

Research

In-situ reinforcement of AA6063/Al₂O₃ hybrid composite: comparative wear and hardness evaluation of *Manihot esculenta* and green *Plantago major* particulates

Festus Ben^{1,2}  · Peter A. Olubambi¹ 

Received: 12 March 2024 / Accepted: 8 May 2024

Published online: 17 May 2024

© The Author(s) 2024 

Abstract

The AA6063 alloy, renowned for its 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 contributing to environmental pollution. This study repurposes the *Manihot esculenta* peel ash (MEPA) and *Plantago major* peel ash (PMPA) as innovative reinforcements for the in-situ fabrication of Al₂O₃/AA6063 hybrid and monolithic composites (HMCs) using the two-step stir casting method. MEPA/Al₂O₃/AA6063 and PMPA/Al₂O₃/AA6063 HMCs, fabricated with novel weight percentage variations of 2, 4, 5, 6, 8, and 10%, underwent mechanical and tribological investigations. Although previous studies have examined the physio-mechanical properties of MEPA and PMPA in hybrid composites, their tribological performance remains unexplored. Additionally, using MEPA and PMPA as reinforcing elements in a monolithic aluminium matrix is novel. Oxide compositions and chemical constituents in MEPA and PMPA powders were determined, with fabricated HMCs characterized for SEM and energy-dispersive X-ray studies. Results revealed the presence of hard particulates, including SiO₂ (44%), Al₂O₃ (16%), K₂O (13%), CaO (12%), and Fe₂O₃ (8%) in MEPA powders, while PMPA powders were dominated by K₂O (81%). Morphological studies showed uniform dispersion of reinforcements within the matrix. Composite hardness and wear resistance improved with rising MEPA weight ratios, contrasting with decreasing trends in PMPA particulates. Comparatively, MEPA showed a superior impact on the hardness and tribological performance of Al₂O₃/AA6063 HMCs compared to PMPA. These findings highlight MEPA and PMPA as sustainable engineering solutions for aluminium matrix reinforcement.

Article Highlights

- The study demonstrates using MEPA and PMPA agro wastes as innovative reinforcements for AA6063/Al₂O₃ composites.
- Lightweight composites with improved hardness and wear resistance were fabricated using MEPA and PMPA particulates.
- Comparatively, MEPA showed superior mechanical properties compared to those of the PMPA-reinforced AA6063/Al₂O₃ composites.

✉ Festus Ben, festusb@uj.ac.za | ¹Centre of Nanoengineering and Advanced Materials, Department of Metallurgy, University of Johannesburg, Johannesburg, South Africa. ²Centre for Advanced Material Research and Development, Department of Physics, Federal Polytechnic Ede, Ede, Nigeria.



Keywords *Manihot esculenta* · Sustainable engineering · *Plantago major* · Wear performance · Hardness · In-situ stir casting · Agro waste

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 (Mg_2Si) with good heat-treatment properties, facilitating easy weldability. The alloy is commonly used for applications such as door frames, roofs, and window frames, owing to its smooth surface finish and good corrosion resistance. Despite these promising properties, the Brinell hardness number (BHN) of the medium-strength AA6063 metal matrix is relatively low at 25 BHN [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 Mg_2Si reinforcement of $\text{Al-Si}_{12}\text{-Mg}_{(5,10,20)}$ 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 (Al_2O_3) with a density (3.9 g/cm^3) greater than Al (2.7 g/cm^3) 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 (SiO_2), silicon carbide (SiC), carbon nanotubes (CNTs), graphite, and tungsten carbide (WC), that impact positively on the hardness and wear characteristics of AMCs [5–9]. Bodunrin et al. [10] further classified Al-reinforcements into agro waste, synthetic ceramic, and industrial waste particulates. Like the SCRs, the use of agro waste as reinforcements have 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 are relatively cost-effective owing to their abundance in nature [11] compared to SCRs [12, 13].

Furthermore, literature reports indicate favorable engineering properties for NCRs, including mechanical strength, wear resistance, corrosion resistance, and porosity [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 the production of AMCs include rice-husk ash (RHA) [14–16], coconut-shell ash (CSA) [17–20], palm-kernel shell ash (PKSA) [6, 21, 22], corn cob ash (CCA) [23], date palm seeds ash (DPSA) [24], bean pod ash (BPA) [25–28], groundnut shell ash (GSA) [29], plantain peel ash (PPA) [30, 31], bamboo leaf ash (BLA) [32, 33]. For example, when combined with alumina as reinforcements in the Al–Mg–Si matrix, RHA was reported to produce lightweight composites [11]. AMCs reinforced with agro waste particulates have equally demonstrated enhanced hardness with increasing percent weight variation as reported for RHA/SiC [34], RHA/ B_4C [35], RHA/Cu [15], CSA/ Al_2O_3 [20], CSA [36], BPA [28], and DPSA with an optimum increase at 7.5 wt.% [24]. In contrast, a decrease in hardness has also been reported for AMCs with increasing weight ratio variations in NCRs/SCRs such as RHA/ Al_2O_3 with about 10% decrease reported [11], CCA/SiC [23], BLA/ Al_2O_3 with about 9% reduction for a 40% Al_2O_3 reduction [37], and GSA/SiC [29].

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 [38]. Poor wettability, agglomeration, and uneven distribution of reinforcement particulates contribute significantly to mechanical properties such as hardness in AMCs [30]. The use of Mg has been recommended to improve wettability [11], while production methods such as two-step stir casting have been found to ameliorate issues relating to agglomeration and non-uniform distribution of particulates [39]. Increasing the stirring time and speed in the double-step stir casting method has also been reported to significantly influence the hardness properties of AMCs [7]. Commonly investigated Al alloys reinforced singly with either SCRs or NCRs or a hybrid of SCR-NCRs include AA2014 [40], A356 [41], LM13 [42], AA5083 [43], AA7075 [44], Al6061 [16, 20], AA2009 [28], ADC12 [35], and AA6063 [6, 43]. Studies involving the use of AA6063 have employed fabrication routes like ballistic impact [43] and the compo-casting method [6], with limited information on the use of a double stir-cast route, particularly for

SCR–NCR hybrid reinforcement. Furthermore, several studies have reported the pivotal role of tribological properties in manufacturing sectors such as aerospace, automotive, and machining of hard-to-cut materials [9, 16, 17, 27, 45–58].

Prasad and Krishna [58] studied the tribological performance of monolithic RHA/A356.2 AMCs fabricated using a mechanical stirrer. They utilized the pin-on-disc dry sliding wear technique for assessment and reported significant improvement in the hardness and wear resistance of the composites. Muni et al. [16] observed enhanced hardness properties in hybrid RHA/Cu/AA6061 AMCs manufactured via the two-step stir casting method. The investigation involved different RHA/Cu concentrations, specifically 6:0, 6:3, 8:3, and 10:3 ratios. Apasi et al. [17] assessed the wear characteristics of a monolithic CSA-reinforced Al–Si–Fe alloy produced via stir casting, while Lakshmikanthan and Prabu [56] studied the mechanical and wear properties of CSA/AA6061 AMCs. The studies reported enhancement in the wear resistance of the monolithic composites during dry sliding wear testing conducted with a pin-on-disc apparatus. Subramaniam et al. [57] utilized the stir casting method to reinforce AA7075 with CSA/B4C, resulting in hybrid AMCs. Their tribological investigations, employing varying wt.% of 0:3, 3:3, 6:3, 9:3, and 12:3 for the CSA/B4C hybrid reinforcement, revealed significant improvements in the composite's tribological properties, obtained via the pin-on-disc dry sliding wear tests conducted. Aigbodion et al. [27] utilized the double stir casting and double layer feeding method to fabricate BPAnp-reinforced AA2009 AMCs, followed by wear testing using a pin-on-disc heated at 373.15 and 473.15 K. Their study revealed a significant increase in the wear behavior of the monolithic AMCs. Bhuvaneswari et al. [9] explored the tribological performance of AA219 alloy reinforced with sea-shell powder (SSP) biocomposite fabricated via stir casting. Their experimental findings, analyzed using surface methodology for tribological analysis, demonstrated a notable enhancement in the hardness and wear resistance of the monolithic SSP/AA219 AMCs. Palanivendhan and Chandradass [46] examined the mechanical and wear properties of GSA and hemp fiber ash (HFA) as reinforcements in AA6063 hybrid AMCs manufactured via the stir casting method. They investigated various GSA/HFA ratios (2.5:0, 0:2.5, 5:0, 0:5, 7.5:0, 2.5:2.5, 2.5:5, and 5:2.5), noting a decrease in hardness and a relative enhancement in wear performance. Furthermore, they conducted additional research on the tribological behavior of ADC12 alloy reinforced with boron nitride (BN) and lemon grass ash (LGA) prepared through the stir-squeeze casting method, with varying wt.% compositions of 0:6, 1.5:6, 3:6, 4.5:6, and 6:6 for BN/LGA [47]. Their findings, obtained using a linear reciprocating tribometer, indicated improvements in the hardness and wear resistance of the BN/LGA/ADC12 hybrid AMCs.

The review of existing studies underscores the potential of monolithic and hybrid composites (MHCs) to address the mechanical and chemical limitations associated with unreinforced Al alloy matrices in sustainable engineering applications. Green manufacturing, increasingly popular among researchers, explores agro waste-based NCRs as alternatives to the costly SCRs for developing innovative MHCs [51]. Despite the extensive studies conducted on agro waste reinforcements, many potential agro waste materials remains unexplored or lack investigations into their tribological properties. Among these materials are the *Manihot esculenta* peels (MEP) and the *Plantago major* peels (PMP), which are the focus of this study. Research on the tribological performance of MEP and PMP ashes in hybrid composites have been limited, with existing studies concentrating solely on the physio-mechanical properties of these composites, leaving their tribological performance unexplored. [30, 59]. However, there have been extensive reports of the *Manihot esculenta* peels ash (MEPA) and *Plantago major* peels ash (PMPA) as reinforcement and replacement materials in polymer composites, and admixture concretes [60–67]. This knowledge gap motivated the investigation of the mechanical and tribological performance of MEPA and PMPA as reinforcements using the two-step stir casting method to fabricate in-situ Al_2O_3 /AA6063 MHCs, presenting a novel approach in this study. Comparative analysis between MEPA/ Al_2O_3 /AA6063 and PMPA/ Al_2O_3 /AA6063 reinforced MHCs further enhances the novelty of this research.

The choice of MEP and PMP agro waste byproducts for this study is premised on their widespread global consumption and extensive cultivation in sub-Saharan African countries. According to FAO statistics [68], the global production of *Manihot esculenta* (ME), commonly known as Cassava, and *Plantago major* (PM), also referred to as Plantain, in sub-Saharan Africa was approximately 208 million and 30 million tonnes, respectively in 2022. ME is largely cultivated in Nigeria at ~60 million tonnes [68], surpassing global production by over 18% [69], while PM is predominantly cultivated in Uganda at ~10 million tonnes [68]. Considering these statistics, it can be inferred that a significant portion of these food crops, especially the peels, will become environmental waste and significant contributors to environmental pollution [70–72]. To mitigate against the problem arising from the indiscriminate disposal and environmental pollution caused by these solid wastes, repurposing them as sustainable materials for engineering applications is crucial. This approach will further reduce the substantial costs associated with processing and importing of SCRs.

