

In-Situ Reinforcement of AA6063/Al2O3 Hybrid Composite: Comparative Wear and Hardness Evaluation of Manihot Esculenta and Green Plantago major Particulates

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Abstract

The AA6063 alloy, renowned for its effective resistance against corrosion and favourable mechanical properties, has limited applications within the automotive and aerospace sectors owing to its reduced hardness and wear properties. Manihot *esculenta* and Plantago *major* are essential food crops cultivated largely within sub-Saharan Africa. The peels of these food crops contribute to environmental pollution through indiscriminate disposal. This study aims to contribute to the current understanding exploring the potential use of the Manihot *esculenta* peel ash (MEPA) and Plantago *major* peel ash (PMPA) as innovative reinforcements for in-situ fabrication of AA6063/Al₂O₃ hybrid composites. Comparative assessments of the hardness behaviours and wear performances of MEP-based aluminium matrix composites (AMCs) and the PMP-based AMCs reveal MEP's superior impact, enhancing AA6063 matrix hardness to 107 BHN, in contrast to PMP's 86 BHN. MEP and PMP particulates as reinforcements notably improved AA6063 hardness by 328% and 244%, respectively. Incorporating the ashes of these solid wastes also enhanced the abrasion resistance of the fabricated AMCs. While the MEP ash particles performed better than the PMP ash particles in hardness and wear, natural ceramic agro waste reinforcements (MEPA and PMPA) provide an economical alternative to expensive artificial ceramic reinforcement (Al₂O₃). These findings highlight the potential of using MEPA and PMPA agro wastes as sustainable engineering solutions to reinforce AMCs for improved applications.

1. Introduction

The AA6063 alloy is renowned for its good mechanical properties and formability, mainly suited for aluminium (Al) extrusion [1]. Comprising elements such as Al, Magnesium (Mg), and Silicon (Si), this alloy forms an intermetallic compound (Mg₂Si) with good heat treatment properties facilitating easy weldability. The alloy is commonly used for applications such as door frames, roofs, window frames, etc., owing to its smooth surface finishing and good corrosion resistance. Despite these good properties, the AA6063 metal matrix is a medium-strength alloy with a Brinell hardness of 25 HB [2]. This relatively low hardness value and wear resistance of the AA6063 alloy further limits its use in the automobile and aerospace industries, making it unsuitable for high-strength applications, despite its lightweight and unique thermal properties. In a bid to improve its hardness and wear properties, researchers have considered the use of different reinforcements with varying results. For instance, the use of precipitation hardening by artificial ageing to improve wear resistance [3] and in-situ Mg₂Si reinforcement of Al-Si₁₂-Mg_(5,10,20) to enhance hardness properties and wear resistance [4] of the AA6063 matrix have been documented in the literature.

The quest for enhanced mechanical and tribological properties has continued to spur research interest in innovative methods for reinforcing Aluminium Matrix Composites (AMCs). Among these, the utilization of synthetic ceramic reinforcements (SCRs) like alumina (Al₂O₃) with density (3.9 g/cm³) greater than Al (2.7 g/cm³) holds the capability to enhance the hardness and wear properties of AMCs significantly. There are also documented reports of other SCRs like titanium carbide (TiC), silica (SiO₂), silicon carbide

(SiC), carbon nano-tubes (CNTs), graphite, and tungsten carbide (WC), that impact positively on the hardness and wear characteristics of AMCs [5–7]. Bodunrin et al. [8] further classified Al-reinforcements into agro waste, synthetic ceramic, and industrial waste particulates. Like the SCRs, the use of agro waste as reinforcements has also garnered research interests, aiming to repurpose engineering practices to ameliorate environmental pollution caused by the indiscriminate disposal of agricultural solid wastes. These solid wastes, known as natural ceramic reinforcements (NCRs), are employed in ash form and have been found to be relatively cost-effective owing to their abundance in nature [9] compared to SCRs [10, 11].

Furthermore, literature reports indicate favourable engineering properties, encompassing mechanical strength, wear resistance, corrosion resistance, and porosity, for NCRs [6]. NCRs exhibit high strength, improved hardness, and enhanced wear resistance as the load on the matrix is efficiently transferred onto these reinforcements. Examples of NCRs that have been utilized in production of AMCs include rice-husk ash (RHA) [12–14], coconut-shell ash (CSA) [15–18], palm-kernel shell ash (PKSA) [6, 19, 20], corn cob ash (CCA) [21], date palm seeds ash (DPSA) [22], bean pod ash (BPA) [23–26], groundnut shell ash (GSA) [27], plantain peel ash (PPA) [28, 29], bamboo leaf ash (BLA) [30, 31]. For example, when combined with alumina as reinforcements in Al-Mg-Si matrix, RHA was reported to produce lightweight composites [9]. AMCs reinforced with agro waste particulates have equally demonstrated enhanced hardness with increasing percent weight variation as reported for RHA/SiC [32], RHA/B₄C [33], RHA/Cu [13], CSA/Al₂O₃ [18], CSA [34], BPA [26], and DPSA with an optimum increase at 7.5 wt.% [22]. In contrast, a decrease in hardness has also been reported for AMCs with increasing weight ratio variations in NCRs/SCRs such as RHA/Al₂O₃ with about 10% decrease reported [9], CCA/SiC [21], BLA/Al₂O₃ with about 9% reduction for a 40% Al₂O₃ reduction [35], and GSA/SiC [27].

