A review of ceramic/bio-based hybrid reinforced aluminium matrix composites

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Abstract: The quest for light and durable materials which can withstand harsh conditions of modern advanced applications in many fields such as aviation, automobile, sport, and so on, has been scientifically sought for. Studies in the last few decades have found aluminium metal composites (AMCs) reinforced with bio-based fibres of diverse origins as a suitable advanced material because of improved physical and mechanical properties that are obtainable. Such reinforcements may be single (usage of one reinforcement) or hybridized (more than one reinforcement) with synthesized particulate materials; however, they impart better physico-mechanical and wear behavior on the aluminium alloy matrix. Thus, this review examines some of these composites produced by stir-casting procedures and their properties currently trending in materials research circles. It has been established that by varying parameters such as stirring speed/time and reinforcement types and composition, the use of stir casting process is a viable method to produce AMCs with good physical properties, mechanical properties, and wear behavior. AMCs are eminently useful in the production of parts for the automotive, aerospace and aviation industries.

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PUBLIC INTEREST STATEMENT
Development of light and durable materials for applications in automobile, aerospace industries and other industries have been the major focus of numerous researchers over the past two decades. Aluminium metal composites have been produced through the introduction of ceramic reinforcements into the aluminium matrix. In recent years, agro/industrial wastes have been introduced as partial reinforcement materials which are mixed at various weight percentages with the ceramic reinforcements. The aluminium metal composites produced from the usage of the ceramic reinforcements and the hybrid reinforcements of the ceramic and agro/industrial waste have been found to have better physical and mechanical properties than the pure aluminium or its alloys. This study reviewed the physical, mechanical and wear properties of aluminium metal composites produced through the stir casting process. The areas needing more studies have been highlighted and further studies should be done on these areas.
1. Introduction

A material system with the composition of a suitable and arranged combination of two or more constituents can be termed composite. The constituents in a composite product have an interface that is different in both the form and chemical composition which allow for separation. Composite constituents are insoluble in each other (Kala, Mer, & Kumar, 2014; Prasad, Shoba, & Ramanaiah, 2014; Smith & Hashemi, 2008). The classification of a composite can be determined based on the chemical nature of the matrix phase. The classifications include; ceramic matrix composites (CMCs), polymer matrix composites (PMCs), and metal matrix composites (MMCs) (Kala et al., 2014). Over the last two decades, the MMCs have become advanced materials to be reckoned with, especially in sectors like the automobile and aerospace, owing to their physical and mechanical characteristics that can be altered through variation of the reinforcements in the matrix (Allison & Cole, 1993; Baradeswaran, 2011; Madhusudan, Sarcar, & Rao, 2016; Narula, Allison, Bauer, & Gandhi, 1996; Vamsi Krishna & Xavior, 2014). The requirement of most modern technologies is based on materials with different and unusual combinations with improved properties than conventional materials (Mehdi, Kumar, Mahmood, & Saini, 2014). According to Deuis, Subramanian, and Yellup (1996) and Christman, Needleman, and Suresh (1989), when MMCs are compared to matrix alloys, a substantial rise in mechanical strength and toughness are discovered. Therefore, MMCs can withstand tensile and compressive stresses. This is possible through transference and applied force distribution from the ductile matrix to the phase of the reinforcement (Deuis et al., 1996).

Composite materials involve both the base metal (matrix) and the inclusions (reinforcement). More so, the combination of the matrix ductility and reinforcement strength helps to retain the desirable properties of MMCs (Kurumlu et al., 2012). Based on good corrosion resisting properties, oxidation properties, and so on; matrix made of materials like iron, aluminium, copper, titanium, lead, magnesium, silver, tin, nickel, zinc, etc., can be selected. However, aluminium (Al), magnesium (Mg), and titanium (Ti) are the widely used matrix materials (Taya & Arsenault, 1989). This is due to their good resistance to corrosion, low density and exceptional mechanical characteristics. Researchers and scientists have largely focused developmental efforts on Al and its alloys. For aluminium metal composites (AMCs), pure Al or Al-alloy is the base metal (matrix) while the reinforcement materials that have been used by many researchers include ceramics (Alumina (Al$_2$O$_3$)), Silicon carbide (SiC), Boron carbide (B$_4$C), Silica (SiO$_2$), Aluminium nitride (Al-N) and so on), industrial wastes (red mud and fly ash), and agro-waste (rice husk ash, corn cob ash, coconut shell ash, and so on). Some of their sources, as displayed in Figure 1, are from waste materials (Bodunrin, Alaneme, & Chown, 2015; Gireesh, Prasad, Ramji, & Vinay, 2018; Mahendra & Radha Krishna, 2010; Prasad & Krishna, 2011; Prasad et al., 2014). According to Smith and Hashemi (2008), AMCs have been found useful in functional and structural applications such as automobile parts (See Figure 2). This is owing to the mechanical properties variation which can be dependent on the reinforcement proportion and chemical composition of the Al matrix. However, in terms of usage, the relative costs of production coupled with the cost of reinforcement materials significantly place AMCs at disadvantage especially with the use of squeeze casting, plasma spraying, powder metallurgy (PM), spray atomization and co-deposition, and so on. Recently, instead of using one reinforcing material (single reinforcement like SiC only), the combinations of reinforcing materials (like combining SiC and Al$_2$O$_3$, SiC and B$_4$C) have been in use in which one reinforcement material complements the other such that new hybrid composites are developed with improved features and performance (Alaneme, Adewale, & Olubambi, 2014; Dolata & Wieczorek, 2007; Singh & Chauwan, 2016). One of the methods of AMCs production is through stir casting. The stir casting process is relatively cost-effective and can be easily utilized for producing composites. This study presents the overview of physical properties, mechanical properties and wear characteristics of AMCs developed via the stir casting method.
2. Stir casting