This research aims to contribute to the discourse on agro waste reinforcement of MMCs by exploring the potential of using NCRs (MEPA and PMPA) as single reinforcements with AA6063 in the absence of SCR (Al_2O_3) to produce environmentally sustainable lightweight AMCs for strength-based and wear-resistant engineering applications. Novel weight

percentage variations will be employed for fabricating MEPA and PMPA-reinforced $\text{Al}_2\text{O}_3/\text{AA6063}$ MHCs. In addition, a detailed analysis of the oxide compositions present in the MEPA and PMPA particulates and their influence on the density and tribological properties of the fabricated AMC's will be conducted, providing further novelty to this study.

2 Experimental methodology

2.1 Processing

Material selection and preparation Materials used for this study are novel and include ingots of AA6063, alumina powder of 26 μm particle size, MEPA powder, and PMPA powder. Spectral 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 placed in an oven for 24 h at 353.15 K. The ashes were removed and conditioned inside an electric muffle furnace maintained at 923.15 K for 180 min to eliminate carbonaceous constituents. Figure 1 shows the powdered ash samples prepared for MEPA and PMPA utilized in this study.

Composite fabrication The experiment was formulated to yield a 10% weight ratio reinforcement of SCR (alumina) and NCRs (MEPA and PMPA). Table 2 presents the novel weight percentage (wt.%) variations of 2, 4, 5, 6, 8, and 10% employed in fabricating the MEPA/ Al_2O_3 /AA6063 and PMPA/ Al_2O_3 /AA6063 HMCs in this study. The matrix was heated to approximately $1023.15 \text{ K} \pm 20 \text{ K}$ 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 reinforcements within the alloy of the molten matrix. Adopting the double-stir casting methodology, the preheated reinforcement particulates and 0.001 weight fractions of Mg (for improving wettability) were added to the molten matrix and agitated for 10–15 min. The slurry of the 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 the method

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

Fig. 1 Powdered ash samples of **a** MEPA and **b** PMPA, used as reinforcements



Table 2 The weight percentages 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

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. The as-cast HAMCs were hot-mounted and metallographically prepared by grinding and polishing the surfaces of the specimens.

2.2 Experimentation

Microstructure The surface morphologies of the MEPA and PMPA reinforcements were characterized using a JSM-7900F JEOL field emission scanning electron microscope (SEM) equipped with an OXFORD elemental dispersive X-ray (EDX) device for elemental composition identification. The chemical constituents of the elemental oxides were identified through X-ray fluorescence (XRF) spectroscopy of the as-prepared powders. Elemental phases present in the MEPA and PMPA powder samples were analyzed at 0.017 step size, 30 s per step screening rate, 40 kV (voltage), and 45 mA (current) using a Rigaku X-ray diffractometer.

Density For each as-cast HAMC fabricated in this study, the theoretical (ρ_{th}) and experimental (ρ_{ex}) densities were determined using Eqs. (1) and (2), respectively, per the ASTM D2734 standard [73]. A pycnometer was used to estimate the theoretical densities of Al_2O_3 , MEPA, and PMPA powders. The experimental density was estimated by measuring the sample mass (m) in air using a high-precision digital weighing scale, whereas the volume (V) of the HAMCs was measured using the principle of flotation.

$$\rho_{th} = Wt_{AA6063} \times \rho_{AA6063} + Wt_{SCF} \times \rho_{SCF} + Wt_{NCF} \times \rho_{NCF} \quad (1)$$

$$\rho_{ex} = m/V \quad (2)$$

Hardness The hardness investigations of the fabricated HAMCs were conducted per the ASTM E10-23 standard [74] 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 s. 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 20× microscope affixed to the Innovatest Falcon 500 hardness tester. The Brinell hardness of the as-cast HAMCs was estimated using Eq. (3). The average of the three indentations was used to obtain the BHN of each as-cast HAMC sample.

$$BHN = (2 \times F_N) / \pi D(D - \sqrt{D^2 - d^2}) \quad (3)$$

Wear Using a pin-on-disc wear tester device, an 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 high-precision digital weighing scale. The test specimens were positioned onto the sample holder, and a 10 N load (F_{LOAD}) applied. The test specimens were rotated under this load conditions for 20 cycles. The test specimens final weight (W_{FINAL}) and the sliding distance ($D_{SLIDING}$) were measured. Using the experimental density of the test specimens, the volume of wear loss (ΔV_{LOSS}) and specific wear rate (K_S) were computed from Eqs. (4) and (5) [75]. The wear coefficients (K) are estimated by taking the average hardness (H_C) of the corresponding composite into consideration and using Archard's wear equation given by Eq. (6) [76].

$$\Delta V_{LOSS}(\text{mm}^3) = (W_{INITIAL} - W_{FINAL}) / \rho \quad (4)$$

$$K_S(\text{mm}^3/\text{Nmm}) = \Delta V_{LOSS} / (F_{LOAD} \times D_{SLIDING}) \quad (5)$$

$$K(\text{mm}^3\text{BHN}/\text{Nmm}) = (\Delta V_{LOSS} \times H_C) / (F_{LOAD} \times D_{SLIDING}) \quad (6)$$

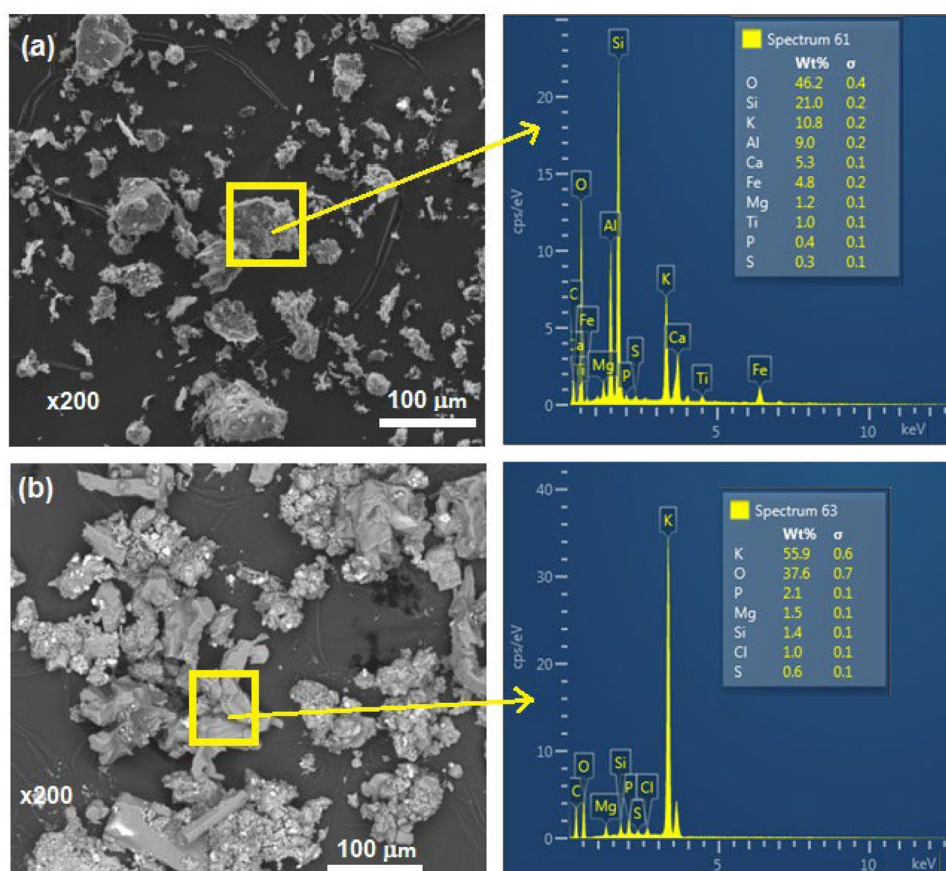
3 Result and discussion

3.1 Microstructural results

The structural features and elemental compositions of the as-prepared ash samples of MEPA and PMPA are shown in Figs. 2 and 3, respectively. SEM results for MEPA particles revealed a roundish-shaped surface with some longitudinal portions (Fig. 2a), consistent with [63, 77]. For PMPA particles, the surfaces were angular in shape, some portions were roundish, with fibrous and spongy distributions, (Fig. 3a), which aligns with the observation by [78–80]. No defects or surface contours were observed on the surface morphologies of the MEPA and PMPA particulates. This observation is significant as wettability is influenced to a large extent by the surface layer [81, 82]. The EDX spectra further revealed that MEPA particles contained significant wt.% of elements like oxygen (46%), silicon (21%), potassium (9%), aluminium (9%), calcium (5%), and iron (5%). Trace amounts of Mg, Ti, phosphorus (P), and Sulphur (S) were also observed in the MEPA particles. This observation suggests that silica (SiO_2) is most likely to dominate within the MEPA particles, with the particles also containing substantial portions of Al_2O_3 . 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), which is consistent with the elemental compositions reported by [83–85]. Oxides of potassium (K_2O) are likely dominant in the PMPA surface. The dominance of potassium in PMPA particles have also been reported by [80, 83, 86, 87], with wettability and mechanical properties found to significantly impact the nature of oxides on the surface layers [88–90].

The surface morphologies of the fabricated MEPA and PMPA Al_2O_3 /AA6065 hybrid composites are shown in Fig. 3. A distinct interfacial appearance is observed amongst the MEPA and alumina reinforcement particles, which are homogeneously distributed along the visible grain boundaries within the matrix (Fig. 3i[a-e]). This showed one of the benefits offered by the two-step stir casting methodology in relieving the surface tension between the reinforcements and the matrix. This observation aligns with the study by [59], who also reported uniform distribution of the reinforcing phase within the aluminium-rich matrix. The PMPA HAMCs, on the other hand, showed uniform

