other input costs such as energy, equipment, overheads, and others. This assumption is justified because PKS is a waste product whose cost may not be greater than the cost of collection

ii. cost of PKS, C_m, is equal to the cost of collecting it as a waste product from palm kernel oil (PKO) processing. PKO mills are supplied with palm kernel seeds cracked by small businesses which discard the shells as waste. This collection cost depends on the distance between the points of collection and usage. If we assume a collection radius of 30 km, going by existing prices, cost of delivering a 10-ton truck load may be about N50,000. Thus, PKS cost per kg is shown as follows:

$$C_m = \text{N } 50{,}000/(10 \text{ tons} \times 1000 \text{ kg}) = \text{N}5/\text{kg} \tag{6}$$

From Eq. (5), for x_m = 0.2, production cost is

$$C_p = C_m/x_m = \text{N}5/0.2 = \text{N}25/\text{kg} \tag{7}$$

If we assume a profit margin of 25%, then the selling price of PKS particles is as follows:

$$C_s = \text{N}25/\text{kg}\ (1 + 0.25) = \text{N}31.25/\text{kg} \tag{8}$$

Thus, a ton of PKS reinforcement particles will cost N31,250 = N31,250/(N640/1US$) = $48.83/ton.

This analysis shows that a ton of PKS particles will cost about $49. This is in sharp contrast to the cost of alumina at $339.25 [106] and silicon carbide of $800–$2000 per ton [107]. That is, the cost of PKS reinforcing particles per ton is less than 15% of alumina, and between 2.5% and 6.1% of silicon carbide. Thus, it appears that there may be financial benefits in using this biodegradable material, as with others, such as listed in **Table 1**, as reinforcement materials for AMMCs.

3.10 Lightweighting index or effectiveness, L_x

The lightweighting index or effectiveness L_x is the dimensionless specific strength of the composite which we define as the ratio of specific strength of composite to the specific strength of the reference metal matrix, that is:

$$L_x = |\sigma| = \{(\sigma_c/\rho_c)/(\sigma_m/\rho_m)\} \quad (9)$$

The higher this value, the more strength per weight, the reinforcing material has over the reference metal matrix.

The table in the Appendix **Table A1** shows the L_x values for some of the references reviewed for which the density and tensile strength values for the reference metal matrix and composites were available.

Figure 5 shows the plots of lightweighting index L_x against wt.% composition of composites reinforced with egg shell ash [44] and breadfruit seed hull ash [33]. The figure shows that the breadfruit reinforcement seems to have a better strengthening power than the egg shell, going by these two test results [33, 44]. From the data points, the average lightweingthing index was found to be, $L_{xoEggShell}$ = 1.1487 and $L_{xoBreadfruit}$ = 1.1822.

3.11 Reinforcement performance index

Usually, it could be of interest to rate the reinforcing performance of different reinforcing materials from carefully conducted experiments or to rate the

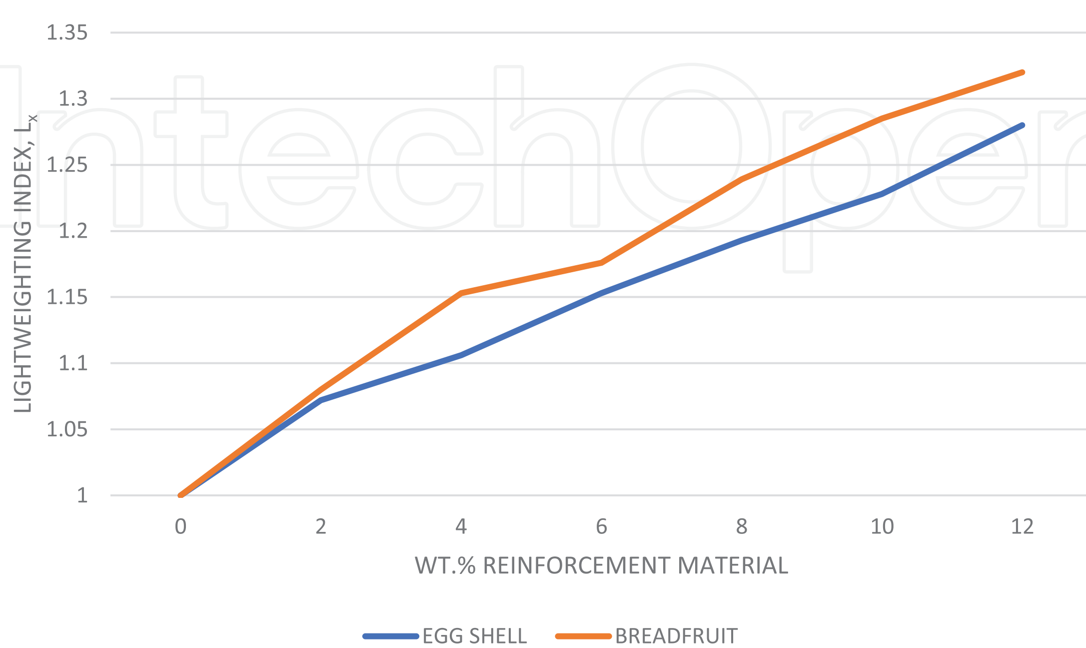

Figure 5.
Lightweighting index for two biodegradable green reinforcements

Property	Desirable change in property wrt reference metal matrix	Limiting condition
Density, ρ	Decrease	$\rho_c/\rho_m < 1$
Tensile strength, σ	Increase	$\sigma_c/\sigma_m > 1$
Hardness, H	Increase	$H_c/H_m > 1$
Impact energy, E	Increase	$E_c/E_m > 1$
Wear rate, W	Decrease	$W_c/W_m < 1$
Percent elongation, e	Increase	$e_c/e_m > 1$
Creep rate, c_r	Decrease	$c_{rc}/c_{rm} < 1$
Corrosion rate, K	Decrease	$K_c/K_m < 1$
Melting temperature, T	Increase	$T_c/T_m > 1$

Table 6.
Desirable changes of properties of composites for IC engines.

performance of various wt.% compositions for a particular reinforcement. We limit this analysis to the physical and mechanical properties of density, ρ, tensile strength σ, hardness H, impact energy E, percent elongation e, creep rate c_r, wear rate W, corrosion rate K and melting point T as may be applicable for IC engine parts.