By using stir casting, the reinforcing material particles can be dispersed in the Al melt through mechanical stirring. However, in the stir casting process, reinforcing particles are segregated because of particles settling during solidification (Smith & Hashemi, 2008). Therefore, the final solid particle distribution relies upon the stirring strength, particle wetting condition, relative density, and solidification rate. The mechanical stirrer geometry, stirrer position in the molten metal, temperature of the melt, and added reinforcement particles determine the spreading of the particles in the melt (Girot, Albingre, Quenisset, & Naslain, 1987; Harnby, Edward, & Nienow, 1985; Sahu & Sahu, 2018). It is a low-cost process for AMC fabrication and can produce composites with about 30% volume fraction of reinforcement (Mavhungu, Akinlabi, Onitiri, & Varachia, 2017). Moreover, the stir casting process is simple, effective and easily adaptable. It is easier to control the matrix structure through the use of different stirrer blades and cooling times (Parswajinan, Vijaya Ramnath, Abishek, Niharishsagar, & Sridhar, 2018).

Double stir casting, also referred to as two-step mixing, is a newly developed casting process. It has been employed by some researchers (Alaneme et al., 2014; Alaneme & Sanusi, 2015;...
Prasad et al., 2014). The process involves heating matrix metal (aluminium) to a temperature above its liquidus state. Afterward, when the melt is allowed to cool, a semi-solid state is reached. This is the state when the temperature of the melt is between liquid and solid states. During the semi-solid state, preheated reinforcement materials are incorporated. At elevated temperature, the slurry has been turned into the liquid state which is thoroughly mixed by a mechanical stirrer. The layer of gas surrounding the surface of the particle surface is broken, thereby hampering the wetting of the molten metal and reinforcement particle. This is the strength of this method. Therefore, a more uniform microstructure would be achievable by this process compared with conventional stirring (Kala et al., 2014). It is important to state that different mechanical stirring speeds have been utilized in the production of AMCs. These speeds include; 200 rpm (Rajesh & Santosh, 2017; Vamsi Krishna & Xavior, 2014); 300 rpm (Alaneme & Bodunrin, 2011); 400 rpm (Alaneme & Sanusi, 2015); 500 rpm (Jeykrishnan et al., 2016); and 600 rpm (Pooernesh, Harish, & Aithal, 2016; Prasad et al., 2014) and so on. The speed utilized in stirring the molten metal may affect the final microstructure of the produced AMCs. Raei, Panjepour, & Meratian (2016) reported that the greater the mixing speed and mixing time, the better and excellent would be the mechanical properties of the AMCs obtained. Hence, the addition of the reinforcing materials is homogeneously dispersed throughout the microstructure. A simple diagrammatic representation of the stir casting process is displayed shown in Figure 3.

Other production methods of AMCs that have been used by various researchers include: squeeze casting, spray deposition, liquid infiltration, PM route, high energy ball milling, diffusion bonding, compo-casting among others (Cheng, Chen, Wu, & Wang, 2007; Mavhungu et al., 2017; Zakaria, 2014). Like stir casting, PM route can also find application in a wide range of shapes. However, this route has a limited application when considering producing large-size products. In making AMCs, stir casting method is the most utilized because other competing methods are relatively more expensive. Moreover, the stir casting method gives better quality (both physically and mechanically) of the products if parameters for processing such as mixing time, mixing speed, and so on; can be carefully monitored and optimized. This suggests that more research works are required to optimize the process parameters for stir casting methods. For even distribution of particles, the stirring speed, blade angle of the stirrer, the impeller diameter, the impeller position, mixing time, and the feed rate should be critically examined for more improved physical and mechanical properties of AMCs.
3. Properties of AMCs

3.1. Physico-mechanical properties

3.1.1. Density and porosity

Density and porosity measurements are the major physical tests that have been carried out on AMCs. Density is majorly determined using the principle of Archimedes. The obtained samples are usually weighed in air and another liquid (water) with known density (Prasad et al., 2014). It can be expressed mathematically using Equation (1):

\[ \rho_c = \frac{m}{m - m_1} \rho_w \]  

where \( \rho_c \) is the density of the composites (kg/m\(^3\)), \( m \) is mass of sample in air (kg), \( m_1 \) is mass of sample in distilled water (kg) and \( \rho_w \) is density of the distilled water (at 20°C which is 1000 kg/m\(^3\)).

Porosity can be controlled during casting processes but cannot be entirely evaded. To control the mechanical properties in AMCs, porosity volume fraction, size, and distribution in a cast product should be critically examined (Prasad et al., 2014). The determination and evaluation of the porosity in a composite can be achieved using Equation (2) (Prasad et al., 2014).

\[ \text{Porosity} = \frac{\rho_{th} - \rho_m}{\rho_{th}} \]  

where \( \rho_{th} \) is theoretical density (kg/m\(^3\)) and \( \rho_m \) is measured density (kg/m\(^3\)).

Theoretical density can be derived from rules of mixtures that can be formulated for hybrid composites.