In-situ composites have multiple phases, with the reinforcing phase generated within the matrix during production. The in-situ processes can be used to fabricate reinforced composites with varying characteristics, such as ceramic or ductile phases and continuous or discontinuous morphologies [4]. In-situ AMC fabrication benefits from weight reduction, enhanced mechanical properties, and relatively low cost [36]. Poor wettability, agglomeration, and uneven distribution of reinforcement particulates contribute significantly to mechanical properties such as hardness in AMCs [28]. The use of Mg has been recommended to improve wettability [9], while production methods such as two-step stir casting have been found to ameliorate issues relating to agglomeration and non-uniform distribution of particulates [37]. Increasing the stirring time and speed in the double-step stir cast method has also been reported to significantly influence the hardness property of the AMC [7]. Commonly investigated Al alloys reinforced singly with either SCRs or NCRs or a hybrid of SCR-NCRs include AA2014 [38], A356 [39], LM13 [40], AA5083 [41], AA7075 [42], Al6061 [14, 18], AA2009 [26], ADC12 [33], and AA6063 [6, 41]. Studies involving the use of AA6063 have employed fabrication routes like ballistic impact [41] and the compo-casting method [6], with limited information on the use of a double stir-cast route, particularly for SCR-NCR hybrid reinforcement. While some studies have reported the use of *Plantago major* peel ash (PMPA) as

reinforcement in AMCs [28, 29], there is no report, to the best of the authors knowledge, on incorporating *Manihot esculenta* peel ash (MEPA) as a reinforcing element in fabrication of hybrid AMCs (HAMCs).

Manihot esculenta (ME) and *Plantago major* (PM) are agricultural products largely consumed across the globe in raw or processed forms. ME, also known as Cassava, is widely cultivated in Nigeria at ~ 60 million tonnes as at 2022 [43], surpassing global production by over 18% [44]. Conversely, PM, also known as Plantain, is predominantly cultivated in Uganda at ~ 10 million tonnes [43]. Globally, ME and PM are majorly produced in sub-Saharan Africa at ~ 208 million and ~ 30 million tonnes, respectively [43]. This regional prominence serves as motivation for selecting these crops in this study. Furthermore, these food crops have been associated with the indiscriminate disposal of solid wastes, contributing significantly to environmental pollution [45–47]. Repurposing these solid wastes for engineering applications offers an environmentally sustainable solution with socio-economic benefits for sub-Saharan Africa and helps reduce the considerable costs incurred in importing SCRs. This research effort aims to comparatively evaluate the impact of utilizing MEPA and PMPA as reinforcements in In-situ AA6063/ Al_2O_3 , focusing on hardness and wear performance. Additionally, the research will explore the potential of using NCRs from MEPA and PMPA as single reinforcements with AA6063 in the absence of Al_2O_3 to produce environmentally sustainable AMCs for strength-based and wear-resistant engineering applications. The two-step stir-casting procedure will be utilized in this study to guarantee the even dispersion and distribution of particulate reinforcements within the matrix.

2. Experimental Methodology

3.1 Processing

Material selection and preparation

Materials used for this study include ingots of AA6063, alumina powder of 26 μm particle size, ME peels, and PM peels. Spectra analysis was carried out on the AA6063 matrix, and the findings are presented in Table 1. The ME and PM peels were acquired from a regional commodity marketplace in Ede, Nigeria. The peels were incinerated separately inside a crucible and kept inside an oven for 24 h at 80 °C. The ashes were removed and conditioned inside an electric muffle furnace maintained at 650 °C for 180 mins to eliminate the carbonaceous constituents. Figure 1 shows the prepared powdered ash samples for MEPA and PMPA utilized in this research.

Table 1
Result of Spectra analysis for AA6063 alloy and its chemical composition

Elements	Al	Si	Fe	Ti	Mg	Mn	Cu	Zn	Cr	Pb	Others
Wt. ratio	98.50	0.48	0.18	0.02	0.52	0.04	0.05	0.05	0.01	0.01	0.02

Composite fabrication

The experiment was formulated to yield a 10% weight ratio reinforcement of SCR (alumina) and NCRs (MEPA and PMPA). Table 2 illustrates the rule of mixture applied in fabrication of the composites utilized in this research. The matrix was heated to about $1023.15\text{ K} \pm 20\text{ K}$ using a gas-fired charged crucible furnace to obtain a molten liquid, which was subsequently left to cool. Conversely, the SCR and NCRs were preheated simultaneously at 523.15 K to allow for easy distribution of the reinforcements within the alloy of the molten matrix. Adopting the double-stir casting methodology, the preheated reinforcement particulate and 0.001 weight fraction of Mg (for improving wettability) were added to the molten matrix and agitated for 10–15 minutes. The slurry of molten composite was heated to an elevated temperature of $1143.15\text{ K} \pm 20\text{ K}$ and agitated using a mechanical agitator ($300 \pm 50\text{ rpm}$) for about 15 min for sample homogeneity. Sand moulds prepared using a method described by Festus et al. [48, 49] were used to receive the molten mix for the casting process, forming composite ingots. The ingots were subsequently machined and cut into test pieces, as detailed in Table 2, to facilitate further experimental investigations. It is imperative to highlight that the hybrid composites of MEPA/ Al_2O_3 /AA6063 and PMPA/ Al_2O_3 /AA6063 were prepared independently, utilizing the same methodology for each. The as-cast HAMCs were hot-mounted and metallographically prepared by grinding and polishing the specimen surfaces.

Table 2
The weight percentage of (a) MEPA/ Al_2O_3 and (b) PMPA/ Al_2O_3 reinforcements.

