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Recycling and Valorization of Agro-Waste Ash in Ceramic Matrix Composites: A Comprehensive Review

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ABSTRACT

West Africa generates hundreds of millions of tonnes of crop residues each year that are largely under-utilised, openly burned, or dumped in waterways. This review examines the recycling of agro-waste ashes (AWA)—principally rice husk ash (RHA), cassava peel ash (CPA), cocoa pod husk ash (CPHA), palm-oil fuel ash (POFA) and maize-stalk ash (MSA)—as silica sources, fluxes and porogens in ceramic matrix composites. The silica-, alumina- and alkali-rich chemistry of these ashes allows them to substitute quartz, feldspar and lime in clay bricks, vitrified stoneware, refractories, glass-ceramics and wall tiles. Cocoa-pod, cassava-peel and rice-husk ashes accumulated between 2015 and 2025 are the most attractive ceramic feedstocks because of high amorphous silica (70–95% in selected RHA), substantial K₂O/CaO fluxes, and a demonstrated ability to lower sintering temperatures by 50–200 °C. Experimental West-African work shows that ≥15% CPA substitution can raise fired-clay flexural strength from 7.8 to 16.5 MPa, that 10% cocoa-cortex ash yields ISO 13006 stoneware (flexural strength 32 MPa; water absorption 2%), and that potash leached from cocoa pods produces stabilised bricks above the 4 MPa load-bearing threshold. AWA valorization is therefore a strategic route for the regional ceramics industry to cut raw-material imports, firing energy, and the environmental burden of agricultural residues.

Keywords: agro-waste ash; valorization; ceramic matrix composites; West Africa; rice husk ash; cassava peel ash; cocoa pod husk ash; palm-oil fuel ash; circular economy

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1. Introduction

The agricultural sector generates approaching 2.9 billion tonnes of residue a year globally. West Africa alone produces an estimated 95 Mt/yr of crop residue, of which about 80 Mt are cereal straws and a further 6 Mt cassava and yam peels [1]. The default disposal route in many communities is open-field burning, releasing CO₂, CH₄, N₂O, CO, NO_x and particulates while wasting a feedstock rich in silica, potassium, calcium and iron.

The regional ceramics industry—bricks, refractories, tiles, household ware—depends on finite ball-clay, kaolin, feldspar and quartz whose extraction raises both land degradation and cost [2]. Between 2015 and 2025 these twin pressures stimulated a body of work converting rice-husk, cocoa-pod, cassava-peel, palm-oil and maize residues into ash that can re-enter ceramic bodies as silica, flux or porogen [2], [3]. Rice husk yields about 20 wt% ash containing 80–97% amorphous SiO₂; cocoa-cortex ash is dominated by K₂O (~30

wt%) with subordinate CaO; cassava-peel ash is alkaline with K, Ca and Mg; palm residues combine silica and iron oxide [4], [5].

This review catalogues the West-African resource base, compares residue generation over 2015–2025, reviews ash chemistry and mineralogy, summarises processing routes, and quantifies mechanical and functional performance in bricks, stoneware, refractories, geopolymers, tiles and glass-ceramics.

2. West-African Agro-Waste Resources (2015–2025)

2.1 Rice

West-African rice output climbed from about 3.2 Mt in 1980 to 18.5 Mt in 2018, with Nigeria reaching 8.17 Mt of paddy in 2020 [6], [7]. Paddy comprises 18–22 wt% husk and the husk yields 20–25 wt% ash, typically >60% SiO₂ [8], [9]. Regional husk potential is of order 1.5–3 Mt/yr (Nigeria ~0.6–1.0 Mt/yr). Ash from five large Nigerian mills contained 70.11–81.14 wt% SiO₂, with at least one meeting ASTM C618 Class N [10].

2.2 Cassava

Cassava is the largest West-African crop by tonnage. In 2017 Nigeria produced 59.49 Mt and Ghana 18.47 Mt [11]. Peelings are 30–50 wt% of the fresh root; Nigerian peel available for ashing is roughly 17 Mt/yr at a residue-to-product ratio of 3.0, with stems adding a further large stream [12].