Table 1 shows the variation of density and porosity with percentage reinforcement as obtained in some previous studies. Aluminium alloy 2024 (Al 2024) with weight percentages of SiC and fly ash (FA) was used in the study of Boopathi, Arulshri, & Iyandurai (2013). 1.5 wt. % of magnesium was added as a wetting agent. The density obtained for each composition is shown in Table 1. There was no record for porosity. In the work of Vamsi Krishna & Xavior (2014), aluminium alloy 6061 (Al 6061) was mixed with SiC at different weight percentages, and with a constant weight percentage of graphite. Through observation, the density for each weight percentage without graphite was higher than the composite with graphite. No data were obtained for porosity. The density increased for Al/18%Si/5%SiC when the 5%SiC was added to the Al alloy. However, the porosity value reduced when the reinforcing particle was added (Pooernesh et al., 2016). Al-Mg-Si was the matrix worked upon by Alaneme, Ademilua, and Bodunrin (2013) with weight percentage reinforcement of SiC and bamboo leaf ash (BLA). It was detected that the higher the BLA percentage, the lower the density. There was no consistent pattern for the porosity value based on the weight percentage used. Singh and Goyal (2016) reported a decrease in density when equal weight percentages of both SiC and B\(_4\)C reinforcement particles increase in Al (AA6082-T6) matrix. The rise in porosity values was influenced with the rise in the reinforcement particle weight percentage. Prasad et al. (2014) investigated the mechanical properties of AMCs using A356.2 Al alloy with reinforcing particles of rice husk ash (RHA) and SiC at different weight ratios. It was discovered that the increment of the reinforcing particles caused density reduction. It was also stated that the presence of reduced density of RHA particles influenced the density reduction of the AMCs. In other studies, by Singh and Chauwan (2016), Alaneme, Akintunde, Olubambi, and Adewale (2013), and Olugbenga and Akinwole (2010), it was discovered that light-weight reinforcement addition caused a reduction in hybrid composites’ density. In the studies conducted by Boopathi et al. (2013) and Rao, Rao, and Bhargava (2010), the densities of hybrid composites decrease with an increment of reinforcement materials such as SiC, FA and SiC-FA particles. Using reinforcement (RHA and Al\(_2\)O\(_3\)) particles, Alaneme et al. (2013) observed a reduction of...
up to 6% in the hybrid composites' density compared with ceramic reinforcement materials. An increment in the RHA particle caused a linear decrease in composite density. As reported by Alaneme et al. (2013), the presence of SiO$_2$ in RHA may be the cause of the reduction. Also, lower porosity levels can be obtained by using a stir casting fabrication process which symbolized that the fabrication process was reliable (Alaneme & Aluko, 2012; Kok, 2005). Generally, the volume fraction and reinforcing particle size and distribution play significant roles and should be monitored to bring porosity level to minimum (Prasad et al., 2014). Porosity is said to play a crucial role as it enhances the damping capacity of AMCs owing to the relative motion of the particulates of the reinforcements in areas that voids are present (Prasad & Shoba, 2016). Therefore, to reduce the porosity of AMCs using the stir casting method, some experimental parameters such as the matrix melting temperature, stirring time, mixing speed should be optimized. This will invariably increase the density of the AMCs produced when porosity is reduced.

| Composition | Density (kg/m$^3$) | Porosity | Reference |
|-------------|-------------------|----------|-----------|
| Al$_2$O$_3$/1.5%Mg | 2.6 |  | Boopathi et al., 2013 |
| Al$_2$O$_3$/5%SiC/1.5%Mg | 2.4 |  |  |
| Al$_2$O$_3$/10%SiC/1.5%Mg | 2.3 |  |  |
| Al$_2$O$_3$/5%FA/1.5%Mg | 2.4 |  |  |
| Al$_2$O$_3$/10%FA/1.5%Mg | 2.2 |  |  |
| Al$_2$O$_3$/5%SiC/5%FA/1.5%Mg | 2.2 |  |  |
| Al$_2$O$_3$/5%SiC/10%FA/1.5%Mg | 2.1 |  |  |
| Al$_2$O$_3$/10%SiC/5%FA/1.5%Mg | 2.1 |  |  |
| Al$_2$O$_3$/10%SiC/10%FA/1.5%Mg | 2 |  |  |
| Al$_6$O$_6$/15%SiC | 2.7 |  |  |
| Al$_6$O$_6$/15%SiC/Gr | 2.66 |  | Vamsi Krishna & Xavior, 2014 |
| Al$_6$O$_6$/10%SiC | 2.71 |  |  |
| Al$_6$O$_6$/10%SiC/Gr | 2.64 |  |  |
| Al$_6$O$_6$/15%SiC | 2.73 |  |  |
| Al$_6$O$_6$/15%SiC/Gr | 2.63 |  |  |
| Al/18%Si | 2.62 | 3.5 | Pooernesh et al., 2016 |
| Al/18%Si/5%SiC | 2.64 | 2 |  |
| Al-Mg-Si | 2.81 |  | Alaneme et al., 2013 |
| Al-Mg-Si/10%SiC | 2.74 | 1.14 |  |
| Al-Mg-Si/2%BLA/8%SiC | 2.69 | 0.9 |  |
| Al-Mg-Si/3%BLA/7%SiC | 2.66 | 1.24 |  |
| Al-Mg-Si/4%BLA/6%SiC | 2.64 | 1.06 |  |
| Al | 2.67 | 0.4 | Singh & Goyal, 2016 |
| Al/5% (SiC+B$_4$C) | 2.64 | 0.7 |  |
| Al/10% (SiC+B$_4$C) | 2.59 | 1.1 |  |
| Al/15% (SiC+B$_4$C) | 2.56 | 1.8 |  |
| Al/20% (SiC+B$_4$C) | 2.53 | 2.2 |  |

*FA-Fly Ash, Gr-Graphite, BLA- Bamboo Leaf Ash, SiC-Silicon carbide, Mg- Magnesium, B$_4$C- Boron carbide
3.1.2. Hardness