(a)	Sample-ID	ALMA-0	MEPA-2	MEPA-4	MEPA-5	MEPA-6	MEPA-8	MEPA-10
	MEPA (wt.%)	0	2	4	5	6	8	10
	Al_2O_3 (wt.%)	10	8	6	5	4	2	0

(b)	Sample-ID	ALMA-0	PMPA-2	PMPA-4	PMPA-5	PMPA-6	PMPA-8	PMPA-10
	PMPA (wt.%)	0	2	4	5	6	8	10
	Al_2O_3 (wt.%)	10	8	6	5	4	2	0

3.2 Experimentation

Microstructure

The surface morphology of the MEPA and PMPA reinforcements was investigated with the aid of a TESCAN Vega 3xm Scanning Electron Microscopy (SEM) equipped incorporating an OXFORD Elemental Dispersive X-ray (EDX) device for identification of the elemental compositions. The SEM has a working distance of 15mm and magnification values of 1000x. The chemical constituents of the elemental oxides

were identified through X-ray Fluorescence (XRF) spectroscopy investigations conducted on the as-prepared powders.

Density

For each as-cast HAMC fabricated in this study, the theoretical and experimental (densities were determined using equations (1) and (2), respectively, per the ASTM D2734 standard [48]. A pycnometer was used to estimate the theoretical density of Al_2O_3 , MEPA, and PMPA powders. Experimental density was estimated by measuring the sample mass (m) in the air employing a high-precision digital weighing scale, while the volume (V) of the HAMCs was measured using the principle of flotation.

$$\rho_{th} = Wt_{AA6063} \times \rho_{AA6063} + Wt_{SCF} \times \rho_{SCF} + Wt_{NCF} \times \rho_{NCF}$$

1

$$\rho_{ex} = \frac{m}{V}$$

2

Hardness

The hardness investigations of the fabricated HAMCs were conducted per the ASTM E10-23 standard [49] using the Innovatest Falcon 500 hardness tester. The indenter was placed in contact with the composite specimen, and a test force (F_N) of 980.67 N was applied perpendicular to the surface for a dwell time of 10 sec. The size of the indenter's ball diameter (D) used was 10 mm, while the indentation diameter (d) was measured in perpendicular directions with a 20x microscope affixed to the Innovatest Falcon 500 hardness tester. The Brinell hardness number (HBW) of the as-cast HAMCs is estimated using Eq. (3). The average of three indentations was used to obtain the HBW of each as-cast HAMC sample.

$$HBW = \frac{(2 \times F_N)}{\pi D(D - \sqrt{D^2 - d^2})}$$

3

Wear

Using a pin-on-disc wear tester device, a arid wear test was conducted on the as-cast HAMCs per the ASTM G99 standard [52]. Each HAMC specimen's initial weight ($W_{INITIAL}$) was determined with a digital weighing scale having high-precision. The test specimen is positioned onto the sample holder, and a 10 N load (F_{LOAD}) applied. The test specimen was rotated under the load conditions for 20 cycles. The test specimen's final weight (W_{FINAL}) and the sliding distance ($D_{SLIDING}$) are measured. Using the experimental density of the test specimen, the volume of wear loss () and specific wear rate (K_S) are computed from equations (4) and (5) [50]. The wear coefficient (K) is estimated by taking the average hardness (H_C) of the corresponding composite into consideration and using Archard's wear equation given by Eq. (6) [51].

$$\Delta V_{LOSS} (mm^3) = (W_{INITIAL} - W_{FINAL})/\rho$$

4

$$K_S (mm^3/Nmm) = \Delta V_{LOSS}/(F_{LOAD} \times D_{SLIDING})$$

5

$$K (mm^3 BHN/Nmm) = (\Delta V_{LOSS} \times H_C)/(F_{LOAD} \times D_{SLIDING})$$

6

3. Result and discussion

3.1 Microstructural results

The structural features and elemental compositions of the as-prepared ash samples of MEPA and PMPA are shown in Fig. 2. SEM results for MEPA particles reveal a roundish-shaped surface with some longitudinal portions. For PMPA particles, the surfaces are angular in shape, and some portions are roundish. No defects or surface contours are observed on the MEPA and PMPA surface morphologies. This observation is significant as wettability is influenced to a large extent by the surface layer [52, 53]. The EDX spectra, on the other hand, reveals that MEPA particles contain significant wt.% of elements like oxygen (46%), silicon (21%), potassium (9%), aluminium (9%), calcium (5%), iron (5%). Trace amounts of Mg, Ti, phosphorus (P), and Sulphur (S) were also observed from the MEPA particles. This observation suggests that silica (SiO₂) is most likely to dominate in the MEPA particles, with the particles also containing substantial portions of Al₂O₃. For the PMPA particulates, EDX spectra show substantial wt.% portions of potassium (56%) and oxygen (38%) elements, with trace quantities of P, Mg, S, Si, and chlorine (Cl). Oxides of K₂O are likely to dominate in the PMPA surface. It has been reported that wettability and mechanical properties are significantly impacted by the nature of oxides on the surface layers [54–56].

XRF results showing the oxide compositions of the MEPA and PMPA ash samples and the as-received alumina powder are presented in Table 3. As earlier suggested from the EDX result, the MEPA particulates are dominated by oxides of SiO₂ at 44%, Al₂O₃ at 16%, K₂O at 13%, CaO at 12%, and Fe₂O at 8%. The XRF results for PMPA particulates correlate with the EDX elemental peaks observed in Fig. 2b as oxides of K₂O (81%) and CaO (5%) dominate. For the Al₂O₃ particulate, 99 mass% of alumina particles are observed. A closer look at Table 3 reveals that the first eight oxides are present in varying quantities in SCR and NCR particulates, suggesting that these oxides will largely impact the mechanical performance of the resulting HAMCs.

Table 3
XRF oxide results of (a) MEPA, (b) PMPA, and (c) Al₂O₃ particulates.