2.3 Cocoa

West Africa supplies about 70% of world cocoa beans. Pod husk is 70–75 wt% of the whole pod; 10 t of fresh pod accompany each tonne of dry bean, implying 12–15 Mt/yr of CPH [13], [14]. Cumulative CPH over two decades has been estimated in the hundreds of megatonnes, with Côte d'Ivoire and Ghana dominant. Annual biochar potential from CPH alone has been put at 869 kt, sequestering >1.59 Mt CO₂-eq/yr [13].

2.4 Oil palm and maize

Ghanaian crude palm-oil output was estimated at 243,852–375,000 t by 2019 [15]. Nigerian empty-fruit-bunch, shell, fibre and effluent streams were already of order 0.3–0.6 Mt each in 2012 [16]; EFB and mesocarp-fibre ashes are rich in SiO₂, K₂O and CaO [17]. Maize expanded rapidly (regional output 18.9 to 56.7 Mt in the early 2010s). Nigerian maize residues alone include 2.06 Mt of cobs and 11.45 Mt of stalks; West-African cereal straw (millet and sorghum) is about 80 Mt/yr [1].

2.5 Comparative generation

Table 1 consolidates mid-range residue and ash estimates. In aggregate the stream treated here now exceeds 50 Mt/yr of residue and is still growing by about 4–6 Mt/yr [18].

Table 1. Principal West-African residues and indicative ash potential, 2015–2025.

Residue	Product trend	Residue (Mt/yr)	Ash (Mt/yr)	Core producers
Rice husk	Paddy doubled	1.3–3.7	0.30–0.80	NG, Mali, CI, SN
Cassava peels	+30% since 2017	12–18	1.5–2.5	NG, GH, CI
Cocoa pod husk	Records every 2–3 yr	12–15	1.0–1.5	CI, GH, NG, CM
Oil-palm EFB + fibre	Slow rise	0.6–1.0	0.10–0.15	GH, NG, CI
Maize stalk	Steady rise	~11.5	~1.7	NG, GH, BJ
Sugarcane bagasse	Marginal in WA	<0.5	0.05–0.10	NG small mills

3. Chemistry and Mineralogy

3.1 Typical compositions

Nigerian RHA contains 70–81 wt% SiO₂ with minor K₂O and LOI [10]. Cocoa-pod ash is K₂O-dominant with secondary CaO and MgO, which is why it fluxes stoneware and porcelain bodies [19]–[21]. Cassava-peel ash is alkaline with appreciable K, Ca and Mg. Table 2 gathers reported oxide ranges.

Table 2. Reported oxide composition (wt%) of West-African agro-waste ashes.

Oxide	RHA	CPA	CPHA	POFA	MSA
SiO ₂	70.1–81.1	55–70	30–45	40–55	60–80
Al ₂ O ₃	0.3–1.5	1–5	2–6	3–8	1–4
Fe ₂ O ₃	0.1–0.6	1–3	2–4	4–7	0.5–1.5
CaO	0.2–1.5	4–8	8–15	5–10	4–8
MgO	0.5–1.5	1–3	3–5	2–5	1–3
K ₂ O	1–3	5–12	25–35	8–15	8–14
Na ₂ O	0.1–0.5	0.5–1.0	0.5–1.5	0.5–1.0	0.5–1.5
LOI	2–8	5–12	8–15	4–10	5–10

3.2 Mineralogy and reactivity

Combustion below 700 °C preserves amorphous SiO₂ and maximises pozzolanic reactivity; above 800 °C cristobalite/tridymite appear and reactivity falls [22], [23]. Optimal calcination is typically 500–700 °C for 2–5 h at heating rates under 10 °C/min [24]. Cassava-peel and cocoa-pod ashes carry alkali carbonates and chlorides that flux early and enable eutectic sintering 100–200 °C below conventional maturing temperatures [19], [21].

4. Processing Routes

4.1 Pre-treatment

As-received ash is sieved to drop unburnt carbon and oversize, then milled to <45 µm [25]. Pre-calcination at 600–800 °C removes residual carbon without crystallising silica [22], [24]. Some Nigerian RHA needed only light grinding to reach pozzolanic compliance [10].