Table 6 shows the desirable changes required of the composites with respect to the use of type of reinforcement and/or as the percentage weight of reinforcement increases.

From **Table 6**, the reinforcement performance index, P_x of the reinforcing material is maximized if

$$P_x = \frac{\frac{\sigma_c}{\sigma_m} \cdot \frac{H_c}{H_m} \cdot \frac{E_c}{E_m} \cdot \frac{e_c}{e_m} \cdot \frac{T_c}{T_m}}{\frac{\rho_c}{\rho_m} \cdot \frac{W_c}{W_m} \cdot \frac{K_c}{K_m} \cdot \frac{c_{rc}}{c_{rm}}} \tag{10}$$

If any property value is unavailable, that property ratio is set equal to 1 in Eq. (10).

Table 7 shows the computations of reinforcement performance index, P_x for breadfruit seed hull ash (BSHA) [33] and egg shell ash (ESA) [44] which do not have wear rate, elongation, creep rate, corrosion rate and melting point values. The table shows that the breadfruit seed hull ash has a higher performance index than the egg shell ash reinforcement.

3.12 The future of green materials as lightweighting reinforcement materials

There is a bright future for green materials as reinforcement materials for AMMCs as shown in **Table 1** for the following reasons:

i. As waste materials, they have the potential of being sources of low-cost reinforcements for AMMCs, as shown in the cost analysis in Section 3.9.

ii. Their lightweigthing potential is enormous because of their low densities compared to the aluminum metal matrix.

Reinforcement	Wt.%	ρ, g/cm³	ρ/ρ_m	σ, MPa	σ/σ_m	H, HRB	H/H_m	E, J	E/E_m	P_x
Breadfruit Seed hull Ash (BSHA)	0 (ref. metal matrix)	2.775	1.0000	172.5	1.0000	65	1.0000	12.6	1.0000	1.0000
	2	2.755	0.9928	185	1.0725	68	1.046	12	0.9523	1.0761
	4	2.735	0.9856	196	1.1362	72.5	1.115	11.2	0.8889	1.1426
	6	2.715	0.9784	198.5	1.1507	77.25	1.188	10.85	0.8611	1.2031
	8	2.675	0.9640	206	1.1942	81.25	1.25	10.4	0.8254	1.2781
	10	2.635	0.9495	210.5	1.2203	82.5	1.269	10.25	0.8135	1.3268
	12	2.620	0.9441	215	1.2464	85	1.308	10.15	0.8056	1.3911
	Average performance index, P_{xa}									**1.0597**
Egg shell ash (ESA)	0	2.775	1.000	98	1.000	58.5	1.000	14.5	1.000	1.0000
	2	2.675	0.964	101.25	1.033	62.5	1.068	12.6	0.869	0.9945
	4	2.65	0.955	103.5	1.056	64.5	1.103	12	0.828	1.0099
	6	2.615	0.942	106.5	1.087	67.5	1.154	11.8	0.814	1.0839
	8	2.6	0.937	109.5	1.117	68.5	1.171	9.8	0.676	0.9437
	10	2.56	0.923	111	1.133	69	1.179	9.6	0.662	0.9581
	12	2.5	0.901	113	1.153	74	1.265	8.3	0.572	0.9260
	Average performance index, P_{xa}									**0.9880**

Table 7.
Computation of reinforcement performance index, P_x for breadfruit seed hull ash (BSHA) [33] and egg shell ash (ESA) [44].

iii. Their relatively simple processing methods offer greater potential for use as AMMC reinforcement.

The following gaps exist for further research.

i. Carefully carried out experiments to determine the lightweighting effectiveness of these green reinforcing materials with respect to each other.

ii. Comparable tests on use of straight untreated particles, uncarbonized and carbonized ashed particles to determine the cost-effectiveness of these reinforcing particle modes.

4. Conclusion

This chapter has discussed the possibility of using biodegradable green materials as reinforcements for aluminum metal matrix composites. The following conclusions are drawn:

i. There is a wide range of biodegradable green materials that could be used as reinforcement materials for the lightweighting of aluminum alloys.

ii. The significant reduction in weight from use of these biodegradable green reinforcement materials depends on their smaller densities compared to the metal matrix.

iii. As waste materials, they provide a potential cheap source for reinforcing materials for AMMCs. The cost analysis shows that their cost per ton could be 15% of the cost of alumina and as low as 2.5% of cost of silicon carbide.

iv. Their use in composites gives lower densities, higher strength, and higher hardness over the reference metal matrix. However, their use decreases the impact strength of the composites.

v. Their strength values show that they can be used to make engine parts.