(a)	Component	Mass %	(b)	Component	Mass %	(c)	Component	Mass %
	<i>Al₂O₃</i>	<i>15.6892</i>		<i>Al₂O₃</i>	<i>0.2236</i>		<i>Al₂O₃</i>	<i>99.3814</i>
	<i>SiO₂</i>	<i>43.5902</i>		<i>SiO₂</i>	<i>2.5765</i>		<i>SiO₂</i>	<i>0.1738</i>
	<i>Na₂O</i>	<i>0.1045</i>		<i>Na₂O</i>	<i>0.0000</i>		<i>Na₂O</i>	<i>0.1846</i>
	<i>P₂O₅</i>	<i>1.4837</i>		<i>P₂O₅</i>	<i>3.8391</i>		<i>P₂O₅</i>	<i>0.0196</i>
	<i>Fe₂O₃</i>	<i>8.4605</i>		<i>Fe₂O₃</i>	<i>0.9395</i>		<i>Fe₂O₃</i>	<i>0.0597</i>
	<i>K₂O</i>	<i>12.5582</i>		<i>K₂O</i>	<i>80.8674</i>		<i>K₂O</i>	<i>0.0198</i>
	<i>SO₃</i>	<i>1.1055</i>		<i>SO₃</i>	<i>1.1628</i>		<i>SO₃</i>	<i>0.1045</i>
	<i>CaO</i>	<i>11.7339</i>		<i>CaO</i>	<i>5.0198</i>		<i>CaO</i>	<i>0.0460</i>
	MgO	1.1650		MgO	0.6994			
	TiO ₂	2.3477		MnO	0.2947			
	Co ₂ O ₃	0.0208		Cl	3.7937			
	MnO	0.5804		CuO	0.0209			
	Cl	0.3065		Rb ₂ O	0.3516			
	CuO	0.0347		Br	0.0350			
	NiO	0.0238		ZnO	0.1204			
	Cr ₂ O ₃	0.0644		SrO	0.0556			
	ZnO	0.0839						
	ZrO ₂	0.2423						
	SrO	0.1425						
	Rb ₂ O	0.0497						
	BaO	0.2127						

3.2 Density and void fraction results

Densities of Al₂O₃, MEPA, and PMPA measured using the Pycnometer are 3.9796 g/cm³, 2.6792 g/cm³, and 2.3821 g/cm³, respectively. Table 3 reveals that the denser oxides with the highest mass%, exert a dominant influence on the overall density of the reinforcement particulates. The measured powder

densities are consistent with their literature values within an uncertainty of 0.19%, 1.18%, and 1.37%, respectively, for Al_2O_3 , MEPA, and PMPA particles.

A graphical plot showing the variations in theoretical densities, experimental densities, and void fractions of the MEPA and PMPA particulates is presented in Fig. 4. Theoretical densities of the as-cast HAMCs are estimated through the rule of mixtures and the measured densities of the powder samples.

Comparatively, theoretical densities for MEPA/ Al_2O_3 /AA6063 HAMCs ranged from 2.69 to 2.78 g/cm^3 , while PMPA/ Al_2O_3 /AA6063 HAMCs varied from 2.66 to 2.78 g/cm^3 . Likewise, experimental densities of MEPA-HAMCs varied from 2.64 to 2.74 g/cm^3 , while that of PMPA-HAMCs ranged from 2.59 to 2.74 g/cm^3 . With increasing wt.% of NCRs (MEPA or PMPA) and decreasing SCR (Al_2O_3) particulates in the matrix (AA6063), a consistent decline in density values below that of the matrix was observed, confirming the production of lightweight HAMCs.

Void fractions for each of the wt.% variations for MEPA-HAMCs and PMPA-HAMCs were estimated as percent porosity and found to be within the acceptable 4% for cast aluminium composites [9]. However, void fractions are comparatively lower in MEPA/ Al_2O_3 /AA6063 HAMCs (< 2%) compared to PMPA/ Al_2O_3 /AA6063 HAMCs (> 2%). Void fractions in AMCs are associated with hetero-phases like reinforcements or precipitates, resulting in local deformation that affects the mechanical properties of the resulting AMCs [57–59].

3.3 Hardness performance

Figure 4 shows the graphical comparative performance of hardness tests conducted on the MEPA and PMPA-reinforced HAMCs. For MEPA HAMCs, the hardness of reinforced composites rises with ascending weight variation of MEPA and decreasing wt.% of Al_2O_3 particulates. Compared to the singly reinforced ALMA-0 (74.70 BHN), the singly reinforced MEPA-10 (107.47) showed a better hardness result at 22.62%. This can be linked to the combined density contributions of the oxides present in MEPA particles (Table 3a) and the reduced porosity (< 2%) observed in Fig. 3a. Even dispersion of reinforcements within the matrix reduces the interparticle distance [26] resulting in an increased density of crystal defects, due to the accumulation of dislocations within the composite. The elevated density of dislocations augments the surface area [60] of the MEPA particles, enhancing resistance to further material deformation while suppressing grain boundary effects [61]. This factor contributes significantly to the overall hardness observed with increasing MEPA wt.%.

Conversely, for PMPA-reinforced HAMCs fabricated in this study, hardness declines with a rise in wt.% of PMPA and a decrease in Al_2O_3 wt.%. Notably, the sharp increase observed in PMPA-2 (8 wt.% Al_2O_3 – 2 wt.% PMPA) compared to ALMA-0 (10 wt.% Al_2O_3 – 0 wt.% PMPA) was due to the combined densities of Al_2O_3 (3.98 g/cm^3) and K_2O (2.35 g/cm^3) of the reinforcements in the matrix. However, a reduction in hardness is observed as the wt.% of Al_2O_3 decreases and the wt.% of PMPA increases. This outcome is expected for two primary reasons: firstly, the K_2O density is significantly lesser to that of Al_2O_3 , and

secondly, Fig. 3b confirms a significant increase in porosity levels (> 2%) for PMPA particles compared to the MEPA particles. Porosity weakens the composite's structure by creating pores, preventing the formation of localized stress fields [62, 63]. This allows the material to undergo plastic deformation, resulting in decreased hardness. A closer examination of the hardness values reveals that the singly reinforced PMPA-10 (86.03 BHN) experiences a 1.84% decrease compared to the singly reinforced ALMA-0 (87.64 BHN). This further validates that crystal planes glide more smoothly when the dislocation densities are significantly reduced, adversely impacting the hardness of the HAMCs fabricated.