Fig. 2 SEM/EDX investigations of MEPA (a) and PMPA (b) reinforcements



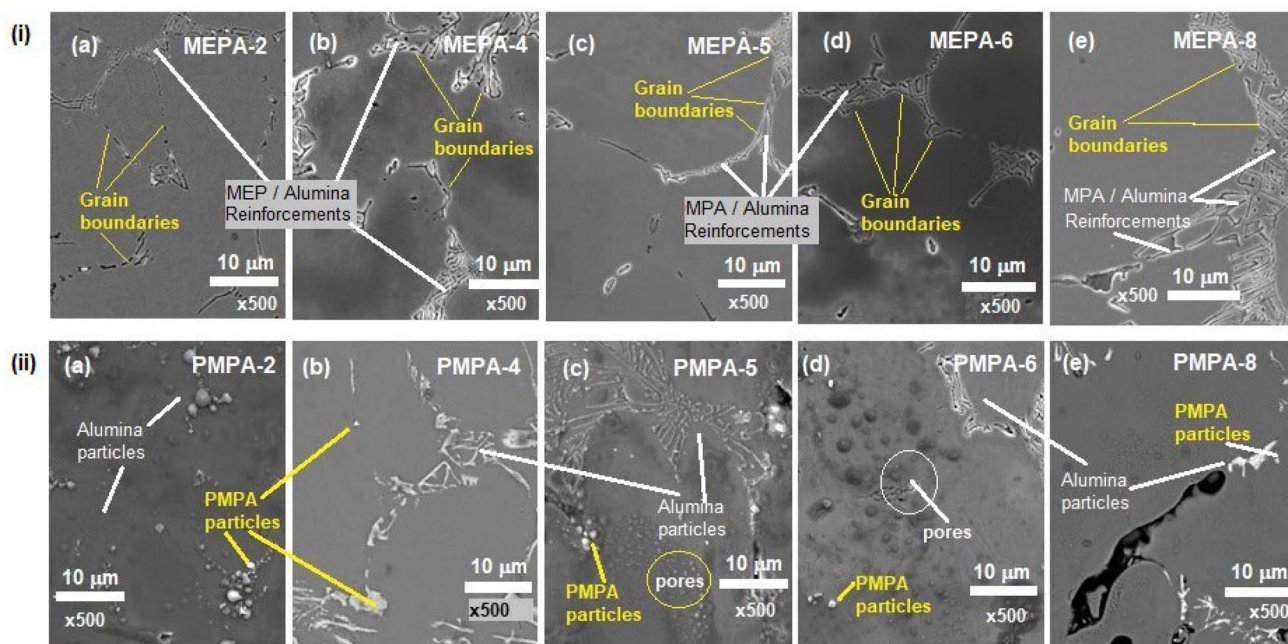


Fig. 3 SEM results for MEPA (i) and PMPA (ii) HAMCs

dispersion of reinforcement within the matrix, with visible grain boundaries. Clustering of reinforcements was observed in PMPA-2 HAMCs (Fig. 3ii[a]). The PMPA composites also showed high porosity levels with mesopores and micropores evident in Figs. 3ii(c, d), which agrees with the observation by [80, 83, 87]. As a polymeric material, agro waste-based ceramic reinforcement contains lignin, which inhibits efficient bonding between the matrix and the reinforcements, owing to its smooth surface. The effect of the cellulose and hemicellulose bonding becomes pronounced with an increase in the weight percent of PMPA particulates [91], as evidenced by Fig. 3iic, d.

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 suggested by the EDX results, the MEPA particulates were dominated by oxides of SiO_2 at 44%, Al_2O_3 at 16%, K_2O at 13%, CaO at 12%, and Fe_2O at 8%. The oxide composition observed in the MEPA particles is consistent with previous reports, indicating the presence of various oxides [60, 62, 92, 93]. The silica content measured in this study (44%) falls within the range reported in other studies (36.79% to 83.00%). The XRF results for PMPA particulates correlate with the EDX elemental peaks observed in Fig. 2b, as oxides of K_2O (81%) and CaO (5%) dominate. Other studies have reported similar observations regarding the oxide composition of PMPA. However, the potassium (K) content in this study (81%) exceeded the range of 45.16% to 68.37% found in previous studies [83, 84, 94, 95]. For the Al_2O_3 particulate, 99 mass% of alumina particles were observed, which was consistent with [11]. A closer look at Table 3 reveals that the first eight oxides were present in varying quantities in the SCR and NCR particulates, suggesting that these oxides would largely impact the mechanical performance of the resulting HAMCs.

The XRD diffractogram in Fig. 4 exhibited matched peak patterns for MEPA and PMPA particulates. In Fig. 4a, the XRD peaks confirm the presence of abundant silica (SiO_2) in an amorphous phase structure, followed by the monoclinic hatrurite (Ca_3SiO_5) and hexagonal wüstite (Fe_2O) phase lattice structures. This observation aligns with the EDX result depicted in Fig. 2a. Additionally, previous studies [79, 96] have also confirmed the presence of amorphous silica peaks in MEP particles. For PMPA particles, the XRD diffraction pattern in Fig. 4b confirms the dominant presence of potassium compounds. The observed peaks correspond to the face-centered cubic potassium chloride (KCl) and monoclinic potassium carbonate hydrate ($\text{K}_2\text{CO}_3 \cdot 1.5\text{H}_2\text{O}$) phase structures, consistent with findings reported by previous researchers [80, 83, 86, 87] and the EDX results shown in Fig. 2b for the PMPA sample. Additionally, peaks indicative of silica (SiO_2) and calcium metaphosphate ($\text{Ca}_3\text{P}_2\text{O}_8$) phases were observed in the XRD diffractogram for PMPA particulates.

Table 3 XRF oxide results for (a) MEPA, (b) PMPA, and (c) Al_2O_3 particulates

(a) Component	Mass %	(b) Component	Mass %	(c) Component	Mass %
Al_2O_3	15.6892	Al_2O_3	0.2236	Al_2O_3	99.3814
SiO_2	43.5902	SiO_2	2.5765	SiO_2	0.1738
Na_2O	0.1045	Na_2O	0.0000	Na_2O	0.1846
P_2O_5	1.4837	P_2O_5	3.8391	P_2O_5	0.0196
Fe_2O_3	8.4605	Fe_2O_3	0.9395	Fe_2O_3	0.0597
K_2O	12.5582	K_2O	80.8674	K_2O	0.0198
SO_3	1.1055	SO_3	1.1628	SO_3	0.1045
CaO	11.7339	CaO	5.0198	CaO	0.0460
MgO	1.1650	MgO	0.6994		
TiO_2	2.3477	MnO	0.2947		
Co_2O_3	0.0208	Cl	3.7937		
MnO	0.5804	CuO	0.0209		
Cl	0.3065	Rb_2O	0.3516		
CuO	0.0347	Br	0.0350		
NiO	0.0238	ZnO	0.1204		
Cr_2O_3	0.0644	SrO	0.0556		
ZnO	0.0839				
ZrO_2	0.2423				
SrO	0.1425				
Rb_2O	0.0497				
BaO	0.2127				

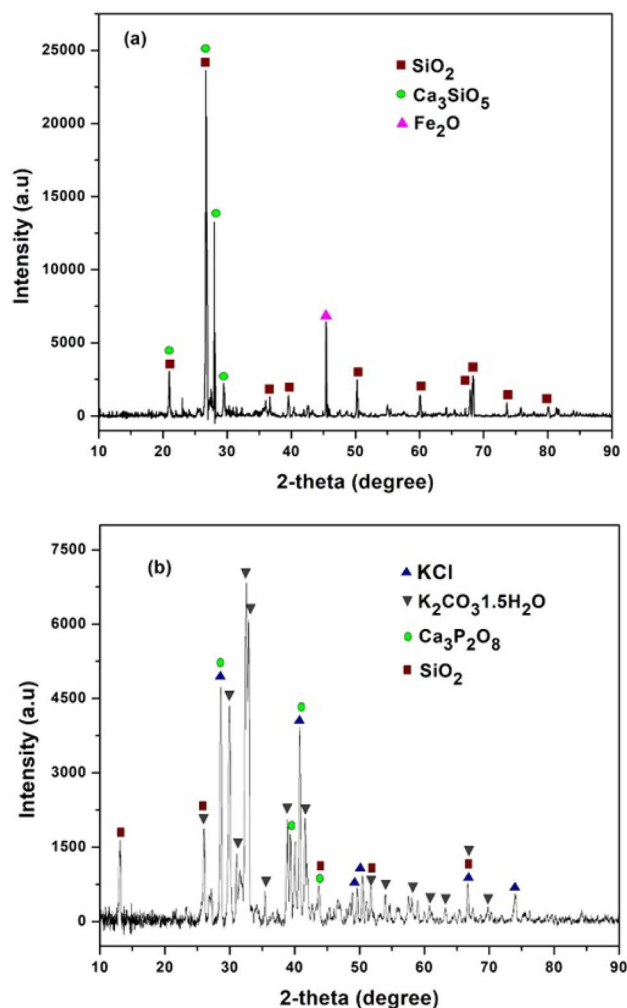
3.2 Density and void fraction results

The densities of Al_2O_3 , MEPA, and PMPA measured using the pycnometer were 3.9796 g/cm³, 2.6792 g/cm³, and 2.3821 g/cm³, respectively. Table 3 revealed that the denser oxides with the highest mass% exerted a dominant influence on the overall density of the reinforcement particulates. The measured powder densities were 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 was presented in Fig. 5. Theoretical densities of the as-cast HAMCs were estimated through the rule of mixtures and the measured densities of the powder samples per Eq. (1). Comparatively, theoretical densities for MEPA/ Al_2O_3 /AA6063 HAMCs ranged from 2.69 to 2.78 g/cm³, while PMPA/ Al_2O_3 /AA6063 HAMCs varied from 2.66 to 2.78 g/cm³. Likewise, experimental densities of MEPA-HAMCs varied from 2.64 to 2.74 g/cm³, while that of PMPA-HAMCs ranged from 2.59 to 2.74 g/cm³. 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. This supports Islam et al.'s [51] observation that NCRs are more suitable for producing low-density reinforced metal matrix composites (MMCs) than SCRs. Other studies on NCRs-reinforced MMCs also reported the production of lightweight composites [15, 30, 93, 97].

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 [11]. However, the void fractions were comparatively lower in MEPA/ Al_2O_3 /AA6063 HAMCs (< 2%) than in 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 [98–100]. The sudden rise in the void fraction observed in the MEPA-10 reinforced AA6063 composite could be attributed to the inherent porosity associated with the MEPA particulates. MEPA has been documented to undergo the formation of mesopores and micropores during the carbonization process [101–106]. The activation process, influenced by impregnation ratios and activation temperatures, plays a crucial role in creating the porous nature of MEPA [104, 106]. For instance, Andiani et al. [104]

Fig. 4 XRD diffraction pattern results for MEPA (a) and PMPA (b) reinforcements

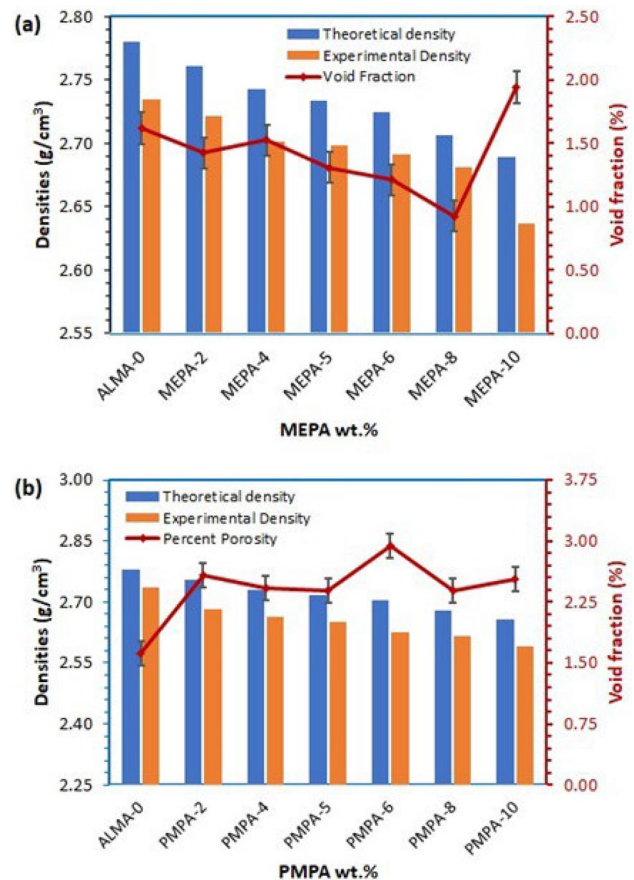


observed the formation of hollow structures in MEPA, resulting in porosity at an activation temperature of 973.15 K. SEM micrograph studies, such as those depicted in Fig. 3i(e) and reported by other studies [104, 105], have confirmed the formation of a rough and porous surface in biochar-derived MEPA. This observation is consistent with the study by Hartini et al. [107], which reported the formation of pores in MEPA-activated carbon derivatives within the structure of γ -alumina composites.