Hardness is a typical mechanical property assessment that is carried out on AMCs. It is normally carried out using hardness testing machine which can be Vicker’s hardness scale (Alaneme & Sanusi, 2015; Pooernesh et al., 2016) or Brinell’s hardness scale (Ikubanni, Adediran, Adeleke, Ajao, & Agboola, 2017) using American Society for Testing and Materials (ASTM) standard. Various hardness values of AMCs have been reported by several previous studies. The hardness values reported by Boopathi et al. (2013) are presented in Table 2. Different hardness values were obtained for different compositions; however, the composition of Al 2024/10%SiC/10%FA/1.5% Mg gave the highest hardness value which implied that it might lead to deformation when subjected to strain. It was reported that the rise in weight fraction of SiC, FA and their combinations, increase the hardness value. The utilization of FA particles as reinforcement was reported to cause significant improvement to the hardness value as well as the Al-matrix deformation. No consistent trend of hardness value was obtained for composites involved in the work of Parswajinan et al. (2018). Carbon nanotubes (CNTs) weight percentage was made constant (0.2%) while SiC weight percentage was varied from 2-4%. The work of Alaneme et al. (2013) presented that the addition of SiC and BLA increased the hardness. The reduction in the SiC weight percentage with the corresponding increment in BLA showed a reduction in hardness value. This implied that the more the BLA particles and the less the SiC particles, the lower the hardness value. The study of Singh and Goyal (2016) showed an increment in hardness value with increment in weight percentage of both SiC and B4C. It was stated that SiC and B4C are ceramic materials that improve the hardness properties of composites. As observed, the more the percentage weight of Titanium carbide (TiC) in Al-alloy 2219 (Al 2219), the better the hardness value (Harti, Prasad, Nagaral, & Rao, 2016). This was also revealed by Xavier & Suresh (2016) that increment of wet grinder stone dust (WSD) weight percentages increase the hardness value. Jeykrishnan et al. (2016) and Selvam, Smart, & Dinaharan (2013) also observed an increase in hardness when there was an increase in SiC, and SiC and FA reinforcing materials, respectively. Alaneme & Sanusi (2015) observed the general decrease in hardness when RHA weight ratio in composites increased. Also, hardness decreases when the graphite content increases in the composites. When compared to alumina, the hardness reduction when there was an increment in the RHA and graphite content was said to be based on lower hardness properties of both reinforcing materials (Escalera-Lozano, Gutierrez, Pech-Canul, & Pech-Canul, 2008). The hardness of aluminium (A356.2) alloy increases when hybrid reinforcements (RHA and SiC) were added. As observed by Prasad & Shoba (2016), the existence of relatively hard ceramic particulates might be accountable for the increase in the hardness. Hybrid AMCs reinforced with SiC and graphite were developed and their hardness values were reported by Suresha & Sridhara (2012). The study noted that the addition of SiC particulate improved the hardness, and the graphite addition decreases the hardness due to increment in porosity level. It was opined that the existence of ceramic particulates is helpful in improving composites’ hardness. More so, soft particulates presence caused a reduction in composites’ hardness value. Pooernesh et al. (2016) reported the hardness value between Al-18wt%Si and Al-18%Si-5%SiC. It was opined that the presence of SiC gave a better value of hardness for Al-18%Si-5%SiC over Al-18wt%Si. This was also evident in the work of Uvaraja & Natarajan (2012), where the presence of hybrid reinforcement improved the hardness value, as shown in Table 2. More so, as observed in the study of Rajesh & Santosh (2017), an increment in SiC present in the composite increased the hardness value. Copper addition into Al showed good resultant hardness effect. The increment in reinforcement concentrations was observed to enhance the hardness value in the homogenized condition when compared to the as-cast (Madhusudan et al., 2016). Aging time effect on the hardness values of reinforced and unreinforced A356.2 alloy was investigated by Prasad et al. (2014). The study observed that after the age treatment, an increase in AMCs hardness happened. Furthermore, it was reported that a lower age treatment, optimum hardness was obtained for hybrid AMCs as against Al-alloy with indications that the aging kinetics can be accelerated with the reinforcement addition into the Al-matrix owing to high dislocation density. Porosity affects the hardness of composites. A rise in the porosity of AMCs caused a decline of the hardness value. Therefore, the impact of particle size and volume fraction of reinforcing materials on the hardness of AMCs should be further investigated.
| Composition                                      | Hardness (BHN) | Reference          |
|-------------------------------------------------|----------------|--------------------|
| Al2024/1.5%Mg                                   | 80.00          | Boopathi et al., 2013 |
| Al2024/5%SiC/1.5%Mg                             | 85.00          |                    |
| Al2024/10%SiC/1.5%Mg                            | 87.00          |                    |
| Al2024/5%FA/1.5%Mg                             | 80.00          |                    |
| Al2024/10%FA/1.5%Mg                             | 83.00          |                    |
| Al2024/5%SiC/5%FA/1.5%Mg                        | 88.00          |                    |
| Al2024/5%SiC/10%FA/1.5%Mg                      | 90.00          |                    |
| Al2024/10%SiC/5%FA/1.5%Mg                      | 93.00          |                    |
| Al2024/10%SiC/10%FA/1.5%Mg                    | 95.00          |                    |
| Al/2%SiC                                       | 55.40          | Parswajinan et al., 2018 |
| Al/2%SiC/0.2%CNT                                | 55.20          |                    |
| Al/3%SiC/0.2%CNT                                | 47.50          |                    |
| Al/4%SiC/0.2%CNT                                | 54.90          |                    |
| Al/18%Si                                       | 96.25          | Pooernesh et al., 2016 |
| Al/18%Si/5%SiC                                  | 95.75          |                    |
| Al-Mg-Si                                        | 67.00          | Alaneme et al., 2013 |
| Al-Mg-Si/10%SiC                                 | 77.00          |                    |
| Al-Mg-Si/2%BLA/8%SiC                            | 74.00          |                    |
| Al-Mg-Si/3%BLA/7%SiC                            | 72.00          |                    |
| Al-Mg-Si/4%BLA/6%SiC                            | 67.00          |                    |
| Al                                              | 95.95          | Singh & Goyal, 2016 |
| Al/5%(SiC+B4C)                                  | 98.84          |                    |
| Al/10%(SiC+B4C)                                 | 103.96         |                    |
| Al/15%(SiC+B4C)                                 | 107.40         |                    |
| Al/20%(SiC+B4C)                                 | 105.80         |                    |
| Al2219                                          | 75.00          | Harti et al., 2016 |
| Al2219/2%TiC                                    | 85.00          |                    |
| Al2219/4%TiC                                    | 110.00         |                    |
| Al2219/6%TiC                                    | 145.00         |                    |
| Al6063                                         | 43.00          | Xavier & Suresh, 2016 |
| Al6063/10%WSD                                   | 63.00          |                    |
| Al6063/20%WSD                                   | 75.00          |                    |
| Al7075                                         | 67.00          | Uvaraja & Natarajan, 2012 |
| Al7075/3%B4C                                    | 77.00          |                    |
| Al7075/3%B4C/5%SiC                              | 82.00          |                    |
| Al7075/3%B4C/10%SiC                             | 85.00          |                    |
| Al7075/3%B4C/15%SiC                             | 88.00          |                    |
| A356.2                                         | 68.00          | Prasad et al., 2014 |
| A356.2/2%RHA/2%SiC                              | 74.00          |                    |
| A356.2/4%RHA/4%SiC                              | 83.00          |                    |
| A356.2/6%RHA/6%SiC                              | 96.00          |                    |
| A356.2/8%RHA/8%SiC                              | 104.00         |                    |