3.4 Wear assessment

The mass loss of MEPA and PMPA-reinforced AA6063/Al₂O₃ HAMCs before and after the conducted wear test, under a 10 N applied load, and 15 mm sliding distance is presented in Table 4. For the MEPA-HAMCs specimens, the mass loss ranged from 0.031 g to 0.090 g. The singly reinforced ALMA-0 recorded the highest wear loss at 0.090 g, and the singly reinforced MEPA-10 showed the lowest wear loss at 0.031 g. It was also observed that mass loss decreased with an increase in MEPA wt.% at 27.7% (MEPA-2), 1.1% (MEPA-4), 7.9% (MEPA-5), 25.8% (MEPA-6), 27.5% (MEPA-8), and 3.1% (MEPA-10), compared with ALMA-0. Volumetric loss ranged from 11.72 mm³ (MEPA-10) to 32.91 mm³ (ALMA-0). The MEPA-HAMCs experienced a gradual decline in volumetric loss with an increase in MEPA wt.%. The reduction in mass and volumetric losses are due to the impact of MEPA particle reinforcements on improved hardness of the fabricated HAMCs. Complex composites contribute to grain refinement due to increased density dislocations within the material [38]. Archard's equation postulates that the wear rate is inversely related to hardness [51, 64], thus validating the enhanced wear resistance observed. The singly reinforced MEPA-10 particle had the maximum hardness result (Fig. 4), thus, recording the least wear rate (Table 4). Wear resistance for MEPA was observed to increase with rising wt.% of MEPA to a maximum value of 1.28 mm/mm³, while specific wear rate and wear coefficient declined with reducing wt.% of MEPA particles (Fig. 5a).

The PMPA-based HAMC specimens exhibited a mass loss ranging from 0.029 g to 0.090 g. PMPA-2 had the lowest mass loss, with the mass loss increasing with increasing PMPA wt.%. Volumetric loss for the PMPA HAMC also varied from 10.808 mm³ to 32.906 mm³, with PMPA-2 recording the most negligible loss. Volumetric loss also increased with rising PMPA wt.%. The consistent rise in volumetric and mass loss accounts for elevation in the wear rate, as these losses impacts on the fabricated HAMCs hardness. The steady rise in wear rate observed in Table 4 for PMPA HAMCs is consistent with the decrease in hardness (Fig. 4). This finding is validated by the Archard's wear-hardness equation [51]. Wear resistance was lowest at the singly reinforced PMPA-10 HAMCs (5.39 mm/mm³) and highest at PMPA-2 (13.88 mm/mm³). Wear resistance of PMPA-10 was, however, 18.35% superior to that of ALMA-0, while decreasing with an increase in PMPA wt.%. The specific wear rate and wear coefficient increased with rising wt.% variation of PMPA particulates (Fig. 5b). This implies that more surface materials are removed from the HAMCs during sliding due to a consistent decline in hardness of the PMPA HAMCs. The void

fraction (> 2%) observed in the PMPA HAMCs (Fig. 3b) provided less wear resistance at the contact surface during the rubbing action between the pin and rotating disc.

Table 4
Effect of (a) MEPA and (b) PMPA weight variation on mass loss before and after wear.

Wt. %	Initial mass (g)		Final mass (g)		Mass loss (g)		Vol. loss (mm ³)		Wear rate (mm ³ /mm)	
	MEPA	PMPA	MEPA	PMPA	MEPA	PMPA	MEPA	PMPA	MEPA	PMPA
0-wt. %	6.33	6.33	6.24	6.24	0.090	0.090	32.906	32.906	2.194	2.194
2-wt. %	6.30	5.71	6.23	5.68	0.065	0.029	23.916	10.808	1.594	0.721
4-wt. %	5.95	5.00	5.88	4.96	0.064	0.042	23.843	15.771	1.590	1.051
5-wt. %	6.85	5.37	6.79	5.32	0.059	0.049	21.980	18.477	1.465	1.232
6-wt. %	6.20	4.83	6.16	4.78	0.044	0.053	16.347	20.189	1.090	1.346
8-wt. %	6.00	5.32	5.96	5.26	0.032	0.059	11.896	22.549	0.793	1.503
10-wt. %	6.81	5.63	6.78	5.56	0.031	0.072	11.719	27.805	0.781	1.854

Comparatively, the wear properties of MEPA-based HAMCs outperform those of PMPA-based HAMCs (Table 4 and Fig. 5). This superiority stems from the greater hardness and enhanced wear resistance exhibited by composites fabricated using MEPA, attributable to the oxide compositions present in MEPA particulates. In contrast, PMPA particles are predominantly composed of K₂O, which has a lower density than Al₂O₃. Consequently, composites fabricated with PMPA exhibit reduced hardness and wear resistance. Additionally, while the specific wear rate and wear coefficient reduced with increasing weight ratio for MEPA particulates, these wear properties show an opposite trend, increasing with the growing weight fraction for PMPA particles.

4. Conclusion

This study presents valuable comparative insights into using two solid agro wastes (MEPA and PMPA) for In-situ reinforcement of AA6063/Al₂O₃, focusing on their mechanical properties. Findings from the experimental investigation conducted are summarized as follows:

1. The MEPA particulates are characterized by a dominance of SiO₂, followed by substantial amounts of Al, K, Ca, and Fe oxides. K₂O and significant amounts of Ca, P, and Si oxides primarily influence

PMPA particulates.