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A. Appendix

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S/No	Green material	Ref	Work done	Results	Lightweighting parameter		
					Specific strength, $\sigma/\rho (N/mm^2)$		Lightweighting index, L_x, $\|\sigma\| = \|[\sigma_c/\rho_c]/[\sigma_m/\rho_m]\|$
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
1	Bagasse	[18]	A general review of reinforced AMMCs with little mention of published works on use of bagasse as reinforcement.	A feeble conclusion that bagasse can be used as reinforcement for AMMCs			
		[19]	Sugarcane Bagasse Ash from the co-generator boiler (SCBAB) of a Cuban sugar mill, was used as reinforcement for AMMC fabricated by employing powder metallurgy technique	The comparative study of the Al-SCBAB composite with respect to the reference metal matrix showed an increment in the hardness of the SCRAB reinforced AMMC over the reference matrix			
		[20]	The aging behavior for Al-Cu-Mg/Bagasse ash particulate composites with 2-10 wt% bagasse ash particles produced by double stir-casting method was investigated. The aging behavior of the solution and age-hardened reinforced composite was determined by use of hardness values and microstructural analysis	The reinforced composite exhibited an accelerated hardening response compared to the reference metal matrix			
		[21]	Fly ash and bagasse were used as reinforcement of Eutectic Al-Si alloy LM6 containing 10.58% Si to produce composites by liquid casting. Brinell hardness and ultimate tensile strength were determined	The result showed that 10 wt% fly ash +10 wt % bagasse ash can be used as reinforcement in aluminum composites especially for engine part			
		[22]	The properties of composites produced from an aluminum alloy Al-7%Si as matrix and two agro wastes Rice Husk Ash (RHA) and Bagasse Ash (BA) as reinforcement were compared	The results showed that BA had a better composite density lowering ability than RHA. However, the results show somewhat better improvement in mechanical properties with RHA addition	57.54	68.08	1.18
		[23]	Al6061 was reinforced with 4 wt.%, 8 wt.% and 12 wt.% bagasse ash to produce aluminum metal matrix composites. Microstructural and mechanical properties tests were carried out	The results showed that maximum tensile strength, minimum hardness, and maximum coefficient of friction occurred for 8 wt.% of bagasse ash content.			

S/No	Green material	Ref	Work done	Results	Lightweighting parameter		
					Specific strength, σ/ρ(N/mm^2)		Lightweighting index, L_x, |σ| = |[σ_c/ρ_c]/[σ_m/ρ_m]|
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
2	Bamboo leaf	[24]	Bamboo leaf ash (BLA) and alumina were used to reinforce Al-Mg-Si alloy matrix. The corrosion and wear behaviors of the resulting composites in 3.5% NaCl were investigated.	The corrosion resistance of the composites decreased with BLA addition. The composites at 2 and 3 wt.% of BLA showed superior wear resistance.			
		[25]	Bamboo leaf ash (BLA) and silicon carbide were used in various combined ratios to reinforce Al-Mg-Si alloy. Mechanical properties and corrosion behaviors of the composites were studied	The results indicated that all mechanical properties studied except fracture toughness decreased with increase in BLA content. Corrosion results were obtained for the composites in NaCl and H_2SO_4 media			
		[26]	Bamboo leaf ash (BLA) and alumina were used in various combined ratios to reinforce Al-Mg-Si alloy. Mechanical and microstructural properties of the composites were studied	The results indicated that all mechanical properties studied except fracture toughness decreased with increase in BLA content. The mechanical properties behavior were similar to that of silicon carbide/BLA reinforcement [6]. However, silicon carbide/BLA reinforcements tends to have a lower reduction on tensile strength than the alumina/BLA counterparts			
		[27]	Aluminum alloy AA6061 was reinforced with various combinations of silicon carbide and bamboo leaf ash (BLA), neem leaf ash (NLA) and tamarind leaf ash (TLA). Density and hardness measurements of the resulting composites were taken	The composite having only silicon carbide (1.5wt.%SiC) reinforcement had the highest density and highest hardness, while the composite with 0.75wt.%BLA and 0.75wt.%SiC had the least density and least hardness			
		[28]	This is an extension of Ref. [27] by one of the authors where more tests were carried out.	The results showed that BLA reinforcement (0.75wt.%BLA and 0.75wt.%SiC) had the highest tensile strength, highest hardness and least density and least wear. Some of these results are at variance with [29]	45.30	58.79	1.30

S/No	Green material	Ref	Work done	Results	Lightweighting parameter		
					Specific strength, $\sigma/\rho (N/mm^2)$		Lightweighting index, L_x, $\lvert\sigma\rvert = \lvert[\sigma_c/\rho_c]/[\sigma_m/\rho_m]\rvert$
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
3	Bone	[30]	Al6063 alloy was reinforced with alumina and chicken bone ash to produce five composite samples each having a total of 8 wt.% content. In each of the five compositions, bone ash was 2, 3, 4, 5 and 6 wt.% while alumina took up the balance in 8 wt.%. Machining tests were carried out on the composites to determine surface roughness	The results showed that the 2 wt.%Alumina and 6 wt.% chicken bone ash best surface roughness compared to the others			
		[31]	Al6063 alloy was reinforced with calcined cow bone (CB) particles and crushed periwinkle shell (PS) particles separately with 1, 2, 4, 6, 8 and 10 wt.% to produce six compositions each. They were used to make knee braces. Physical and mechanical tests were carried out on them.	The periwinkle shell reinforcement had the best mechanical properties and smaller density at all compositions compared to the cow bone. For the cow bone reinforcement, the density decreased and tensile strength increased as its percent content increased, while it maximum hardness occurred at 6 wt.%	47.62	51.57 (CB)	1.09
		[32]	This paper claims that aluminum 8081 alloy was reinforced with chicken bone particles.	The presentation of results was not clear. However, the authors claimed that “it was found that the Chicken Bone Ash contents were able to improve the Wear rate of aluminum metal matrix composite compared to the aluminum-8011”.			
4	Breadfruit seed hull	[33]	Al-Si-Fe alloy was reinforced with breadfruit seed hull ash in weight percentages of 0–12 in steps of 2 wt.% to produce composites. The mechanical and microstructural properties were determined	The results showed that density decreased, tensile strength and hardness as breadfruit content in composites increased	62.16	81.90	1.32