(Continued)
3.1.3. Tensile characteristics

The tensile test is one of the mechanical tests that are normally carried out on AMCs. It indicates how the product will react to forces under an applied load. Yield strength (YS), modulus of elasticity (MOE), ultimate tensile strength (UTS), elastic limit, elongation, and so on, can be determined from tensile experiments. YS, UTS, and percentage elongation of various AMCs have been reported by many researchers as discussed in this section. From Table 3, it was observed that the more the reinforcement in the matrix, the better the YS and UTS while the percentage elongation reduces (Boopathi et al., 2013; Su, Gao, Feng, & Lu, 2012; Singh & Goyal, 2016; Harti et al., 2016; Xavier & Suresh, 2016; Prasad et al., 2014). However, in the study by Alaneme et al. (2013), there were reductions in the YS, UTS, and percentage elongation when there was BLA increment and decrease in SiC particulates. As evaluated by Kamat, Hirth, and Mehrabin (1989), the YS and UTS of the Al2024/Al2O3 composite was observed to rise as the volume fraction of the reinforcement increases. Jeykrishnan et al. (2016) specified that the tensile strength of AMCs produced with different reinforcement volume fractions was greater than the as-cast Al alloy. The study highlighted that the volume fraction increment of the reinforcing particulates increased the ductility of the AMCs. This increment can be ascribed to plastic distortion occurrence within the matrix caused by the inclusion of the reinforcement particles. The weight fractions of reinforcement of Al/SiC and Al/SiC/Gr composites increased as the tensile strength increases. A higher tensile strength was achieved using hybrid reinforcements than single reinforcement (Vamsi Krishna & Xavior, 2014). As reported by Madhusudan et al. (2016), the strength of AMCs is been enhanced by reinforcement; however, the formability of the matrix reduces simultaneously. This could result in decreased strain. More so, the effect of copper content as reinforcement in aluminium was evaluated. An increase in reinforcement increased the strength until later reduction. It was opined that the decrease in the strength values might be as a result of agglomeration due to increased reinforcement contents (Madhusudan et al., 2016). Alaneme et al. (2013) investigated the impact of hybrid reinforcement of SiC and BLA on the mechanical properties of Al-Mg-Si alloy hybrid composite as well as the corrosion behaviour of the AMCs produced. From the study, the increment in the percentage weight of the BLA influenced the decrease observed in the YS and UTS values.

Prasad et al. (2014) observed that YS and UTS increased, and percentage elongation decreased. This can be attributed to the rise in percentage weight fraction of RHA and SiC (See Table 3). The higher the particle content, the lower the elongation based on YS and UTS increment. It was stated that the strengthening effect was mostly through the increment in dislocation density. This could have resulted from a mismatch that occurred through heat in the interaction of the matrix and reinforcement. However, in another study by Alaneme & Sanusi (2015), it was observed that there was no consistent trend obtainable for percentage elongation when RHA and graphite content were increased. The study conducted by Chen, Lwabuchi, Shimizu, Shin, & Mifune (1997) revealed that a strong phenomenon existed between the reinforcement and matrix interface. The reinforcement addition caused both the composite elastic modulus and strength to increase. In AMCs, the strengthening mechanisms have identified by Alaneme & Aluko (2012) are the direct strengthening and the indirect strengthening.

| Composition                  | YS (ksi) | UTS (ksi) | Elongation (%) |
|------------------------------|----------|-----------|----------------|
| Al 6061                      | 110.00   |           |                |
| Al 6061/5%SiC                | 140.00   |           |                |
| Al 6061/10%SiC               | 150.00   |           |                |
| Al 6061/15%SiC               | 175.00   |           |                |
| Al 6061                      | 38.00    |           |                |
| Al 6061/7.5%SiC/7.5%FA       | 50.00    |           |                |
| Al 6061/10%SiC/7.5%FA        | 59.00    |           |                |