2. The double-step stir cast technique, coupled with the absence of impurities in the as-prepared ash particulates (MEPA and PMPA), ensured uniform distribution and dispersion of reinforcement particulates within the AA6063 matrix, as seen from SEM analysis.
3. MEPA reinforced AA6063/Al₂O₃ HAMCs demonstrated an increase in hardness with rising MEPA wt.%, surpassing the hardness of the singly reinforced AA6063/Al₂O₃ AMC. Conversely, the hardness of PMPA/AA6063/Al₂O₃ reinforced HAMCs significantly reduced with increasing PMPA wt.%, with the singly reinforced PMPA/AA6063 recording the lowest hardness value.
4. MEPA and PMPA particulates, when used singly to reinforce the matrix, enhanced the hardness of AA6063 from 25 BHN to 107 BHN and 86 BHN, respectively, showcasing their potential as lightweight alternatives to SCR-based materials for Al-reinforcements.
5. Volumetric loss and wear rate in MEPA-based HACMs decreased with increasing MEPA wt.%. Conversely, the wear rate increased with increasing PMPA particles, aligning with the reduction in hardness reported for PMPA/AA6063/Al₂O₃ HAMCs. MEPA/AA6063/Al₂O₃ HAMCs demonstrated superior wear resistance compared to PMPA/AA6063/Al₂O₃ HAMCs.
6. The singly reinforced MEPA/AA6063 AMC show enhanced hardness and wear behaviour compared to the singly reinforced AA6063/Al₂O₃ and PMPA/AA6063 AMCs. MEPA particles, therefore, demonstrated potential as a cost-effective replacement for the relatively expensive Al₂O₃, offering sustainable engineering application for the *Manihot Esculenta* solid waste.

The comparative analysis concluded that the fabricated MEPA/AA6063/Al₂O₃ HAMCs have better mechanical properties than the PMPA/AA6063/Al₂O₃ HAMCs, with enhanced hardness and wear performance. This superiority is primarily attributed to the elemental compositions and oxides found in MEPA. Both solid agro wastes, MEPA and PMPA, emerge as promising materials of engineering interest for enhancing the hardness and wear performance of AA6063, suggesting their potential applications in the automotive and automobile industries.

Declarations

Competing/conflicting interests

The authors assert that no identifiable, competing personal or financial interests influenced the results reported in this paper.

Data availability

No data was used for the research work presented in this paper.

Author's contributions

Festus Ben: Conceptualization, Investigation, Writing of original draft, Methodology, Formal and Data analysis, Writing – reviewing and editing.

Peter A. Olubambi: Resources, Supervision, Project coordination, Writing – reviewing and editing

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Figures



Figure 1

Powdered ash samples of (a) MEPA and (b) PMPA used as reinforcements.