S/No	Green material	Ref	Work done	Results	Lightweighting parameter		
					Specific strength, σ/ρ(N/mm²)		Lightweighting index, L_x, |σ| = |[σ_c/ρ_c]/[σ_m/ρ_m]|
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
5	Coconut shell	[34]	Aluminum alloy 6063 was reinforced with coconut shell ash (CSA). The properties of the composites were measured, and the corrosion properties in 0.3 M H2SO4 and 3.5 wt% NaCl solutions were also determined	The results showed that density decreased, tensile strength and hardness increased as CSA content increased. Composites with 12 wt.% CSA had the least corrosion in both 0.3 M H_2SO_4 and 3.5 wt.% NaCl solutions	—	—	
		[35]	Coconut shell particles (CSP) of sizes 50, 75, 150, 212, and 300 μ were used to reinforce recycled waste aluminum cans at 5 wt.% and 10 wt.% to produce composites. The mechanical and wear properties were determined	The tensile strength and hardness increased and impact strength decreased as CSP content increased. As CSP contentment increases, the wear rate becomes significant at bearing load over 14.21 N	—	—	
		[36]	99.70% purity aluminum was reinforced with coconut shell ash (CSA) at 3 – 15 wt.% in steps of 3 wt.%. The microstructure and mechanical properties were determined	Hardness increased as CSA content increased, while maximum tensile strength occurred at 9 wt.% of CSA	—	—	
		[37]	Density, particle size, refractoriness, SEM, XRD, XRF and FTIR spectroscopic methods were used for the characterization of the coconut shell ash to determine its suitability as a reinforcement material in metal matrix composites.	From the microstructural analysis of the composites, the authors conclude: "The coconut shell ash can withstand a temperature of up to 1500oC with a density of 2.05 g/cm3. That means this ash can be used in production of light weight MMCs component with good thermal resistance"	—	—	
		[29]	Pure aluminum was reinforced with 5wt.%SiC for three sample compositions of 3 wt.%, 5 wt.% and 10 wt.% coconut shell ash (CSA). The composites were tested for density, hardness, tensile strength and impact energy.	Density and impact strength decreased, while hardness and tensile strength increased with CSA content.	19.64	69.44	3.54
		[38]	99.3% purity aluminum was reinforced with finely ground coconut shell particles in amounts of 2 wt.% to 10 wt.% in steps of 2 wt.%. Microstructural and mechanical property studies were carried out.	Tensile strength and hardness increased while density and impact energy decreased as coconut shell particle content increased.	38.89	81.82	2.10

S/No	Green material	Ref	Work done	Results	Lightweighting parameter		
					Specific strength, $\sigma/\rho(N/mm^2)$		Lightweighting index, L_x, $\lvert\sigma\rvert = \lvert[\sigma_c/\rho_c]/[\sigma_m/\rho_m]\rvert$
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
		[39]	Paper claims that Al1100 was reinforced with 15% coconut shell ash to produce composites for machining to determine wear characteristics using Taguchi experimental design approach.	The relevant result was that the coconut shell ash reinforced composite had higher values of tensile strength and hardness above the reference alloy Al1100			
		[40]	Waste aluminum cans alloy was reinforced with coconut shell ash (CSA) (150 μm) and graphite (150 μm) particles. All five composition samples had 2 wt.% graphite while CSA content was 0, 2, 4, 6 and 8 wt.%. Microstructural, physical and mechanical tests were carried out on the produced composites	The results showed that density and impact strength decreased, while tensile strength and hardness increased as CSA content increased. Graphite increased/decreased the properties of the aluminum alloy, such that addition of CSA gave greater increases/decreases	10.98	22.87	2.08
6	Corncob	[41]	Aluminum alloy 8011 was reinforced separately with cow horn and corncob with contents from 5 wt.% - 20 wt.% in steps of 5 wt.% to produce aluminum metal matrix composites. Microstructural and mechanical tests were carried out	Maximum tensile strength and maximum elongation occurred at 15 wt.%. Hardness decreased as corncob content increased			
		[42]	Al-Mg-Si alloy matrix was reinforced with various percentage weights of SiC and corncob ash to produce aluminum metal matrix composites. Microstructural and mechanical tests were carried out.	Density, hardness, elongation and tensile strength decreased and fracture toughness increased for composites as corncob content increased in the composites			
		[43]	Aluminum alloy 6063 was reinforced with corncob ash in weight percentages of 2.5% - 15% in steps of 2.5%. microstructural and mechanical property tests were carried out	The results showed that density, tensile stress, impact strength, and wear decreased; hardness increased as corncob ash content increased in the composites.			