The porous properties of the MEPA particulates explained why the void fraction was significantly and consistently lower in the hybrid MEPA/ Al_2O_3 /AA6063 composite than in the single MEPA-reinforced AA6063 composite (MEPA-10). This is because the alumina particles, with their uniform shape and relatively dense properties, acted as fillers in the hybrid AMCs, effectively occupying the pores and spaces between the less dense MEPA particles. This improved packing efficiency resulted in a more uniform distribution of particles throughout the matrix, significantly reducing the formation of voids during compaction and consolidation processes and enhancing the structural integrity of the composite, even with a decrease in alumina particles and an increase in MEPA particles. The interfacial solid bond between alumina and the matrix material, which previously reduced void formation, became evident upon the complete removal of alumina from the composite, resulting in a sharp rise in void fraction of the MEPA-10 monolithic AMC (Fig. 5a). In the absence of a synthetic filler agent, such as alumina, the less dense MEPA particles, with their non-uniform dispersion or clustering properties, result in a high degree of void formation.

Interestingly, Hartini et al. [107] reported a decrease in total pore volume with increased activated carbon weight percentages. However, further investigations are needed to understand the interaction and the contributions of hard particulates, such as Al_2O_3 , Fe_2O_3 , and CaO , present within the MEPA particles (Table 3a) in maintaining the structural integrity of singly-reinforced MEPA/AA6063 AMCs at increasing weight percentages in the absence of SCRs like alumina. This is crucial for determining the potential application areas for the monolithic MEPA/AA6063 composite, where the

Fig. 5 Effect of wt.% variations on densities and percent porosity of the MEPA/PMPA HAMCs

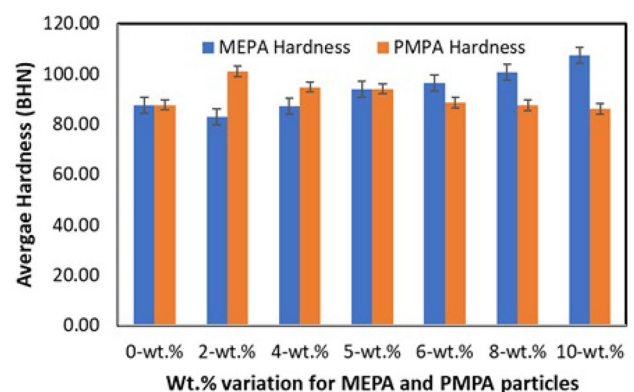


naturally abundant MEPA waste could potentially substitute for the relatively expensive alumina particles. For the PMPA particles, the sharp rise observed with PMPA-6 in Fig. 5b is attributed to the processing conditions during the composite fabrication, including mixing and compaction. Inadequate compaction and mixing issues, particularly for aluminium, have been reported to lead to void formation or porosity within composite structures [108–112]. This explained why the acceptable porosity level in aluminium-cast composites was benchmarked at 4% [11, 113].

3.3 Hardness performance

Figure 6 depicted the graphical comparative performance of hardness tests conducted on the MEPA and PMPA-reinforced HAMCs. For the MEPA HAMCs, the hardness of the reinforced composites increased with increasing weight variation of MEPA and decreasing wt.% of Al_2O_3 particulates. Other studies have reported similar improvements in hardness for MMCs reinforced with MEPA [59, 93]. Compared to the singly reinforced ALMA-0 (74.70 BHN), the singly reinforced MEPA-10

Fig. 6 Wt.% variation effect on hardness performance of MEPA/PMPA HAMCs



(107.47) showed better hardness at 22.62%. This could be linked to the combined density contributions of the oxides present in MEPA particles (Table 3a) and the reduced porosity (<2%) observed in Fig. 5a. Even dispersion of reinforcements within the matrix reduces the interparticle distance [28] resulting in increased density of crystal defects, due to the accumulation of dislocations within the composite. The elevated density of dislocations augments the surface area [114] of the MEPA particles, enhancing resistance to further material deformation while suppressing grain boundary effects [115]. This factor significantly contributed to the overall hardness observed with increasing MEPA wt.%.

Conversely, for PMPA-reinforced HAMCs fabricated in this study, hardness declined with a rise in wt.% of PMPA and a decrease in Al_2O_3 wt.%. Notably, the sharp increase observed in the 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/cm³) and K_2O (2.35 g/cm³) of the reinforcements in the matrix. However, a reduction in hardness was observed as the wt.% of Al_2O_3 decreased and the wt.% of PMPA increased. This outcome was expected for two primary reasons: firstly, the K_2O density was significantly lesser than that of Al_2O_3 , and secondly, Fig. 5b 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 [116, 117]. This allows the material to undergo plastic deformation, resulting in a decreased hardness. A closer examination of the hardness values revealed that the singly reinforced PMPA-10 (86.03 BHN) experienced a 1.84% decrease compared to the singly reinforced ALMA-0 (87.64 BHN). This further confirms that the crystal planes glide more smoothly when the dislocation densities were significantly reduced, adversely affecting the hardness of the fabricated HAMCs. However, Okafor et al. [67] reported an increase in hardness when using PM-based fibers in polyester matrix composites.

3.4 Wear assessment

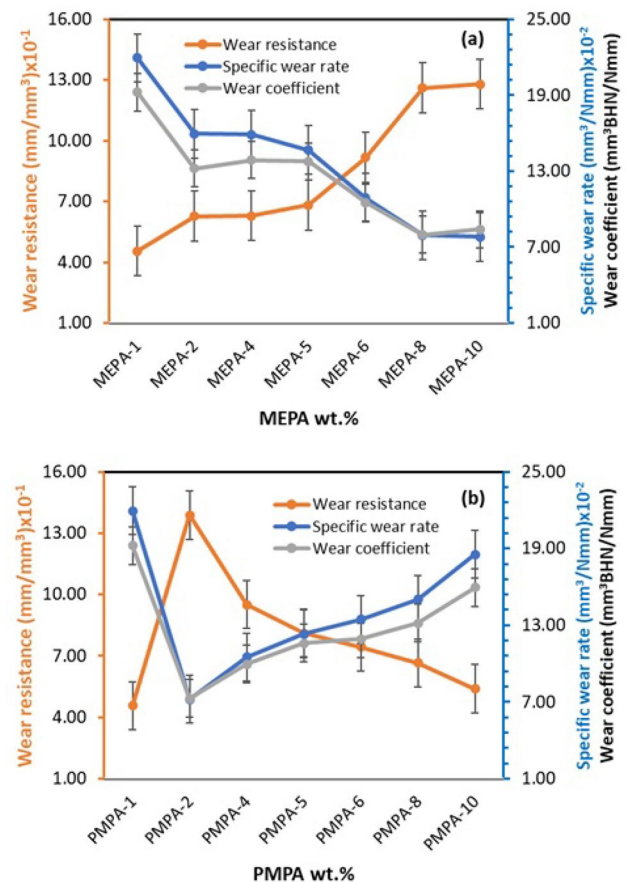
The mass loss of MEPA and PMPA-reinforced AA6063/ Al_2O_3 HAMCs before and after the conducted wear test, under a 10 N applied load and 15 mm sliding distance, is presented in Table 4. For the MEPA-HAMC specimens, the mass loss ranged from 0.031 to 0.090 g. The singly reinforced ALMA-0 exhibited the highest wear loss at 0.090 g, whereas the singly reinforced MEPA-10 showed the lowest wear loss at 0.031 g. It was also observed that the 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 the MEPA wt.%. The reductions in mass and volumetric losses are due to the impact of MEPA particle reinforcements on the improved hardness of the fabricated HAMCs. Complex composites contribute to grain refinement due to increased density dislocations within the material [40]. Archard's equation postulates that the wear rate is inversely related to hardness [76, 118], thus validating the enhanced wear resistance observed. The singly reinforced MEPA-10 particle had the maximum hardness result (Fig. 6), 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. 7a). Olaniran et al. [59] reported similar results, showing enhanced wear resistance with MEPA-based reinforcement in Al–Mg–Si/SiC matrix composites.

The PMPA-based HAMC specimens exhibited mass losses ranging from 0.029 to 0.090 g. PMPA-2 exhibited the lowest mass loss, which increased with ascending PMPA wt.%. The volumetric loss for the PMPA HAMC also varied from 10.808 mm³ to 32.906 mm³, with PMPA-2 recording the most negligible loss. The volumetric loss also increased with an increase

Table 4 Effect of (a) MEPA and (b) PMPA weight variations 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

Fig. 7 Effect of wt.% variation on the wear assessment of MEPA **a** PMPA **b** HAMCs



in the PMPA wt.%. The consistent rise in volumetric and mass losses accounted for the elevation in the wear rate of the fabricated PMPA-reinforced HAMCs. The steady rise in the wear rate observed in Table 4 for the PMPA HAMCs is consistent with the decrease in hardness (Fig. 6). This finding was validated by Archard's wear-hardness equation [76]. Wear resistance was lowest at the singly reinforced PMPA-10 HAMCs ($5.39 \text{ mm}^3/\text{mm}^3$) and highest at PMPA-2 ($13.88 \text{ mm}^3/\text{mm}^3$). However, the wear resistance of PMPA-10 was 18.35% superior to that of ALMA-0 while decreasing with an increase in the PMPA wt.%. However, it is essential to note that the wear resistance, as indicated by the wear coefficient, decreased with increasing weight percentage of PMPA particulates (Fig. 7b). This implies that more surface materials were removed from the HAMCs during sliding, owing to a consistent decline in the hardness of the PMPA HAMCs. The void fraction (> 2%) observed in the PMPA HAMCs (Fig. 5b) may potentially contribute to reduced mechanical properties, which could impact the wear resistance at the contact surface during the rubbing action between the pin and rotating disc.

Hybrid MMCs have been recognized for their superior wear resistance compared to pure matrix alloys [119]. Palanivendhan and Chandradass [46] attributed this to plastic deformation, abrasion, strain rate, and tribo-oxidation during tribological investigation. The wear performance obtained with MEPA particulates in this study aligns with the findings from other studies on NCRs-reinforced MMCs. These studies have consistently shown a significant enhancement in wear resistance with an increase in wt.% of reinforcements, including RHA [15, 44], fly ash [55], BPA nanoparticles [27], CSA [57], locust beans waste [120], and sugarcane bagasse ash [48]. The worn surfaces of the MEPA and PMPA HAMCs are depicted in Fig. 8, revealing transverse sliding tracks indicative of structural changes due to wear mechanisms. Examination of the composite alloy revealed cavities and large grooved regions on the worn surface, with broken ceramic particles found in cavities and loose fragments between the surfaces, indicating an abrasive wear mechanism. The wear mode appeared to be abrasive, with crack propagation observed along the transverse and longitudinal directions. Crushed and fragmented particles were also present, along with patches, indicating material removal from the surface.