*FA-Fly Ash, TiC- Titanium carbide, BLA- Bamboo Leaf Ash, SiC-Silicon carbide, Mg- Magnesium, B4C- Boron carbide, RHA- Rice husk ash, WSD-Wet grinder stone dust, CNT-Carbon Nano Tube*
Table 3. Different compositions of AMCs against tensile characteristics (YS, UTS and % elongation)

| Composition                  | YS (MPa) | UTS (MPa) | %Elongation | Reference                  |
|------------------------------|----------|-----------|-------------|-----------------------------|
| Al2024/1.5%Mg               | 220      | 236       | 19.40       | Boopathi et al., 2013       |
| Al2024/5%SiC/1.5%Mg         | 236      | 248       | 19.00       |                             |
| Al2024/10%SiC/1.5%Mg        | 257      | 265       | 18.20       |                             |
| Al2024/5%FA/1.5%Mg          | 233      | 245       | 16.30       |                             |
| Al2024/10%FA/1.5%Mg         | 252      | 263       | 15.80       |                             |
| Al2024/5%SiC/5%FA/1.5%Mg    | 262      | 276       | 14.40       |                             |
| Al2024/5%SiC/10%FA/1.5%Mg   | 269      | 278       | 13.80       |                             |
| Al2024/10%SiC/5%FA/1.5%Mg   | 275      | 285       | 12.80       |                             |
| Al2024/10%SiC/10%FA/1.5%Mg  | 287      | 293       | 11.90       |                             |
| Al 2024/0.5%Al2O3           | 140      | 197       | 1.00        |                             |
| Al 2024/1.0%Al2O3           | 150      | 210       | 0.90        |                             |
| Al 2024/1.5%Al2O3           | 148      | 205       | 0.60        |                             |
| Al 2024/2.0%Al2O3           | 146      | 200       | 0.50        |                             |
| Al/18%Si                    | -        | 99        | -           | Pooernesh et al., 2016      |
| Al/18%Si/5%SiC              | -        | 116       | -           |                             |
| Al/Mg-Si                    | -        | -         | -           | Alaneme et al., 2013       |
| Al-Mg-Si/10%SiC             | 118      | 155       | 23.0        |                             |
| Al-Mg-Si/2%BLA/8%SiC        | 110      | 146       | 16.0        |                             |
| Al-Mg-Si/3%BLA/7%SiC        | 98       | 138       | 14.0        |                             |
| Al-Mg-Si/4%BLA/6%SiC        | 90       | 125       | 12.0        |                             |
| Al/5%(SiC+B4C)              | -        | 318       | 8.38        | Singh & Goyal, 2016         |
| Al/10%(SiC+B4C)             | -        | 333       | 7.90        |                             |
| Al/15%(SiC+B4C)             | -        | 357       | 7.30        |                             |
| Al/20%(SiC+B4C)             | -        | 385       | 6.96        |                             |
| Al2219                      | 120      | 165       | -           | Harti et al., 2016          |
| Al2219/2%TiC                | 145      | 175       | -           |                             |
| Al2219/4%TiC                | 175      | 195       | -           |                             |
| Al2219/6%TiC                | 210      | 245       | -           |                             |
| Al6063                      | 67       | 131       | 13.00       | Xavier & Suresh, 2016       |
| Al6063/10%WSD               | 115      | 154       | 8.13        |                             |
| Al6063/20%WSD               | 133      | 165       | 6.10        |                             |

(Continued)
Stiffer and harder reinforcement’s inclusion in the soft matrix could result in direct strengthening (Chawla & Shen, 2001). Meanwhile, the high thermal mismatch which occurs between the metallic matrix and the embedded particulates during cooling and solidification could be responsible for indirect strengthening. Metallic matrix is said to have a higher thermal expansion coefficient, while the included particulates are said to have a lower coefficient of thermal expansion (Sudarshan & Surappa, 2008). Thus, temperature changes would cause thermal stresses in composites which could result in the formation of dislocations between the interface of the matrix and reinforcement. The level of strength improvement of composite is a function of the increment in dislocation density (Milan & Bowen, 2004). During microstructural examinations performed on various composite formulations, Harti et al. (2016) revealed that the bond strength between the reinforcing particles and the matrix improved the hardness and strengths of the composites. Solid interface bonding between the matrix and the reinforcing particles acts as an obstacle to dislocations in the microstructure (Mohankumar, Srinivas, Ramachandra, Mahendra, & Nagaral, 2015). Moreover, through plastic flow restriction created in the matrix via particle dispersion, the strength of the composite can be enhanced (Nagaral, Auradi, & Kori, 2015). The uniform distribution of reinforcements through stirring action might be liable for grain restructuring of Al matrix which translates to improvements YS and UTS.

Selvam et al. (2013) examined the tensile properties of SiC and FA reinforced hybrid composite. It was revealed that the tensile strength increased with a rise in the weight percent of the SiC. When compared to the unreinforced alloy, there was an increment in the YS and UTS as observed by Boopathi et al. (2013) from fabricated Al 2024 hybrid MMCs using SiC and FA as the reinforcing materials. Yar, Montazerianb, Abdizadeh, & Boharvandi (2009) developed AMCs using Al (A356.1) alloy which was reinforced with nanoparticles of magnesium oxide (MgO). It was revealed that the matrix alloy exhibited a lower compressive strength. In addition, YS and UTS of the AMC product, studied by Su, Gao, Feng, & Lu (2012) indicated superior strength than pure matrix alloy. This was further corroborated with the work of Sajjadi, Ebatpour, & Beygi (2011) which showed that the compressive strength of stir cast Al (A356)/Al₂O₃p composite rises with increment in Al₂O₃ weight percentage.

| Composition | YS (MPa) | UTS (MPa) | %Elongation | Reference               |
|-------------|----------|-----------|-------------|-------------------------|
| A356.2      | 168      | 263       | 7.35        | Prasad et al., 2014     |
| A356.2/2%RHA/2%SiC | 182  | 296       | 6.25        |                         |
| A356.2/4%RHA/4%SiC | 196  | 310       | 5.60        |                         |
| A356.2/6%RHA/6%SiC | 230  | 333       | 5.15        |                         |
| A356.2/8%RHA/8%SiC | 258  | 356       | 4.90        |                         |
| Al 6061     | -        | 90.12     | -           | Jeykrishnan et al., 2016|
| Al 6061/5%SiC | -   | 98.44     | -           |                         |
| Al 6061/10%SiC | -   | 119.34    | -           |                         |
| Al 6061/15%SiC | -   | 141.91    | -           |                         |
| Al 6061     | -        | 149.00    | 13.5        | Selvam, Selvam et al., 2013|
| Al 6061/7.5%SiC/7.5%FA | -  | 175.00    | 10.0        |                         |
| Al 6061/10%SiC/7.5%FA | -  | 220.00    | 5.5         |                         |