S/No	Green material	Ref	Work done	Results	Lightweighting parameter		
					Specific strength, σ/ρ(N/mm^2)		Lightweighting index, L_x, $\lvert\sigma\rvert = \lvert[\sigma_c/\rho_c]/[\sigma_m/\rho_m]\rvert$
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
7	Cow horn	[41]	Aluminum alloy 8011 was reinforced separately with cow horn and corncob with contents from 5 wt.% - 20 wt.% in steps of 5 wt.% to produce aluminum metal matrix composites. Microstructural and mechanical tests were carried out	Tensile strength increased and elongation decreased as cow horn content increased. Maximum hardness occurred at 15 wt.%			
8	Egg shell	[44]	Eggshell particles (ES) (uncarbonized and carbonized) were used to reinforce Al–Cu–Mg (A2009 alloy) to produce composites. A total of 2–12 wt.% ES particles were added in steps of 2 wt.%. Microstructural and mechanical properties were studied	For both carbonized and uncarbonized egg shell particles, density and impact energy decreased, tensile strength and hardness increased for increase in egg shell particles in composites. For strength and hardness the carbonized values were higher than the uncarbonized; while for density and impact energy, the carbonized had lower values.	35.50	45.20 (carbonized) 41.36 (uncarbonized)	1.27 (carbonized) 1.17 (uncarbonized)
		[45]	Al6061 was reinforced with eggshell uncarbonized powder from 2 wt.% - 10 wt.% in steps of 2 wt.%. microstructural and mechanical properties tests were carried out	Density of composites decreased as eggshell powder content increased. For both tensile strength and hardness, their maximum values occurred at 4 wt.% of eggshell powder	37.65	45.34	1.20
		[46]	AA2014 aluminum alloy was reinforced with carbonized and uncarbonized eggshell particles. Calcium carbonate was also used as reinforcement separately. Microstructural and mechanical properties tests were carried out	Tensile strength, hardness and fatigue strength increased as eggshell content increased up to 12.5 wt.% in AA2014 for both carbonized and uncarbonized reinforced composites. Toughness, ductility and corrosion rate decreased as eggshell increased up to 12.5 wt.% for both carbonized and uncarbonized reinforced composites.	—	—	

S/No	Green material	Ref	Work done	Results	Lightweighting parameter		
					Specific strength, $\sigma/\rho (N/mm^2)$		Lightweighting index, L_x, $\|\sigma\| = \|[\sigma_c/\rho_c]/[\sigma_m/\rho_m]\|$
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
		[47]	Eggshell particles (carbonized and uncarbonized), SiC particles,, and $CaCO_3$ powder were used to reinforce AA2014 aluminum alloy separately. Test properties were carried out on the composites produced.	By addition of SiC particles up to 10 wt.% and waste eggshell particles up to 12.5 wt.%, the tensile strength, hardness, and fatigue strength increased. Toughness and ductility decreased by the addition of SiC and eggshell particles. Corrosion rate decreased by the addition of SiC particle up to 7.5 wt.% and eggshell particles up to 12.5 wt.%. Hardness and heat-treatable properties are improved after the addition of SiC reinforcement particles as compared to eggshell particles			
		[48]	Uncarbonized eggshell particle was used to reinforce AA2014 aluminum alloy. Property tests were carried out on the derived composites. Process parameters of the electromagnetic stir casting process used were varied to find their influence on the properties of AA201/uncarbonized eggshell particles	Reinforcement parameters of preheat temperature, stirring current, stirring time, matrix pouring temperature, and reinforcement weight percentage affected the tensile strength of the composites. The maximum tensile strength of 287.194 MPa was found for reinforcement preheat temperature 537.87 °C, stirring current 12 A, stirring time 179.9 sec, matrix pouring temperature 726.8 °C, and reinforcement weight percentage of 12.46.			
		[49]	Al6061 powder was reinforced with 5 wt%, 10 wt.% and 15 wt.% of eggshell powder and composites were produced by powder metallurgy technique. Microstructural, physical and mechanical properties test were carried out.	Hardness increased, while density and electrical conductivity decreased as eggshell content increased in the composites			

S/No	Green material	Ref	Work done	Results	Lightweighting parameter: Specific strength, $\sigma/\rho (N/mm^2)$ — Ref. metal, σ_m/ρ_m	Lightweighting parameter: Specific strength, $\sigma/\rho (N/mm^2)$ — Best composite sample, σ_c/ρ_c	Lightweighting index, L_x, $\lvert\sigma\rvert = \lvert[\sigma_c/\rho_c]/[\sigma_m/\rho_m]\rvert$
9	Groundnut shell	[50]	Zn-27Al alloy was reinforced with SiC and groundnut shell ash. Corrosion, microstructural and mechanical property tests were carried out on the derived composites	Hardness and ultimate tensile strength of the hybrid composites decreased with increase in GSA content; while the fracture toughness of the hybrid composites increased with GSA content increase. In 3.5% NaCl solution, the composites were resistant to corrosion, while in 0.3 M H2SO4 solution, the composites were not as resistant to corrosion			
		[51]	Al6063 aluminum alloy was reinforced with groundnut shell ash in weight percents of 3, 6, 9, and 12 wt.%. Microstructural and mechanical property tests were carried out on the derived composites	As groundnut shell ash increased, tensile strength increased on toa maximum at 9 wt.% of reinforcement, hardness and compressive strength increased, while percent elongation and impact energy decreased			
		[52]	Al-Mg-Si aluminum alloy was reinforced with silicon carbide and groundnut shell ash to produce composites. Corrosion studies were carried out on the composites	The composites were resistant to corrosion in 3.5% NaCl solution, but more susceptible to corrosion in 0.3 M H2SO4 solution.			
		[53]	Al-Mg-Si aluminum alloy was reinforced with silicon carbide and groundnut shell ash to produce composites. Microstructural, mechanical and fracture property studies were carried out	Hardness and tensile strength increased with increasing GSA content but the strength and hardness dropped slightly with an increase in GSA content. Fracture toughness improved with increase in GSA content.			
10	Lemon Grass	[54]	Aluminum alloy Al6061 was reinforced with 3 wt.%, 5 wt.% and 7 wt.% lemon grass ash. Microstructural and mechanical properties of the derived composites were determined	It was reported that the there was linear increase of tensile strength and hardness with increase in lemon grass ash content			