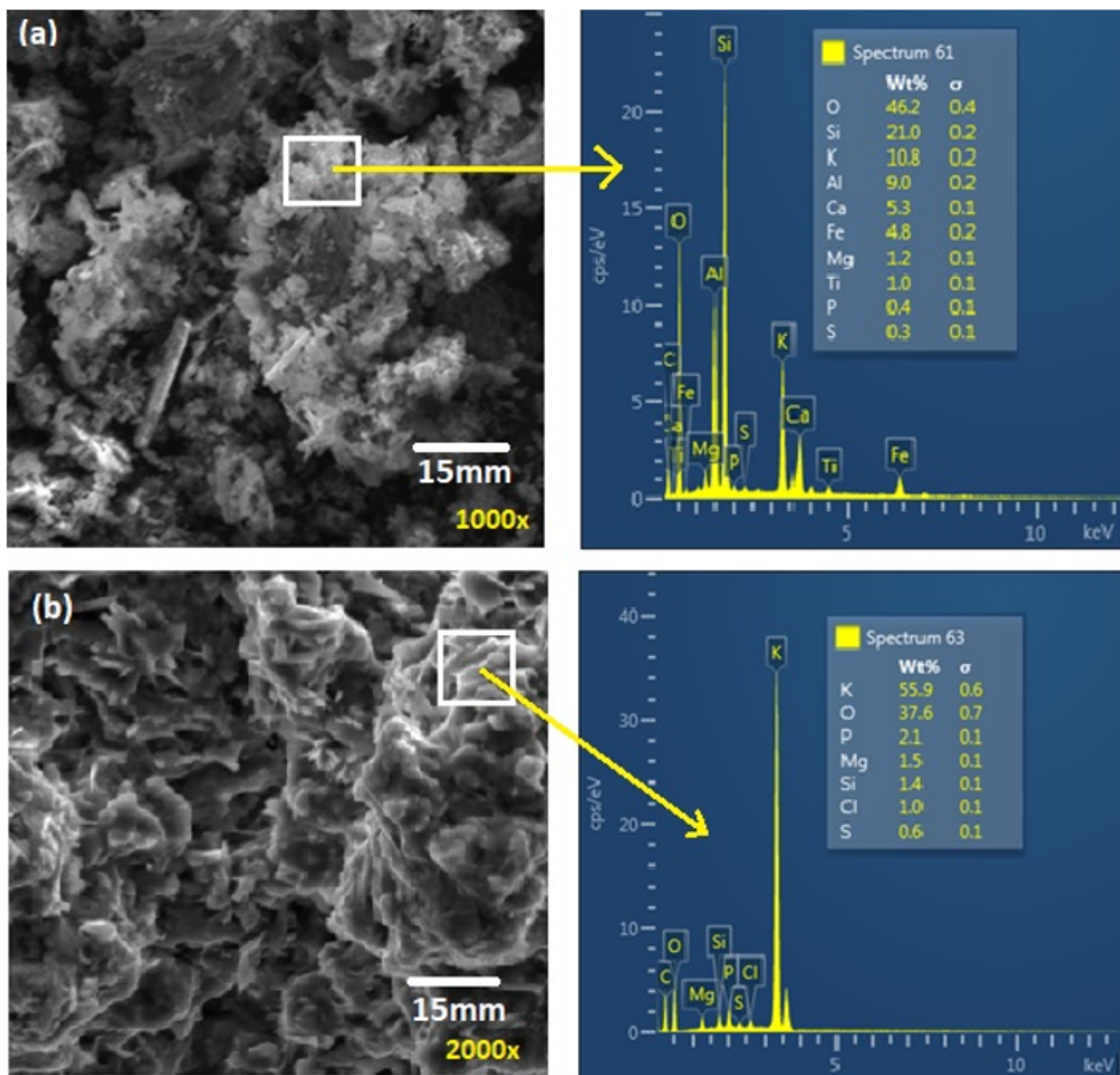


Figure 2

SEM/EDX investigations of (a) MEPA and (b) PMPA as-prepared ash powders

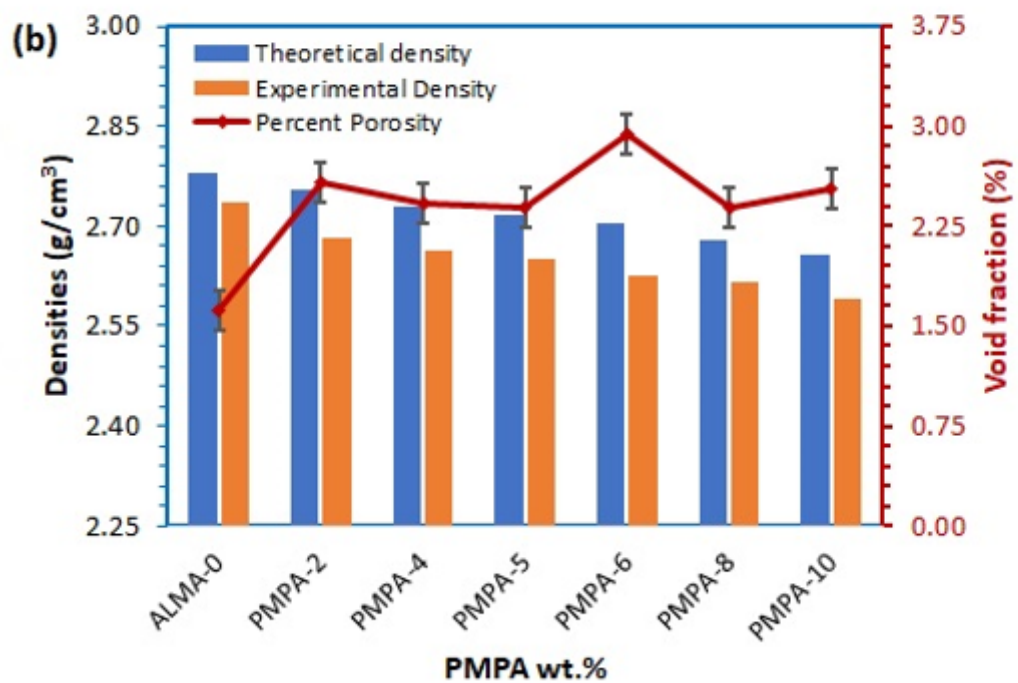
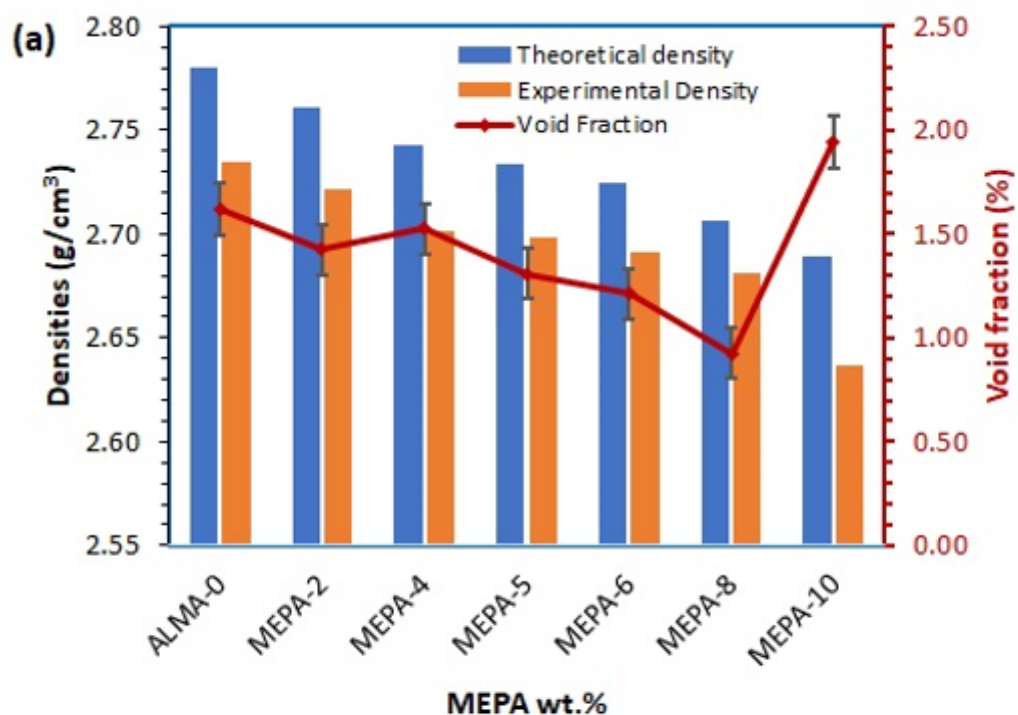


Figure 3

Effect of wt.% variations on densities and percent porosity of the MEPA/PMPA HAMCs.