Interestingly, the wear resistance performance results obtained with the PMPA hybrid AMCs contradict the existing literature on agro waste reinforcement in MMCs. This discrepancy could be attributed to several factors. Firstly, the softening effect of K_2O is known for its potential to act as a flux, thus lowering the melting point of the material [121, 122]. This reduces the hardness of the material, making it more malleable and prone to deformation. Secondly, K_2O ,

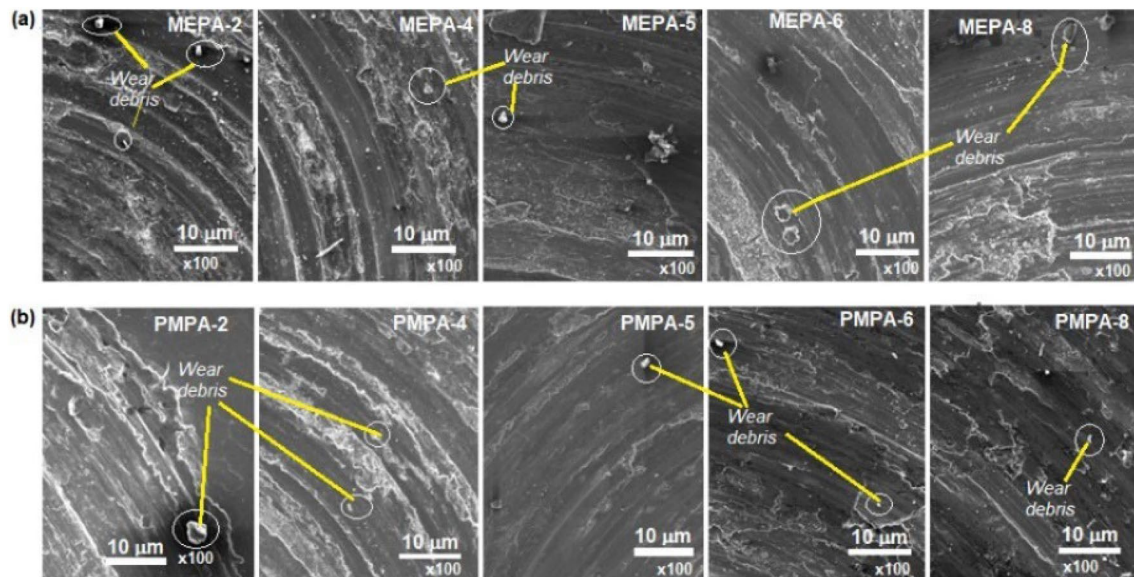


Fig. 8 Surface microstructure morphology showing wear characteristics of MEPA (a) and PMPA (b) HAMCs

due to its high stiffness, forms brittle phases when it reacts with other elements [123, 124], weakening the structural composition of the composites and making them more susceptible to abrasion and wear. For instance, Gao et al. [125] observed the formation of brittle $(K.Na)Al_2O_3$ phases during the sintering of K_2O and Al_2O_3 resulting in a deliquescence effect. Thirdly, K_2O can influence microstructural changes in materials, leading to defects such as voids or porosity, as evidenced in previous studies [126–129]. The instability of potassium with varying oxygen content, coupled with the formation of the $KAlO_2$ phase in the composite structure, can act as a potential stress concentration point, promoting crack initiation and propagation. This accounts for the significant decline in the hardness and wear performance observed in this study for the PMPA/ Al_2O_3 /AA6063 hybrid composites.

Comparatively, the wear properties of the MEPA-based HAMCs outperformed those of the PMPA-based HAMCs (Table 4 and Fig. 7). This superiority stemmed from the greater hardness and enhanced wear resistance exhibited by the composites fabricated using MEPA, attributable to the oxide compositions present in the MEPA particulates. In contrast, the PMPA particles are predominantly composed of K_2O , which has a lower density than Al_2O_3 . The rationale behind the correlation between oxide compositions, particularly hard particulates such as silica, alumina, and hematite, is rooted in the intrinsic properties of these oxides. One major contributing factor is the density of the oxide, which plays a crucial role in enhancing the hardness and wear resistance of the hybrid MMCs. Several studies have provided evidence that supports this relationship. For instance, Alaneme et al. [130] and Apasi et al. [17] underscored the significant hardness and wear resistance enhancement attributed to oxides such as SiC , SiO_2 , Fe_2O_3 , and Al_2O_3 , in composite materials. Similarly, studies by other researchers [10, 11, 131–136] further corroborated these findings, highlighting the pivotal role of specific oxide compositions in improving the mechanical properties of MMCs. This suggests that the oxide density and intrinsic properties, particularly in hard particulates, are key factors driving the enhanced hardness and wear resistance observed in hybrid MMCs.

Consequently, the composites fabricated with PMPA exhibit reduced hardness and wear resistance. Additionally, while the specific wear rate and wear coefficient decreased with increasing weight ratio for the MEPA particulates, these wear properties showed an opposite trend, increasing with the rising weight fraction for PMPA particles. In addition, considering the density, hardness, and wear performance of the hybrid MEPA- and PMPA-reinforced Al_2O_3 /AA6063 composites reported in this study, future research could aim to optimize the compositions and processing parameters to further enhance their mechanical properties and expand their potential applications in various industries. Given their lightweight nature, the composites fabricated in this study hold promise for application in automotive parts, aerospace components, sports gears, and portable devices. However, additional investigation into the corrosion resistance performance of these composites in diverse environments is necessary, along with an assessment of their mechanical properties such as ductility, toughness, and strength. The superior hardness and wear properties observed in the MEPA-reinforced composites suggest their potential application in abrasive wear scenarios, such as cutting tools and wear-resistant coating materials.

4 Conclusion

This study presents valuable comparative insights into the use of two solid agro wastes (MEPA and PMPA) for the in-situ reinforcement of AA6063/ Al_2O_3 , focusing on their mechanical and tribological properties. The findings of the experimental investigation are summarized as follows.

1. The SEM investigations confirmed the uniform dispersion of the reinforcement materials within the AA6063 matrix. The XRD patterns confirmed the presence of SiO_2 and K_2O peaks in the MEPA and PMPA particulates, respectively, indicating their elemental compositions.
2. Lightweight composites were fabricated with MEPA and PMPA reinforcements. The sharp increase in void fraction observed in the MEPA/AA6063 composite was attributed to the inherent porosity of the MEPA particles, stemming from the micropores and mesopores within them.
3. MEPA reinforced AA6063/ Al_2O_3 HAMCs demonstrated an increase in hardness with rising MEPA wt.%, surpassing the hardness of the singly reinforced AA6063/ Al_2O_3 AMC. Conversely, the hardness of PMPA/AA6063/ Al_2O_3 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 to 107 BHN and 86 BHN, respectively, showing their potential as lightweight alternatives to SCR-based materials for Al-reinforcements.
5. Volumetric loss and wear rate in the 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/ Al_2O_3 HAMCs.
6. The decline in the wear resistance of the PMPA/ Al_2O_3 /AA6063 HMCs was attributed to microstructural changes in the material due to the softening effect of K_2O and the formation of brittle phases. The MEPA/AA6063/ Al_2O_3 HAMCs demonstrated superior wear resistance compared with the PMPA/AA6063/ Al_2O_3 HAMCs.
7. The singly reinforced MEPA/AA6063 AMC showed enhanced hardness and wear behaviour compared to the singly reinforced AA6063/ Al_2O_3 and PMPA/AA6063 AMCs. MEPA particles show promise as a cost-effective alternative to the relatively expensive Al_2O_3 , suggesting sustainable engineering applications for *Manihot esculenta* solid wastes.

The comparative analysis indicated that the fabricated MEPA/AA6063/ Al_2O_3 HAMCs had better mechanical properties than the PMPA/AA6063/ Al_2O_3 HAMCs, with enhanced hardness and wear performance. This superiority is primarily attributed to the elemental composition and oxides found in MEPA. Both solid agro wastes, MEPA and PMPA, emerged 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.

Author contributions FB: Conceptualization, investigation, writing of the original draft, methodology, formal and data analysis, writing—reviewing and editing. PAO: resources, supervision, project coordination, writing—reviewing and editing.

Funding Tertiary Education Trust Fund

Data availability Data used for this study will be provided upon reasonable request.