S/No	Green material	Ref	Work done	Results	Lightweighting parameter		
					Specific strength, $\sigma/\rho (N/mm^2)$		Lightweighting index, L_x, $\lvert\sigma\rvert = \lvert[\sigma_c/\rho_c]/[\sigma_m/\rho_m]\rvert$
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
11	Maize Stalk	[55]	Al-Si-Mg alloy was reinforced with maize stalk ash at weight percentages of 2, 4, 6, 8 and 10%. Microstructural and mechanical properties of composites were determined				
12	Mango Seed Shell	[56]	Al-Si-Mg alloy was reinforced with mango seed shell particle at contents of 5 wt.%, 10 wt.%, 15 wt.% and 20 wt.%. Microstructural, wear and some mechanical property tests were carried out on the derived composites	Maximum hardness and maximum impact energy of 43.2 HV and 2.44 J respectively were obtained at 15 wt.% mango seed shell content. Also, at 15 wt.%, wear resistance improved on that of the reference metal matrix			
		[57]	Essentially same work as reference [56] except that the optimum 15 wt.% mango seed shell composite was used to produce a motorcycle hub	The production of the motorcycle hub with the 15 wt.% mango seed shell particles was successful			
		[58]	Taguchi experimental design technique was used to optimize the production parameters of Al-Si-Mg alloy reinforced with mango seed shell ash	Optimal wear rate of the mango seed shell ash reinforced-reinforced Al–Si–Mg composite was found to be 0.001517 $mm^3/N/m$ at stirring time, processing temperature, MSSA content, and particle size of 60 s, 720°C, 20%, and 25 μm respectively.			
13	Marula	[59]	Al-Mg-Si alloy was reinforced with carbonized marula seed cake in percent weights from 0–14% in steps of 2%. It was used for the production of brake pads. Physical and mechanical properties of the composites were carried out	The results showed that tensile strength and hardness increased while the density, percent elongation and impact energy decreased as the carbonized marula seed cake content increased			

S/No	Green material	Ref	Work done	Results	Lightweighting parameter: Specific strength, σ/ρ (N/mm^2)		Lightweighting parameter: Lightweighting index, L_x, $\lvert\sigma\rvert = \lvert[\sigma_c/\rho_c]/[\sigma_m/\rho_m]\rvert$
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
14	Neem Leaf	[60]	Al6061 T6 alloy was reinforced with three reinforcements: 20%SiC,!0%SiC +10%Fly Ash, and 10%SiC +10% Neem leaf Ash to produce three metal composites. Machine lever was produced with the composite	The tests showed that the neem leaf ash reinforcement produced the best property values of highest hardness, highest tensile strength and least wear.			
		[28]	This is an extension of Ref [27] by one of the authors where more tests were carried out.	The composite with 0.75wt.%NLA/0.75wt.% SiC reinforcement had the intermediate tensile strength, intermediate yield strength, intermediate elongation and intermediate wear values. The bamboo leaf ash had the best performance			
		[27]	Aluminum alloy AA6061 was reinforced with various combinations of silicon carbide and bamboo leaf ash (BLA), neem leaf ash INLA) and tamarind leaf ash (TLA). Density and hardness measurements of the resulting composites were taken	The composite having only silicon carbide (1.5wt.%SiC) reinforcement had the highest density and highest hardness, while the composite with 0.75 wt.% neem leaf ash and 0.75wt.%SiC had intermediate values for density and hardness			
15	Palm Kernel Shell (PKS)	[61]	Aluminum alloy 6063 was reinforced with varying weight percentage of 212 µm palm kernel shell (PKS) particles (2.5%, 5%, 7.5%, 10%, 12.5% and 15%). Microstructural, chemical and physical property tests were carried out on the composites produced	Density of composites decreased as PKS content increased while the porosity increased though within acceptable values			
		[62]	Disused engine block aluminum was reinforced with PKS ash particles in weight percentages of 5, 10 and 15. One half of PKS ash was treated with 1 M NaOH, while the other half remained untreated, thus, giving three sample composition each for the treated and untreated. Microstructural, physical and mechanical property tests were carried out on the composites	The mechanical property test results did not follow any discernable pattern, apart from impact energy for treated PKS compositions which showed a trend of increasing impact energy as PKS content increased.			

S/No	Green material	Ref	Work done	Results	Lightweighting parameter		
					Specific strength, σ/ρ(N/mm^2)		Lightweighting index, L_x, $\lvert\sigma\rvert = \lvert[\sigma_c/\rho_c]/[\sigma_m/\rho_m]\rvert$
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
		[63]	Aluminum alloy A356 was reinforced with PKS nanoparticles at weight percentages of 1, 2, 3, and 4. Microstructural, physical and mechanical properties were determined.	The results showed improvements of 30.47%, 41.91%, 49.52%, 40.90% and 65.09% on hardness values, tensile, yield strength, % elongation and impact energy at 4 wt% PKS over reference metal matrix.	40.38	66.75	1.65
		[64]	Aliminum AA6063 was reinforced with different mass fractions of palm kernel shell (PKS) particles (0, 2.5, 5, 7.5, 10, 12.5 & 15 wt %). Microstructural and wear tests were carried out on the composites produced	Better wear properties were obtained by the 10 wt% PKS reinforcement.			
		[65]	Zn-Al alloy was reinforced with 5 wt% SiC added with 0.2%, 0.4%, 0.6%, 0.8% and 1.0 wt % PKS ash particles. Microstructural and mechanical properties were determined.	The results showed that tensile strength and hardness of composites increased as percent weight of PKS ash increased in the composites			
		[66]	Commercially pure aluminum was reinforced with combined PKS and periwinkle shell (PS) particles with the optimum percent weights of PKS and PS determined by central composite design (CCD) of response surface methodology (RSM)	The fabricated composite had significantly improved properties over the commercially pure aluminum	27.31	36.21	1.33
		[5]	Same conditions as Ref. [66] but used to produce an engine block for a brush cutter	The test results of the produced engine block showed that the composite could be used for manufacture of engine parts	27.31	36.21	1.33
16	Palm Sprout Shell	[67]/[68]	[67] reported that [68] reinforced aluminum alloy with palm sprout shell ash in weight fractions of 1%,2%, 3%. Stir casting was used to produce the composites. (The reference could not be accessed)	It was stated by [67] that a maximum hardness of 100BHN was obtained for 3% weight fraction of palm sprout shell ash			