*FA-Fly Ash, TiC- Titanium carbide, BLA- Bamboo Leaf Ash, SiC-Silicon carbide, Mg- Magnesium, B₄C- Boron carbide, RHA- Rice husk ash, WSD-Wet grinder stone dust
3.2. Wear properties

Wear can be defined as a material removal process from a surface either mechanically and or chemically (Deuis et al., 1996). Owing to better wear resistance as well as a high specific strength, AMCs have been given intense attentions (Kala et al., 2014). Several investigations have been done on the wear behaviour of AMCs because of their numerous applications. These applications include bearing materials, brushes, contact strips, and so on (Kala et al., 2014). Alaneme & Sanusi (2015) investigated the wear behaviour of hybrid AMCs which was reinforced using Al₂O₃, graphite and RHA. It was reported from the study that the usage of B-series composites (containing 73.5–74.5% Al₂O₃, 25% RHA, and 0.5–1.5% graphite) was adjudged to be the best wear resistance composites. Generally, greater wear susceptibility was observed for composites without graphite compared to composites with graphite. Thus, the graphite inclusion helps in lowering the degree of wear through the provision of solid lubricating interface between the sample composite and the counter rubbing surface of the wear testing equipment (Ravindran, Manisekar, Narayanasamy, & Narayanasamy, 2013). However, a further graphite content increment reduced the wear resistance of the AMCs, and the increment in RHA content yielded a rise in the wear susceptibility of the AMCs.

Furthermore, the tribological behaviour of the Al-Mg-Si alloy matrix with RHA and SiC hybrid reinforcement was investigated by Alaneme et al. (2014). The authors deduced that the frictional coefficient of some hybrid composites obtained was comparable with those of single-reinforced composites. It was further stated that the addition of RHA to complement SiC reinforcing particles in the matrix, does not affect degrading the wear resistance properties of the AMCs. Moreover, some other hybrid composites of different percentage weight compositions indicated that RHA addition could boost the wear resistance of the AMCs. Hence, the Al alloy and the reinforcements used in this study exhibit great wear properties that have been found useful in industries. Al-Al₂O₃ wear resistance was enhanced when the reinforcement weight percentage increased up to 10 volume percentage (Al-Mosawi, Wexler, & Calka, 2017).

Wilson & Alpas (1996) reported that the ceramic particles (SiC and graphite) and Al₂O₃ inclusion into Al (A356) and Al (6061), respectively, improved the composite seizure resistance at a higher temperature when compared with pure alloy. SiC was adjudged to be more effective than Al₂O₃. At elevated temperature regimes, hybrid composites have improved wear resistance than the remaining two composites. The wear behaviour of a composite with Zirconium Silicate (ZrSiO₄) as reinforcement as examined by James & Annamalai (2017), revealed that the composite exhibited high wear resistance which was attributed to the addition of ZrSiO₄ in the metal matrix. Investigations using some parameters which are likely to influence the properties of abrasive wear like reinforcement size, sliding distance, reinforcement content, and abrasive grit size, were done to determine the wear behaviour of AMCs produced using Al 2024/Al₂O₃p by Kok (2006). The study showed that the wearing volume loss of the composite product was less compared to the pure alloy. Higher wear losses were recorded as the grit size and the sliding distance increased. However, as the reinforcement particle size and weight fraction increased, reduction in the volumetric wear losses were observed. In the study conducted by Das, Das, and Das (2009), Al₂O₃ and zircon sand were the reinforcing particles in an Al matrix. The abrasive wear behaviour of the composites obtained was examined. An inverse relationship was observed between the wear resistance and the particle size of the reinforcements. Hence, the higher the wear resistance, the lower is the particle size of the reinforcement. AMCs made using zircon sand as reinforcement showed an improved wear resistance than when Al₂O₃ was used as reinforcement. This was envisaged since zircon exhibits higher strength than alumina.

Using the stir casting method, there was a reduction in the wear losses of in situ Al-titanium diboride (Al-TiB₂) and Al-15 Vf% Cu-TiB₂ composites when the volume fraction of titanium diboride (TiB₂) increased (Tee, Lu, & Lai, 2000). A direct proportionality was observed between the sliding distance and wear loss. Hence, the increment in the sliding distance directly affects the wear loss. However, the metal removal rate of the AMC when compared with pure alloy gave a less wear rate. Using hybrid reinforcing particles of SiC and graphite, the dry sliding friction behaviour was
investigated by Suresha and Sridhara (2012). It was revealed that the most important factor that has a great impact on the friction coefficient of the hybrid composite was the force applied. The increment in force applied load and sliding distance resulted into an increment to the friction coefficient. Moreover, the mean coefficient of friction for the hybrid composite compared to pure alloy was low. The tribological characteristics of AMCs produced using dual (hybrid) reinforced materials (Zircon and SiC) showed that the hybrid AMC displayed a higher wear resistance compared to the single-reinforced composites and with pure alloy at both low or high loads (Kumar, Panwar, & Pandey, 2013). This implied that the dual particles of Zircon and SiC complemented each other. Rajesh & Santosh (2017) discovered that the wear rate increment was directly proportional to the load applied for all materials investigated in their study. This increasing load produced a heating effect which led to thermal softening and seizure which resulted in enhanced wear.