Declarations

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

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Abdul Jawwad AK, Al-Bashir A, Saleem M, Hasanain B. Qualitative and quantitative interdependence of mechanical properties of industrially extruded AA6063 alloy on process parameters and profile characteristics. *Multidiscip Model Mater Struct*. 2022;18:968–96. <https://doi.org/10.1108/MMMS-06-2022-0111>.
2. Azom. Aluminium: specifications, properties, classifications and classes. 2005; <https://www.azom.com/article.aspx?ArticleID=2863>. Accessed 28 August 2022
3. Gavgali M, Totik Y, Sadeler R. The effects of artificial aging on wear properties of AA 6063 alloy. *Mater Lett*. 2003;57:3713–21. [https://doi.org/10.1016/S0167-577X\(03\)00168-X](https://doi.org/10.1016/S0167-577X(03)00168-X).
4. Sun Y, Ahlatci H. Mechanical and wear behaviors of Al – 12Si – X Mg composites reinforced with in situ Mg 2 Si particles. *Mater Des*. 2011;32:2983–7. <https://doi.org/10.1016/j.matdes.2011.01.009>.
5. Sekhar RA, Pillai RR, Ali MM, Kumar CNS. Enhanced mechanical and wear properties of aluminium-based composites reinforced with a unique blend of granite particles and boron carbide for sustainable material recycling. *J Alloys Compd*. 2023;963: 171165. <https://doi.org/10.1016/j.jallcom.2023.171165>.
6. Edoziuno FO, Nwaeju CC, Adediran AA, Odoni BU, Arun VR. Mechanical and microstructural characteristics of Aluminium 6063 Alloy / Palm Kernel shell composites for lightweight applications. *Sci African*. 2021;12: e00781. <https://doi.org/10.1016/j.sciaf.2021.e00781>.
7. Prabu SB, Karanamooty L, Kathiresan S, Mohan B. Influence of stirring speed and stirring time on distribution of particulates in cast metal matrix composite. *J Mater Process Technol*. 2006;171:268–73.
8. Lim SS, Rossiter PL, Tibballs JE. Assessment of the Al–Ag binary phase diagram. *Calphad*. 1995;19:131–41.
9. Bhuvanewari V, Rajeshkumar L, Sworna KN. Influence of bioceramic reinforcement on tribological behaviour of aluminium alloy metal matrix composites: experimental study and analysis. *J Mater Res Technol*. 2021;15:2802–19. <https://doi.org/10.1016/j.jmrt.2021.09.090>.
10. Bodunrin MO, Alaneme KK, Chown LH. Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics. *J Mater Res Technol*. 2015;4:434–45. <https://doi.org/10.1016/j.jmrt.2015.05.003>.
11. Alaneme KK, Akintunde IB, Olubambi PA, Adewale TM. Fabrication characteristics and mechanical behaviour of rice husk ash—alumina reinforced Al–Mg–Si alloy matrix hybrid composites. *J Mater Res Technol*. 2013;2:60–7. <https://doi.org/10.1016/j.jmrt.2013.03.012>.
12. Zargar K, Singla S. Impact of pet plastic waste on mechanical properties of mix concrete design. *Int J Sci Technol Res*. 2020;9:88–93.
13. Tyagi R. Synthesis and tribological characterization of in situ cast Al–TiC composites. *Wear*. 2005;259:569–76. <https://doi.org/10.1016/j.wear.2005.01.051>.
14. Gladston JAK, Sheriff NM, Dinaharan I, Raja Selvam JD. Production and characterization of rich husk ash particulate reinforced AA6061 aluminum alloy composites by compocasting. *Trans Nonferrous Met Soc China*. 2015;25:683–91. [https://doi.org/10.1016/S1003-6326\(15\)63653-6](https://doi.org/10.1016/S1003-6326(15)63653-6). (English Ed).
15. Dinaharan I, Kalaiselvan K, Akinlabi ET, Davim JP. Microstructure and wear characterization of rice husk ash reinforced copper matrix composites prepared using friction stir processing. *J Alloys Compd*. 2017;718:150–60. <https://doi.org/10.1016/j.jallcom.2017.05.117>.
16. Muni RN, Singh J, Kumar V, Sharma S. Influence of rice husk ash, cu, mg on the mechanical behaviour of aluminium matrix hybrid composites. *Int J Appl Eng Res*. 2019;14:1828–34.
17. Apasi A, Madakson PB, Yawas DS, Aigbodion VS. Wear behaviour of Al–Si–Fe alloy/coconut shell ash particulate composites. *Tribol Ind*. 2012;34:36–43.
18. Oghoghorie O, Ebhojiaye RS, Amiolemhen PE. Assessment of the wear resistance and the density reduction of aluminium when reinforced with coconut shell charcoal and cow bone ash. *World J Eng Res Technol*. 2022;8:27–40.
19. Kumar A, Nirala A, Singh VP, Kumar B, Singh RC, Chaudhary R, Dewangan AK, Kumar G. The utilisation of coconut shell ash in production of hybrid composite: microstructural characterisation and performance analysis. *J Clean Prod*. 2023. <https://doi.org/10.1016/j.jclepro.2023.136494>.
20. Kaladgi ARR, Fazlur Rehman K, Afzal A, Baig MA, Soudagar MEM, S. Bhattacharyya, Fabrication characteristics and mechanical behaviour of aluminium alloy reinforced with Al₂O₃ and coconut shell particles synthesized by stir casting. *IOP Conf Ser Mater Sci Eng*. 2021;1057:12017. <https://doi.org/10.1088/1757-899X/1057/1/012017>.
21. Oyedeki EO, Dauda M, Yaro SA, Abdulwahab M. Analysis of Al–Mg–Si alloy reinforced with optimal palm kernel shell ash particle and its impact on dynamic properties for sounding rocket application. *Funct Compos Struct*. 2023;5: 045001.
22. Odikpo F, Adesoji A, Ufuoma B, Goodluck O, Olayanju A. Materials today: proceedings physico-chemical and morphological evaluation of palm kernel shell particulate reinforced aluminium matrix composites. *Mater Today Proc*. 2021;38:652–7. <https://doi.org/10.1016/j.matpr.2020.03.641>.
23. Fatile OB, Akinruli JI, Amori AA. Microstructure and mechanical behaviour of stir-cast Al–Mg–Si alloy matrix hybrid composite reinforced with corn cob ash and silicon carbide. *Int J Eng Technol Innov*. 2014;4:251–9.
24. Abdulrazaq AA, Ahmed S, Mahdi FM. Agricultural waste and natural dolomite for green production of aluminum composites. *Clean Eng Technol*. 2023;12: 100588. <https://doi.org/10.1016/j.clet.2022.100588>.
25. Aigbodion VS, Agunsoye OJ, Edokpia RO, Ezema IC. Performance analysis of a connecting rod produced with Al–Cu–Mg/bean pod ash nanoparticles. *SILICON*. 2018;10:107–13. <https://doi.org/10.1007/s12633-015-9382-8>.
26. Aigbodion VS, Atuanya CU, Obiorah SO, Isah LA, Neife SI, Omah AD. Effect of particle size on the fatigue behaviour of Al–Cu–Mg/bean pod ash particulate composites. *Trans Indian Inst Met*. 2015;68:495–9. <https://doi.org/10.1007/s12666-014-0474-8>.
27. Aigbodion VS, Atuanya CU, Edokpia RO, Odera RS, Offor OP. Experimental study on the wear behaviour of Al–Cu–Mg/Bean pod ash nano-particles composites. *Trans Indian Inst Met*. 2016;69:971–7. <https://doi.org/10.1007/s12666-015-0594-9>.
28. Aigbodion VS. Bean pod ash nanoparticles a promising reinforcement for aluminium matrix biocomposites. *J Mater Res Technol*. 2019;8:6011–20. <https://doi.org/10.1016/j.jmrt.2019.09.075>.
29. Alaneme KK, Bodunrin MO, Awe AA. Microstructure, mechanical and fracture properties of groundnut shell ash and silicon carbide dispersion strengthened aluminium matrix composites. *J King Saud Univ—Eng Sci*. 2018;30:96–103. <https://doi.org/10.1016/j.jksues.2016.01.001>.

30. Ben F, Amodu FR, Olubambi PA. Influence of green plantain peel ash and alumina reinforcement on the physio-mechanical properties of aluminium matrix hybrid composites. *Mater Sci Forum*. 2023. <https://doi.org/10.4028/p-5CdJMw>.
31. Akpan BJ, Akande IG, Fayomi OSI, Oluwasegun KM. Investigation of hardness, microstructure and anti-corrosion properties of Zn-ZnO composite coating doped unripe plantain peel particles. *Case Stud Chem Environ Eng*. 2022;5: 100187. <https://doi.org/10.1016/J.CSCEE.2022.100187>.
32. Kumar BP, Birru AK. Microstructure and mechanical properties of aluminium metal matrix composites with addition of bamboo leaf ash by stir casting method. *Trans Nonferrous Met Soc China*. 2017;27:2555–72. [https://doi.org/10.1016/S1003-6326\(17\)60284-X](https://doi.org/10.1016/S1003-6326(17)60284-X). (English Ed).
33. Alaneme KK, Adewuyi EO. Mechanical behaviour of al-mg-si matrix composites reinforced with alumina and bamboo leaf ash. *Metall Mater Eng*. 2013;19:177–87.
34. Prasad DS, Shoba C, Ramanaiah N. Investigations on mechanical properties of Al hybrid composites. *J Mater Res Technol*. 2014;3:79–85.
35. Muralimohan R, Kempaiah UN, Seenappa, influence of rice husk ash and B4C on mechanical properties of ADC 12 alloy hybrid composites. *Mater Today Proc*. 2018;5:25562–9. <https://doi.org/10.1016/j.matpr.2018.10.363>.
36. Apasi A, Yawas DS, Abdulkareem S, Kolawole MY. Improving mechanical properties of aluminium alloy through addition of coconut shell-ash. *J Sci Technol*. 2016. <https://doi.org/10.4314/jst.v36i3.4>.
37. Alaneme KK, Ademilua BO, Bodunrin MO. Mechanical properties and corrosion behaviour of aluminium hybrid composites reinforced with silicon carbide and bamboo leaf ash. *Tribol Ind*. 2013;35:25–35.
38. Zhang J, Fan Z, Wang YQ, Zhou BL. Microstructural evolution of the in-situ Al-15 wt.% Mg2Si composite with extra Si contents. *Scr Mater*. 2000;42:1101–6.
39. Ezatpour HR, Torabi-Parizi M, Sajjadi SA. Microstructure and mechanical properties of extruded Al/Al2O3 composites fabricated by stir-casting process. *Trans Nonferrous Met Soc China*. 2013;23:1262–8. [https://doi.org/10.1016/S1003-6326\(13\)62591-1](https://doi.org/10.1016/S1003-6326(13)62591-1).
40. Bharti S, Ghetiya ND, Patel KM. Micro—hardness and wear behavior of AA2014 / Al 2 O 3 surface composite produced by friction stir processing. *SN Appl Sci*. 2020;2:1–16. <https://doi.org/10.1007/s42452-020-03585-2>.
41. Manohar S, Narayana TS, Ravindra K. An investigational analysis of the wear parameters in the friction performance of the A356 alloy with hybrid compounds. *Int J Res Appl Sci Eng Technol*. 2019;7:515–23. <https://doi.org/10.22214/ijraset.2019.11084>.
42. Chelladurai SJS, Arthanari R. Effect of stir cast process parameters on wear behaviour of copper coated short steel fibers reinforced LM13 aluminium alloy composites. *Mater Res Express*. 2018;5.
43. Karamis MB, Tasdemirci A, Nair F. Failure and tribological behaviour of the AA5083 and AA6063 composites reinforced by SiC particles under ballistic impact. *Compos Part A*. 2003;34(34):217–26. [https://doi.org/10.1016/S1359-835X\(03\)00024-1](https://doi.org/10.1016/S1359-835X(03)00024-1).
44. Alaneme KK, Sanusi KO. Microstructural characteristics, mechanical and wear behaviour of aluminium matrix hybrid composites reinforced with alumina, rice husk ash and graphite. *Eng Sci Technol an Int J*. 2015;18:416–22. <https://doi.org/10.1016/j.jestch.2015.02.003>.
45. Sathish T, Karthick S. Wear behaviour analysis on aluminium alloy 7050 with reinforced SiC through taguchi approach. *J Mater Res Technol*. 2020;9:3481–7. <https://doi.org/10.1016/j.jmrt.2020.01.085>.
46. Palanivendhan M, Chandradass J. Experimental investigation on mechanical and wear behavior of agro waste ash based metal matrix composite. *Mater Today Proc*. 2021;45:6580–9. <https://doi.org/10.1016/j.matpr.2020.11.712>.
47. Palanivendhan M, Chandradass J. Fabrication and characterization of ADC-12 hybrid composites utilizing lemon grass ash and boron nitride through stir-squeeze casting method. *Mater Res Express*. 2023;10:1–17.
48. Virkunwar A, Ghosh S, Basak R. Study of mechanical and tribological characteristics of aluminium alloy reinforced with sugarcane bagasse ash. In: *Int Conf Tribol TRIBOINDIA-2018*. 2019. <https://doi.org/10.2139/ssrn.3313510>
49. Thankachan T, Prakash KS, Kavimani V. Investigating the effects of hybrid reinforcement particles on the microstructural, mechanical and tribological properties of friction stir processed copper surface composites. *Compos Part B Eng*. 2019;174: 107057. <https://doi.org/10.1016/j.compositesb.2019.107057>.
50. Sankara Raju RS, Panigrahi MK, Ganguly RI, Srinivasa Rao G. Optimization of tribological behaviour on Al- coconut shell ash composite at elevated temperature. *IOP Conf Ser Mater Sci Eng*. 2018. <https://doi.org/10.1088/1757-899X/314/1/012009>.
51. Islam A, Prakash S, Rajat D, Vijay Y, Dwivedi K. Development of aluminium based composite by utilizing industrial waste and agro-waste material as reinforcement particles. *J Inst Eng Ser D*. 2021;102:317–30. <https://doi.org/10.1007/s40033-021-00292-z>.
52. Natarajan N, Moorthy AA, Sivakumar R, Manojkumar M, Suresh M. Dry sliding wear and mechanical behavior of aluminium / fly ash / graphite hybrid metal matrix composite using taguchi method. *Int J Mod Eng Res*. 2012;2:1224–30.
53. Moustafa EB, Melaibari A, Basha M. Wear and microhardness behaviors of AA7075 / SiC-BN hybrid nanocomposite surfaces fabricated by friction stir processing. *Ceram Int*. 2020;46:16938–43. <https://doi.org/10.1016/j.ceramint.2020.03.274>.
54. Eskandari H, Taheri R, Khodabakhshi F. Microstructural developments and mechanical properties. *Mater Sci Eng A*. 2016;660:84–96. <https://doi.org/10.1016/j.msea.2016.02.081>.
55. Palanivel R, Dinaharan I, Laubscher RF, Davim JP. Influence of boron nitride nanoparticles on microstructure and wear behavior of AA6082/ TiB 2 hybrid aluminum composites synthesized by friction stir processing. *JMADE*. 2016;106:195–204. <https://doi.org/10.1016/j.matdes.2016.05.127>.
56. Purushothaman L, Bala P. Mechanical and tribological behaviour of aluminium AL6061- coconut shell ash composite using stir casting pellet method. *J Balk Tribol Assoc*. 2016;22:4008–18.
57. Subramaniam B, Natarajan B, Kaliyaperumal B, Chelladurai SJS. Wear behaviour of aluminium 7075—boron carbide- coconut shell fly ash reinforced hybrid metal matrix composites. *Mater Res Express*. 2019;6:1–11.
58. Prasad SD, Krishna RA. Tribological properties of A356.21RHA composites. *J Mater Sci Technol*. 2012;28:367–72.
59. Olaniran O, Oyetunji A, Oji B. Influence of silicon carbide-cassava peel ash weight ratio on the mechanical and tribological characteristics of Al-Mg-Si alloy hybrid composites. *J Chem Technol Metall*. 2021;56:1082–8.
60. Olatokeunbo O, Ede AN, Rotimi O, Solomon O, Tolulope A, John O, Adeoye O. Assessment of strength properties of cassava peel ash-concrete. *Int J Civ Eng Technol*. 2018;9:965–74.
61. Salau MA, Ikponmwoa EE, Olonode KA. Structural strength characteristics of cement-cassava peel ash blended concrete. *Civ Environ Res*. 2012;2:68–77. <https://www.iiste.org/Journals/index.php/CER/article/view/3541>.