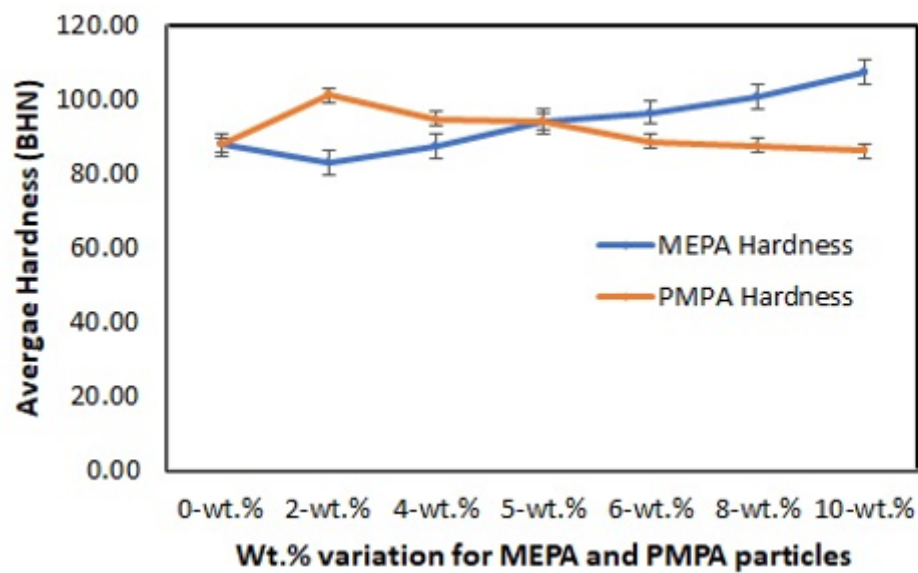


Figure 4

Wt.% variation effect on hardness performance of MEPA/PMPA HAMCs.

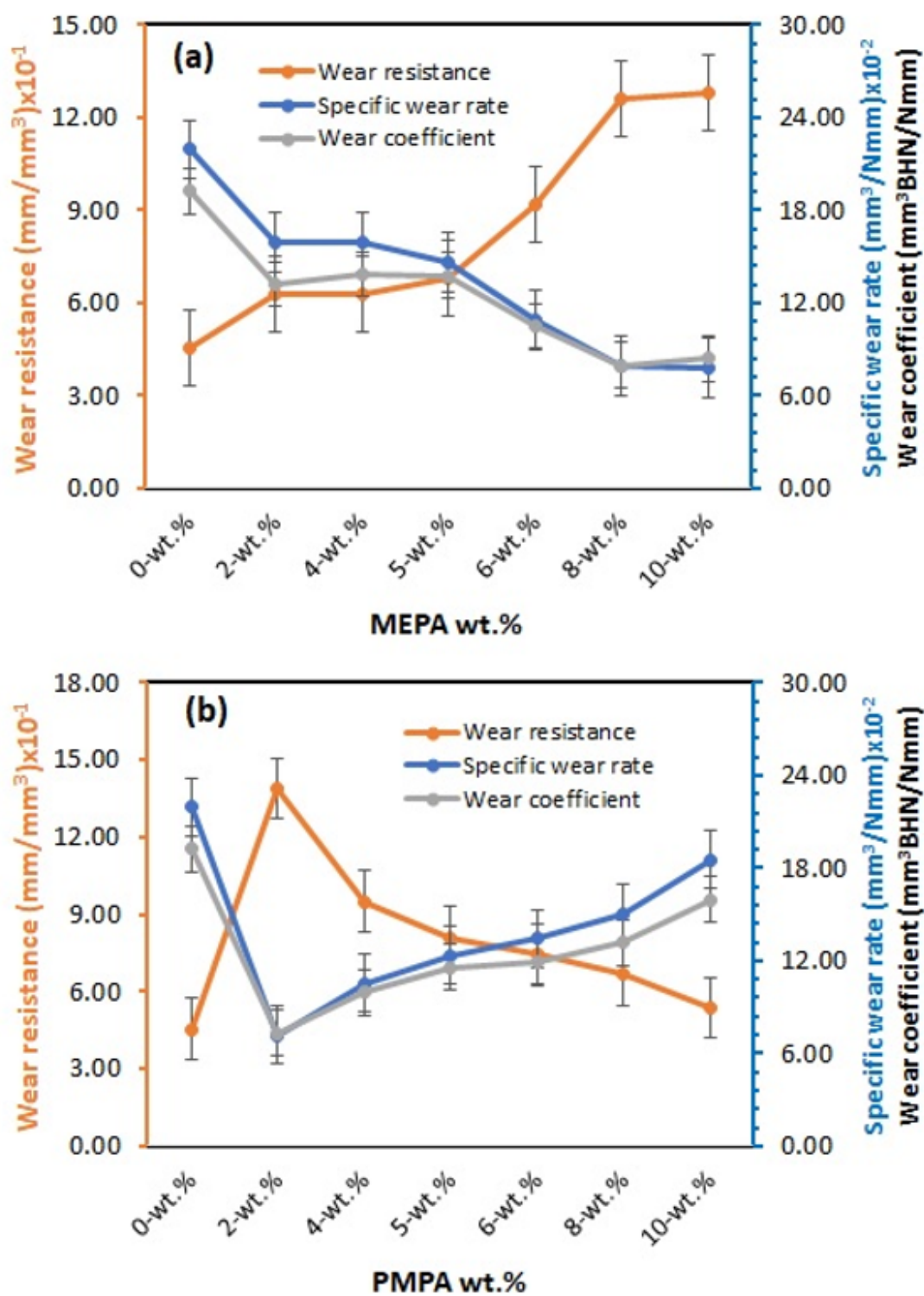


Figure 5

Effect of wt.% variation on the wear assessment of MEPA/PMPA HAMCs.