S/No	Green material	Ref	Work done	Results	Lightweighting parameter		
					Specific strength, $\sigma/\rho(N/mm^2)$		Lightweighting index, L_x, $\lvert\sigma\rvert = \lvert[\sigma_c/\rho_c]/[\sigma_m/\rho_m]\rvert$
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
17	Periwinkle Shell (PS)	[69]	Aluminum 6063 was reinforced with periwinkle shell particle sizes of 75 μm and 150 μm at weight percentages 1, 5, 10 and 15. The mechanical properties and microstructures of the composites were determined	The mechanical results do not present a discernable pattern of variation except for 75 μm particle composites for tensile strength and hardness where these values increase with reinforcement content			
		[70]	Similar to [71] except for determination of density	Similar results to [5] except that density results follow a discernable pattern. Density of composites decreased as reinforcement content increased, and that 150 μm PS particles had less density than corresponding composite densities of 75 μm as the latter had greater porosities.			
		[72]	Al-3.7%Cu-1.4%Mg was reinforced with periwinkle shell ash of weight percentages of 0–30% in steps 5%. The derived composites were tested for microstructure, and physical and mechanical properties	The results of the mechanical properties tests showed that, the addition of periwinkle ash increased the hardness, decreased the density and also decreased the impact energy of the composites produced for all additions. The tensile strength increased from 153.75 N/mm2 at 0 wt% to 202.45 N/mm2at 25 wt% PS.			
		[5]	Same as for PKS				
		[66]	Same as for PKS				
		[31]	Al6063 alloy was reinforced with calcined cow bone (CB) particles and crushed periwinkle shell (PS) particles separately with 1, 2, 4, 6, 8 and 10 wt.% to produce six compositions each. They were used to make knee braces. Physical and mechanical tests were carried out on them.	For both CB and PS reinforcements, density decreased, tensile strength and hardness increased compared to the reference alloy as percent reinforcement increased. PS reinforced composites had superior property values than CB	47.62	54.17 (PS)	1.14

S/No	Green material	Ref	Work done	Results	Lightweighting parameter		
					Specific strength, σ/ρ (N/mm^2)		Lightweighting index, L_x, $\lvert\sigma\rvert = \lvert[\sigma_c/\rho_c]/[\sigma_m/\rho_m]\rvert$
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
18	Rice Husk	[71]	Reviews the works done in using rice husk as a reinforcement in AMMCs	The review concludes that with appropriate processing method and choice of process parameters, use of carbonized rice husk could further enhance the mechanical properties and widen the scope of usage in automotive applications			
		[21]	The properties of composites produced from an aluminum alloyAl-7%Si as matrix and two agro wastes Rice Husk Ash (RHA) and Bagasse Ash (BA) as reinforcement were compared	The results showed that BA had a better composite density lowering ability than RHA. However, the results show somewhat better improvement in mechanical properties with RHA addition			
		[73]	Aluminum alloy, A356.2 was reinforced with 2 wt.%, 4 wt.% and 8 wt.% of rice husk ash (RHA) particles. Microstructural and mechanical tests were carried out on the derived composites	Results showed that tensile strength and harness increased while percent elongation decreased as reinforcement content increased in the composite			
		[74]	Aluminum alloy A356.2 was reinforced with RHA in percent weights of 4, 6 and 8%, and composites were made by vortex casting. Microstructural, physical and mechanical tests were carried out on the composites	Results showed that composites' tensile strength and hardness increased while density of decreased as RHA content increased	100.54	121.40	1.21
		[75]	Al-Mg-Si alloy was reinforced with RHA and SiC mixed in weight ratios 0:1, 1:3, 1:1, 3:1, and 1:0. They were utilized to prepare 5, 7.5 and 10 wt% of the reinforcing phase using two-step stir casting method. Mechanical properties were investigated	The results showed a general increase in tensile strength, specific strength and hardness, and genera decrease in density, impact toughness and ductility with increase in weight percent of RHA/SiC. The composites with composition 25% RHA: 75% SiC offers comparable specific strength values with the SiC single reinforced grades of the composite.	$\simeq$ 38	$\simeq$ 60	1.58