62. Raheem SB, Arubike ED, Awogboro OS. Effects of cassava peel ash (CPA) as alternative binder in concrete. *Int J Constr Res Civ Eng*. 2020;1:27–32.
63. Versino F, López OV, García MA. Sustainable use of cassava (*Manihot esculenta*) roots as raw material for biocomposites development. *Ind Crops Prod*. 2015;65:79–89. <https://doi.org/10.1016/j.indcrop.2014.11.054>.
64. Usman A, Bala N, Bashiru M. Effect of plantain peel ash (PPA) on the mechanical properties of concrete. *Noble Int J Sci Res*. 2018;02:11–8.
65. Adetayo OA, Jubril O. Effect of ripe and unripe plantain peel ash on concrete workability and compressive strength. *FUOYE J Eng Technol*. 2019;4:145–8. <https://doi.org/10.46792/fuoyejt.v4i1.318>.
66. Adeniyi A, Abdulkareem S, Ndagi M, Abdulkareem M, Ighalo J. Effect of fiber content on the physical and mechanical properties of plantain fiber reinforced polystyrene composite. *Adv Mater Process Technol*. 2022;8:4244–56. <https://doi.org/10.1080/2374068X.2022.2054583>.
67. Okafor EC, Ihueze CC, Nwigbo SC. Optimization of hardness strengths response of plantain fibers reinforced polyester matrix composites (PFRP) applying taguchi robust design. *Int J Eng*. 2013;26:1–11. <https://doi.org/10.5829/idosi.ije.2013.26.01a.01>.
68. FAO, Crops and livestock products, 2024. <https://www.fao.org/faostat/en/#data/QCL>.
69. Knoema, Cassava production in the World, 2022. <https://knoema.com/data/cassava+agriculture-indicators-production>.
70. Akinyemi O, Aiyelaagbe I, Akyeampong E. Plantain (*Musa spp*) Cultivation in Nigeria: a review of its production, marketing and research in the last two decades. *Acta Hort*. 2010;879:211–8. <https://doi.org/10.17660/ActaHortic.2010.879.19>.
71. Ayanwale A, Fatunbi O, Ojo M. Innovation opportunities in plantain production in Nigeria. Guide Book 1. Forum for Agricultural Research in Africa (FARA), Accra; 2016.
72. Adejumo IO, Adebisi OA, A. O.A. Agricultural Solid Wastes: Causes, Effects, and Effective Management. In: Saleh HM, editor. Strategies of sustainable solid waste management. London: IntechOpen Limited; 2021. p. 1–6. <https://doi.org/10.5772/intechopen.93601>.
73. D.-23 ASTM. Standard test methods for void content of reinforced plastics (ASTM D2734–23); 2023. <https://doi.org/10.1520/D2734-23.2>.
74. E.-23 ASTM. Standard Test method for brinell hardness of metallic materials (ASTM E10 – 23); 2023. <https://doi.org/10.1520/E0010-23>.
75. Agarwal G, Patnaik A, Sharma RK. Parametric optimization and three-body abrasive wear behavior of sic filled chopped glass fiber reinforced epoxy composites. *Int J Compos Mater*. 2013;3:32–8. <https://doi.org/10.5923/j.comaterials.20130302.02>.
76. Archard JF. Contact and rubbing of flat surfaces. *J Appl Phys*. 1953;24:981–8.
77. Mohd-asharuddin S, Othman N, Nur Shaylinda MZ, Tajarudin HA. A chemical and morphological study of cassava peel: a potential waste as coagulant aid. In: MATEC Web Conf.; 2017, pp. 1–8.
78. Nadew TT, Keana M, Sisay T, Getye B, Habtu NG. Synthesis of activated carbon from banana peels for dye removal of an aqueous solution in textile industries: optimization, kinetics, and isotherm aspects. *Water Pract Technol*. 2023;18:947–66. <https://doi.org/10.2166/wpt.2023.042>.
79. Adebisi JA, Agunsoye JO. Extraction of silica from sugarcane bagasse cassava periderm and maize stalk: proximate analysis and physico-chemical properties of wastes. *Waste Biomass Valoriz*. 2017. <https://doi.org/10.1007/s12649-017-0089-5>.
80. Adedayo E, Oluwatumininu O, Betiku E. Cocoa pod husk-plantain peel blend as a novel green heterogeneous catalyst for renewable and sustainable honne oil biodiesel synthesis : a case of biowastes-to-wealth. *Renew Energy*. 2020;166:163–75. <https://doi.org/10.1016/j.renene.2020.11.131>.
81. Ye H, Yin C, Wang J, Zheng Y. Controllable and gradient wettability of bilayer two-dimensional materials regulated by interlayer distance. *ACS Appl Mater Interfaces*. 2022;14:41489–98. <https://doi.org/10.1021/acsami.2c08282>.
82. Patrakov YF, Semenova SA, Yarkova AV. Study of the wettability of the carbon surface by filtration of liquid through a porous layer. *Fact Lab Diagn Mater*. 2023;89:28–35. <https://doi.org/10.26896/1028-6861-2023-89-5-28-35>.
83. Abiodun O, Oladipo B, Ezekiel A, Tomiwa A, Oyekola OO, Betiku E. Green heterogeneous base catalyst from ripe and unripe plantain peels mixture for the transesterification of waste cooking oil. *Chem Eng J Adv*. 2022;10: 100293. <https://doi.org/10.1016/j.cej.2022.100293>.
84. Balajii M, Niju S. Banana peduncle: a green and renewable heterogeneous base catalyst for biodiesel production from *Ceiba pentandra* oil. *Renew Energy*. 2020;146:2255–69. <https://doi.org/10.1016/j.renene.2019.08.062>.
85. Betiku E, Ajala SO. Modeling and optimization of *Thevetia peruviana* (yellow oleander) oil biodiesel synthesis via *Musa paradisiacal* (plantain) peels as heterogeneous base catalyst: a case of artificial neural network vs. response surface methodology. *Ind Crops Prod*. 2014;53:314–22. <https://doi.org/10.1016/j.indcrop.2013.12.046>.
86. Betiku E, Mistura A, Victor T. Banana peels as a biobase catalyst for fatty acid methyl esters production using Napoleon's plume (*Bauhinia monandra*) seed oil: a process parameters optimization study. *Energy*. 2016;103:797–806. <https://doi.org/10.1016/j.energy.2016.02.138>.
87. Gohain M, Devi A, Deka D. Industrial crops and products *Musa balbisiana* Colla peel as highly effective renewable heterogeneous base catalyst for biodiesel production. *Ind Crop Prod*. 2017;109:8–18. <https://doi.org/10.1016/j.indcrop.2017.08.006>.
88. Qosim N, Supriadi S. Formation of oxide layer and wettability on the surface of electrical discharge machining-based implant engineered by micro-finishing. *J Biomim Biomater Biomed Eng*. 2022. <https://doi.org/10.4028/p-8u998r>.
89. Yoon T, Park S, Chung S, Noh J, Kim K, Kang C. Effect of surface oxidation layer on tensile strength of Cu-Ni alloy in friction stir welding. *Met Mater Int*. 2016;22:501–8. <https://doi.org/10.1007/s12540-016-5620-x>.
90. Chumlyakov YI, Kireeva IV, Saraeva AA, Pobedennaya ZV, Vyrodova AV. Effect of the surface oxide layer on shape memory effect and superelasticity of [011]-oriented Ti-50.1Ni single crystals. *Metals (Basel)*. 2022. <https://doi.org/10.3390/met12111932>.
91. Oladele IO, Ibrahim IO, Aderiran AA, Akinwekomi AD, Adetula YV, Olayanju TMA. Results in materials modified palm kernel shell fiber/particulate cassava peel hybrid reinforced epoxy composites. *Results Mater*. 2020;5: 100053. <https://doi.org/10.1016/j.rinma.2019.100053>.
92. Ogunbode EB, Nyakuma BB, Jimoh RA, Lawal TA, Nmadu HG. Mechanical and microstructure properties of cassava peel ash-based kenaf bio-fibrous concrete composites. *Biomass Convers Biorefin*. 2023;13:6515–25. <https://doi.org/10.1007/s13399-021-01588-6/Published>.
93. Osunmakinde L, Asafa TB, Agboola PO, Durowaju MO. Development of aluminum composite reinforced with selected agricultural residues. *Discov Mater*. 2023. <https://doi.org/10.1007/s43939-023-00069-z>.
94. Ishola K, Olawuyi OA, Bello AA, Yohanna P. Effect of plantain peel ash on the strength properties of tropical red soil. *Niger Res J Eng Environ Sci*. 2019;4:447–59.
95. Akinwumi I, Onyeiwu M, Epelle P, Ajayi V. Soil improvement using blends of coal ash and plantain peel ash as road pavement layer materials. *Resources*. 2023. <https://doi.org/10.3390/resources12030041>.