In general, no single wear behaviour mechanism is totally appropriate to describe the wear behaviour of materials. However, a fundamental and main mechanism to determine the rate of material removal is always available. Therefore, wear mechanism resulting from some underlining factors to the removal of material is very complex. Under any mode of wear, there is an increase in the wear complexity and prediction to be faced in any system (Dasgupta, 2012). Some of the factors that are responsible for metal removal resistance in AMCs include hardness, YS, UTS, lubrication, load, corrosion, surface finish, and many more. It is vital to state that the wear rate should be minimized through designing better wear-resistant materials because failure caused by wear can be catastrophic. However, it has been shown by various researchers that composites derived from hybrid reinforcements such as SiC, B₄C, and some agro and industrial wastes improved wear resistance in AMCs. It is important to note that the smaller the particle size in the matrix, the better the wear resistance. The reinforcement particles serve to protect the wearing of the matrix. Wear rate is said to improve the toughness of composites when they are subjected to age-hardening (Dasgupta, 2012). Most of the studies on AMCs did not put into consideration the age-hardening of the produced composites. To improve the wear rate of AMCs so that it would be used in aerospace, automobile or ship making industries, more studies should be conducted on age-hardening of composites by subjecting them to various possible metal removal mechanisms such as erosion, abrasion, adhesion, and many more. The influence of corrosion on the wear rate of AMCs, when subjected to some harsh environmental conditions, should be considered for further study.

4. Discussion
For various advanced applications in automobile and aerospace industries, hybrid composites made from Al or Al alloys with the additions of ceramic and agro/industrial waste reinforcements have been considered in this study. From Tables 1–3, the density and porosity, hardness, YS, UTS, and the percentage elongation for different reinforcement compositions were presented. In recent decades, ceramic reinforcements have been used in Al alloy to obtain better quality products that have found applications in engineering industries.

For environmental sustainability and greenhouse gas effect, agro-wastes and industrial wastes usage as reinforcement materials have been the research focuses of composite materials’ researchers, scientists, and engineers. These wastes have been in consideration as partial reinforcing materials replacement in the production of AMCs (Alaneme et al., 2013; Prasad et al., 2014; Singh & Chauwan, 2016). It is important to state that agro wastes are burnt experimentally into ashes. When the obtained ash is conditioned in a muffle furnace, silica contents, as well as lower elastic modulus, are obtained. Therefore, due to the silica contents and the lower elastic modulus present in agro-waste ash, the total replacement of ceramic reinforcements such as SiC, B₄C in aluminium matrix with agro/industrial wastes is not possible. However, they can be complementarily used along with ceramic reinforcements because they are eco-friendly; they have reasonably vital mechanical characteristics; they are bio-degradable; they are non-abrasive in nature (Singh & Chauwan, 2016). Hybrid composites development with the usage of these reinforcements have generally improved the physical properties of AMCs (See Table 1); and the mechanical properties (See Tables 2 and 3) have enabled AMCs to be applicable in automotive
and aerospace industries. Some applications of AMCs in automotive industries have been highlighted by Mavhungu et al. (2017) and Sahu and Sahu (2018) which include crankshaft main bearing, cylinder blocks, connecting rods, missile fins, satellite solar reflector, jet engine blade, and so on.

From the results of various studies, the mechanical properties improved for the hybrid composites when the reinforcement contents were increased. As earlier discussed, the increasing inclusion of reinforcing materials at a certain weight ratio and the reduction in a weight ratio of the matrix reduced the hybrid AMCs densities. Nevertheless, the strength to weight ratio is made better. This makes AMCs useful in automobile sectors due to the vital properties they possess such as lightweight, low-cost, and enhanced mechanical properties. More so, these agro-wastes and industrial wastes reinforcements are cheap to be obtained and require simple processing. In general, in the usage of agro-waste and industrial waste ash, the weight percentage of reinforcements should be optimized to obtain lighter, cheaper, and advanced materials for high performance which would be useful for engineering purposes.

5. Future work
Numerous studies, on AMCs with agro-wastes and industrial wastes as useful partial reinforcements in composites, have been conducted, and advancements are still on in this regard. The physical and mechanical properties of composites developed via liquid routes (stir casting method) have been considered in this study. The properties considered were enhanced with the inclusion of bio-based reinforcements. These improved properties made AMCs find applications in automobiles, aerospace, sports sectors, and so on. However, more studies should be carried out on the production of AMCs using other routes such as powder metallurgy, spray atomization, squeeze casting, and many more methods; and considering different process parameters. Moreover, there are little works of literature on the corrosion studies of AMCs. Hence, corrosion studies should be conducted for AMCs to be able to find more applications in harsh conditions such as in warm and cold seawater where they may likely find application as sacrificial anodes for ships’ haul.

6. Conclusion
The utilization of the stir casting method for hybrid MMC production, that will be incorporated with different desired properties, has been successfully reviewed. There has been a generally appreciable enhancement in the mechanical properties of Al and its alloys reinforced with ceramic and organic particles. It was confirmed that AMCs produced by stir casting process find applications in automotive industries. The density of Al alloy is always reduced when the addition of reinforcement materials is increased. Thus, an optimum volume fraction of reinforcement particles gave better density. Particle size should be monitored and stirring time should be optimized to reduce porosity in AMCs. Hardness values, as well as YS and UTS of AMCs, increase with hybrid reinforcement additives. Most especially, ceramic reinforcing particles increase hardness. However, graphite addition lowers hardness value and rate of wear through the provision of a solid lubricating layer. Generally, an increase in reinforcement particles increases the YS and UTS. The addition of reinforcement particles especially hybridized ones improves the resistance to wear when likened to the pure matrix. However, more studies should be done to investigate the tribological properties of hybridized reinforcement composite, especially of agro-waste. Furthermore, the parameters optimization process for AMC development via stir casting route should be looked into. Based on this review, AMCs possess good physicomechanical properties and wear/tribological properties that are useful for advanced applications in the automotive, aviation and industrial sectors.

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