S/No	Green material	Ref	Work done	Results	Lightweighting parameter		
					Specific strength, $\sigma/\rho(N/mm^2)$		Lightweighting index, L_x, $\|\sigma\| = \|[\sigma_c/\rho_c]/[\sigma_m/\rho_m]\|$
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
		[76]	Al-Mg-Si alloy was reinforced with RHA and SiC mixed in weight ratios 0:1, 1:3, 1:1, 3:1, and 1:0. They were utilized to prepare 5, 7.5 and 10 wt% of the reinforcing phase using two-step stir casting method. Corrosion and wear behavior were investigated.	The results showed that in general, hybrid reinforcement of RHA and SiC resulted in improved corrosion resistance of the composites in 3.5% NaCl solution. The coefficient of friction/wear resistance of the hybrid composites were comparable to that of the Al–Mg–Si alloy matrix reinforced with only SiC.			
		[77]	Al–Mg–Si alloy matrix was reinforced with rice husk ash (RHA) and alumina. Alumina added with 2, 3, and 4 wt.% RHA were utilized to prepare 10 wt.% of the reinforcing phase. Corrosion and wear behavior of the composites were investigated	The corrosion resistance of the hybrid composites in 3.5% NaCl solution was less than that of the single reinforced Al–Mg–Si/10 wt.% Al2O3 composite. The corrosion rates increased with increase in wt.% RHA. The coefficient of friction/wear rate of the composites increased with increase in RHA wt.%.			
		[78]	Waste aluminum cans were reinforced rice husk ash particles of 150, 300 and 600 μm in weight percentages of 5, 10 and 15. Physical, mechanical and microstructural properties were investigated	The results shows that density decreases with increase percent weight of RHA, and suggest that for same percent weight of RHA, density decreases as RHA particles reduce in size. Other results are: tensile strength and hardness increase; and impact strength decrease with reduction in RHA particle size.	51.93	70.88	1.36
		[79]	A6061 aluminum alloy was reinforced with silicon carbide and rice husk ash for each composite made at 8 wt.% for each. The ratios of RHA and SiC in the composite were 1:4, 2:3 and 0:1 in the 8 wt.%. The microstructure, density, porosity and mechanical properties of the composites were determined	The results showed that the less dense Al/RHA/SiC hybrid composites have estimated percent porosity levels as low as <2.86% porosity.			

S/No	Green material	Ref	Work done	Results	Lightweighting parameter		
					Specific strength, σ/ρ (N/mm^2)		Lightweighting index, L_x, $\lvert\sigma\rvert = \lvert[\sigma_c/\rho_c]/[\sigma_m/\rho_m]\rvert$
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
		[80]	The paper states that pure aluminum was reinforced with constant 5 wt.% of rice husk ash and 2 wt.%, 4 wt.% and 6 wt.% of silicon carbide to produce hybrid composites. Microstructural, harness and strength tests were carried out	The results showed that as percent weight of silicon carbide increased, the hardness increased, while the compressive strength reached a maximum value at 4 wt.% of SiC			
		[22]	The properties of composites produced from an aluminum alloyAl-7%Si as matrix and two agro wastes Rice Husk Ash (RHA) and Bagasse Ash (BA) as reinforcement were compared	The results showed that BA had a better composite density lowering ability than RHA. However, the results show somewhat better improvement in mechanical properties with RHA addition			
		[81]	86.75Al alloy obtained from meting automobile parts, roofing sheet, can, etc. was reinforced with rice husk ash of content 0 vol.% - 30 vol. % in steps of 5 vol.% to produce composite samples. Physical and mechanical tests were carried out	The results showed that density decreased as RHA content increased, maximum tensile strength, maximum impact strength, maximum hardness occurred at 10 vol.%, 10 vol.% and 25 vol.% of RHA content respectively	57.54	65.34	1.14
		[82]	AluminumA356.2 alloy was hybrid reinforced with 4wt.%rice husk ash (RHA) + 6 wt.% fly ash (FA), 5wt.%RHA + 5wt.%FA and 6 wt.% RHA + 4wt.%FA to produce composites. Mechanical tests were carried out on the composites	The results showed that hardness, tensile strength, compressive strength and impact strength occurred for 6 wt.%RHA + 4wt.%FA, while elongation decreased somewhat as RHA content increased			
		[83]	Aluminum AlSi10Mg alloy was reinforced with RHA in percent weights 3, 6, 9 and 12 to produce composites. They were subjected to microstructural and mechanical tests	The results showed that tensile strength, compressive strength and harness increased while percent elongation decreased as RHA content increased			
		[84]	Eutectic Al-Si alloy LM6 was reinforced separately with RHA and FA. However, the percent weights of the reinforcements were not given. Mechanical property and machining tests were carried out.	The results showed that FA reinforced composite samples had better mechanical properties than the RHA. It was also shown that the FA composite gave lower cutting force and better surface finish			

S/No	Green material	Ref	Work done	Results	Lightweighting parameter		
					Specific strength, $\sigma/\rho (N/mm^2)$		Lightweighting index, L_x, $\lvert\sigma\rvert = \lvert[\sigma_c/\rho_c]/[\sigma_m/\rho_m]\rvert$
					Ref. metal, σ_m/ρ_m	Best composite sample, σ_c/ρ_c	
19	Snail shell	[85]	Aluminum alloy obtained from discarded pistons and roofing sheets was reinforced with snail shell particles of percent weight s from 16 to 48 wt.%. Microstructural and mechanical tests were carried out on the derived composites.	The results showed that, at 48 wt.% and 600 μm particle size, the tensile strength and hardness are maximized to 236 MPa and 48.3 HRF respectively compared to the tensile strength of 92.4 MPa and hardness of 29.2 HRF for the unalloyed samples.			
20	Tamarind leaf	[27]	Aluminum alloy AA6061 was reinforced with various combinations of silicon carbide and bamboo leaf ash (BLA), neem leaf ash INLA) and tamarind leaf ash (TLA). Density and hardness measurements of the resulting composites were taken	The composite having only silicon carbide (1.5wt.%SiC) reinforcement had the highest density and highest hardness, while the composite with 0.75 wt.% tamarind leaf ash and 0.75wt.%SiC had the highest density and least porosity			
		[28]	This is an extension of Ref [27] by one of the authors where more tests were carried out.	The composite with 0.75wt.%TLA/0.75wt.% SiC reinforcement generally had performance values next after NLA. BLA had the best performance values			

Table A1.
Summary of work done in using green materials as reinforcement of AMMCs.

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Author details

Akaehomen O. Akii Ibhadode
Department of Production Engineering, University of Benin, Benin City, Nigeria

*Address all correspondence to: ibhadode@uniben.edu

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