96. Adebisi JA, Agunsoye JO, Bello SA, Haris M, Ramakokovhu MM, Daramola MO, Hassan SB. Extraction of silica from cassava periderm using modified sol-gel method. *Niger J Technol Dev.* 2016;15:57–65. <https://doi.org/10.4314/njtd.v15i2.4>.
97. KanayoAlaneme K, ApataOlubambi P. Corrosion and wear behaviour of rice husk ash—alumina reinforced Al–Mg–Si alloy matrix hybrid composites. *J Mater Res Technol.* 2013;2:188–94. <https://doi.org/10.1016/j.jmrt.2013.02.005>.
98. Gheni M, Anarbek S, Himi N. Experimental observation of final void volume fraction at fracture in constrained metal matrix composites. *Key Eng Mater.* 2003;243–244:399–404. <https://doi.org/10.4028/www.scientific.net/KEM.243-244.399>.
99. Schöbel M, Requena G, Fiedler G, Tolnai D, Vaucher S, Degischer HP. Void formation in metal matrix composites by solidification and shrinkage of an AlSi7 matrix between densely packed particles. *Compos Part A Appl Sci Manuf.* 2014;66:103–8. <https://doi.org/10.1016/j.compositesa.2014.07.011>.
100. Chandra S, Samal MK, Chavan VM, Raghunathan S. An atomistic study of crack-void interaction in aluminum. *AIP Conf Proc.* 2018. <https://doi.org/10.1063/1.5028661>.
101. Kayiwa R, Kasedde H, Lubwama M, Kirabira JB. Mesoporous activated carbon yielded from pre - leached cassava peels. *Bioresour Bioprocess.* 2021. <https://doi.org/10.1186/s40643-021-00407-0>.
102. Taer E, Harahap EW, Apriwandi A, Taslim R. High-performance aqueous electrolyte symmetrical supercapacitor using porous carbon derived cassava peel waste. *Appl Mater Technol.* 2022;4:1–10. <https://doi.org/10.31258/Jamt.4.1.1-10>.
103. Sudaryanto Y, Hartono SB, Irawaty W, Hindarso H, Ismadji S. High surface area activated carbon prepared from cassava peel by chemical activation. *Bioresour Technol.* 2006;97:734–9. <https://doi.org/10.1016/j.biortech.2005.04.029>.
104. Andiani BY, Riyanto CA, Martono Y. Characterization of Cassava (*Manihot esculenta* Crantz) Peel Activated Carbon based on Impregnation Ratio and Activation Temperature. *J Sains Dan Terap Kim.* 2022;4:19–29. <https://doi.org/10.33019/jstk.v4i1.2533>.
105. Odeyemi SO, Iwuozor KO, Chizitere E, Titilayo O, George A. Valorization of waste cassava peel into biochar: an alternative to electrically-powered process. *Total Environ Res Themes.* 2023;6: 100029. <https://doi.org/10.1016/j.totert.2023.100029>.
106. Amakoromo TE, Abumere OE, Amusan JA, Anye V, Bello A. Current research in green and sustainable chemistry porous carbon from *Manihot esculenta* (cassava) peels waste for charge storage applications. *Curr Res Green Sustain Chem.* 2021;4: 100098. <https://doi.org/10.1016/j.crgsc.2021.100098>.
107. Hartini Y, Hidayat M, Jurusan Kimia F. Study pore characterization of γ -alumina – activated carbon composite made of cassava peels (*Manihot esculenta* Cranz). *Alchmy J Penelit Kim.* 2015;11:47–57.
108. Festus B, Ewetumo T, Oluyamo SS, Olubambi PA. Characterization of heater-cooler blocks fabricated from aluminium wastes for steady-state thermal application. *Mater Sci Forum.* 2022;1079:147–55. <https://doi.org/10.4028/p-s7wbe2>.
109. Festus B, Ewetumo T, Adedayo KD, Oluyamo SS. Development of a low-cost thermal heater-cooler blocks using locally recycled waste. *J Biosens. Bioelectron.* 2019;10:1–4. <https://www.hilarispublisher.com/open-access/development-of-a-lowcost-thermal-heater-cooler-blocks-using-locally-recycled-waste.pdf>.
110. Hickmott C, Forghani A, Hutten V, Lorbiecki E, Palmieri F, Coxon B, Fernlund G, Poursartip A. A numerical and experimental approach for modeling porosity due to entrapped air and volatiles off-gassing during manufacturing of composite structures. In: *SAMPE 2019 - Charlotte, NC; 2019*, p. 14. <https://doi.org/10.33599/nasampe/s.19.1627>.
111. DeAlmeida SFM, Neto ZSN. Effect of void content on the strength of composite laminates. *Compos Struct.* 1994;28:139–48.
112. Hong-yan ZHU, Di-hong LI, Dong-xing Z. Influence of voids on interlaminar shear strength of carbon/epoxy fabric laminates. *Trans Nonferrous Met Soc China.* 2009;19:s470–5. [https://doi.org/10.1016/S1003-6326\(10\)60091-X](https://doi.org/10.1016/S1003-6326(10)60091-X).
113. Kok M. Production and mechanical properties of Al₂O₃ particle reinforced 2024 aluminum composites. *J Mater Process Technol.* 2005;161:381–7.
114. Owoputi AO, Inmbao FL, Ebhota WS. Effect of percentage weight and particle size of SiCp reinforcement on the mechanical behaviour of functionally graded aluminum metal matrix composite. *Int J Eng Res Technol.* 2020;13:444–53. <https://doi.org/10.37624/ijert/13.3.2020.444-453>.
115. Babu V, Shanmugavel BP, Padmanabhan KA. On the microstructural homogeneity and mechanical properties of Al 6063 alloy processed by the cyclic expansion extrusion process. *J Mater Eng Perform.* 2020;29:6870–80. <https://doi.org/10.1007/s11665-020-05151-8>.
116. Hudson TB, Follis PJ, Pinakidis JJ, Sreekantamurthy T, Palmieri FL. Porosity detection and localization during composite cure inside an autoclave using ultrasonic inspection. *Compos Part A Appl Sci Manuf.* 2021;147:106337. <https://doi.org/10.1016/j.compositesa.2021.106337>.
117. Yang DG, Shin ES. Micromechanical computational analysis for the prediction of failure strength of porous composites. *Compos Res.* 2016;29:66–72. <https://doi.org/10.7234/composres.2016.29.2.066>.
118. Akbar HI, Surojo E, Ariawan D. Investigation of industrial and agro wastes for aluminum matrix composite reinforcement. *Procedia Struct Integr.* 2020;27:30–7. <https://doi.org/10.1016/j.prostr.2020.07.005>.
119. Chowdhury MA, Khalil MK, Nuruzzaman DM, Rahaman ML. The effect of sliding speed and normal load on friction and wear property of aluminum. *Int J Mech Mech Eng.* 2011;11:53–57. <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84859014187&partnerID=40&md5=bc794c43cb076e91d41eb50140e06b82>.
120. Usman Y, Dauda ET, Abdulwahab M, Dodo RM. Effect of mechanical properties and wear behaviour on locust bean waste ash (LBWA) particle reinforced aluminium alloy (A356 alloy) composites. *FUDMA J Sci.* 2020;4:416–21.
121. Fang S, Junzhi C. Inorfil softening intensifier and preparation thereof; 2011.
122. Shah KV, Goswami M, Aswal DK, Shrikhande VK, Gupta SK, Kothiyal GP. Effect of Na₂O/K₂O substitution on thermophysical properties of PbO based phosphate glasses. *J Thermal Anal Calorim.* 2007;89:153–7.
123. Tulyaganov DU, Agathopoulos S, Fernandes HR, Ferreira JMF, Fabrichnaya O. Influence of Li₂O doping on non-isothermal evolution of phases in K-Na-containing aluminosilicate matrix. *J Am Ceram Soc.* 2006;89:292–7. <https://doi.org/10.1111/j.1551-2916.2005.00696.x>.
124. Manyu H, Yimin L, Chunguang L, Xia L. Structural, electronic and elastic properties of potassium hexatitanate crystal from first-principles calculations. *Phys B Condens Matter.* 2012;407:2811–5. <https://doi.org/10.1016/j.physb.2012.04.033>.
125. Gao L, Zhou W, Luo F, Zhu D. Solid-state reaction mechanism and deliquescence phenomenon of K_{0.5}-Na_{0.5}-Nb_{0.7}-Al_{0.3}-O₃ ceramic. *J Electron Mater.* 2017;46:5563–9. <https://doi.org/10.1007/s11664-017-5647-x>.

126. Bell JL, Driemeyer PE, Kriven WM. Formation of ceramics from metakaolin-based geopolymers. Part II: K-based geopolymer. *J Am Ceram Soc.* 2009;92:607–15. <https://doi.org/10.1111/j.1551-2916.2008.02922.x>.
127. Kim T, Sohn I. Effects of K₂CO₃ addition on the physicochemical properties of goethite composite pellets with different basicities (CaO/SiO₂). *J Mater Res Technol.* 2023;25:4595–608. <https://doi.org/10.1016/j.jmrt.2023.06.247>.
128. Sangster J. K-O (potassium-oxygen) system. *J Phase Equilib Diffus.* 2013;34:43–55. <https://doi.org/10.1007/s11669-012-0142-9>.
129. Burmakin EI, Voronin VI, Akhtyamova LZ, Berger IF. Potassium aluminate crystalline structure and electroconduction. *Russ J Electrochem.* 2004;40:707–13.
130. Alaneme K, Aluko A. Fracture toughness (K_{1C}) and tensile properties of as-cast and age-hardened aluminium (6063)—silicon carbide particulate composites. *Sci Iran.* 2012;19:992–6.
131. Venkatesh VSS, Deoghare AB. Effect of particulate type reinforcements on mechanical and tribological behavior of aluminium metal matrix composites: a review. In: Pandey KM, Misra RD, Patowari PK, Dixit US, editors. *Recent advances in mechanical engineering*. Singapore: Springer; 2021. p. 295–303.
132. Antil P. Experimental analysis on wear behavior of pmcs reinforced with electroless coated silicon carbide particulates. *SILICON.* 2019;11:1791–800.
133. Harsha AP, Tewari US. The effect of fibre reinforcement and solid lubricants on abrasive wear behavior of polyetheretherketone composites. *J Reinf Plast Compos.* 2003;22:751–67. <https://doi.org/10.1177/0731684403022008005>.
134. Oluwatosin M, Kanayo K, Heath L. Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics. *Integr Med Res.* 2015;4:434–45. <https://doi.org/10.1016/j.jmrt.2015.05.003>.
135. Alaneme KK, Aluko AO. Production and age-hardening behaviour of borax premixed SiC reinforced Al-Mg-Si alloy composites developed by double stir-casting technique. *West Indian J Eng.* 2012;34:80–5.
136. Alaneme KK, Aluko AO. Sharif University of Technology Fracture toughness (K_{1C}) and tensile properties of as-cast and age-hardened aluminium (6063)—silicon carbide particulate composites. *Sci Iran.* 2012;19:992–6. <https://doi.org/10.1016/j.scient.2012.06.001>.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.