4.2 Forming

Uniaxial pressing at 50–200 MPa is standard for porcelainized stoneware and tiles [26]. Extrusion at about 10 MPa suits clay–CPHA brick bodies [27]. Slip casting serves complex whiteware and biomedical shapes such as Ca-silicate scaffolds from RHA plus eggshell [28]. Hydraulic pressing of clay plus cocoa-pod potash (100–200 g/L) yields geopolymer blocks cured at 60–150 °C [20].

4.3 Sintering

AWA lowers sintering temperature by 50–200 °C through alkali fluxing [19]. Cassava-peel ash enabled DRC kaolinitic clay to reach 16.5 MPa flexural strength at 1200 °C, against 2.3 MPa at 1000 °C without ash; 7.5 wt% CPA at 1000 °C already recovered useful strength [19]. Ten percent cocoa-cortex ash at 1100 °C produced ISO 13006 stoneware: water absorption 2%, density 2.41 g/cm³, flexural strength 32 MPa [21].

5. Properties of AWA–Ceramic Composites

5.1 Mechanical performance

Table 3 maps the principal West-African systems reported between 2015 and 2025. Two patterns recur. Alkali-rich ashes (CPA, CPHA) densify and strengthen when the firing schedule is held high enough to vitrify. Raw peel or high-porosity additions improve insulation but cut compressive strength—an explicit trade-off for non-load-bearing brick.

Table 3. Mechanical performance of selected AWA–ceramic composites.

System	Loading / fire	Strength (MPa)	Other	Ref.
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System	Loading / fire	Strength (MPa)	Other	Ref.
Kaolinitic clay + CPA (DRC chain)	7.5 wt%, 1200 °C	16.5 flex.	—	[19]
Alluvial clay + CCA stoneware	10 wt%, 1100 °C	32 flex.	WA 2.0%; ρ 2.41	[21]
Clay + syenite stoneware	30 wt%, 1100 °C	29.6 flex.	WA 3.87%	[21]
Clay + cocoa-pod potash geo.	≥ 100 g/L, 100–150 °C	>4 comp.	Water-stable	[20]
Refractory + CPA + PKA (NG)	30+30 wt%	standard met	ρ 1.8–2.0; n 25–26%	[29]
Fired clay + raw cassava peel	16 wt%, 1000 °C	comp. $\downarrow$ 72%	bulk –28.8%	[27]
Earth block + CP + coal ash	5+5 wt%, ambient	2.60 comp.	WA 27.8%	[30]
CPA-laterised concrete (NG)	10%+10%, 28 d	25.57 comp.	ρ 2.32	[31]
PET + POFA wall tile	30% PET, pressed	8.37 comp.	WA 0.12%	[32]

5.2 Microstructure, hardness and tribology

CPA suppresses mullite and promotes a glassy bond; the associated 200 °C energy saving at constant strength is one of the most consequential microstructural effects in the set [19], [33]. CCA stoneware contains wollastonite/anorthite and K-feldspar, which is why it meets ISO 13006 at 10% addition [21]. Honeycomb morphology of RHA and palm-fibre ash survives firing and yields closed-pore foams (density ~ 0.27 g/cm³, $k \approx 0.28$ W/m·K) for cladding and dielectric substrates [23], [34]. Vickers hardness of order 380 HV has been reported in related agro-ash glass-ceramics [2], [35].

6. Application Domains

6.1 Fired clay bricks and refractories

Cassava peel at 4–16 wt% in laterite or kaolinitic clay can improve thermal insulation by up to 27% but may cut compressive strength by up to 72% [27]. Refractory bricks with 30 wt% CPA + palm-kernel ash reach bulk densities and porosities compliant with fire-clay practice (~ 2.0 g/cm³, $\sim 26.5\%$ porosity) [29].

6.2 Vitrified stoneware and porcelain

Cocoa-cortex ash outperforms conventional syenite flux in the Cameroonian alluvial-clay system: 10% CCA meets ISO 13006, whereas 30% syenite remains only semi-vitrified [21]. High K₂O lowers the eutectic enough to porcelainize at or below 1175 °C—an immediate substitute where Nigerian and Ghanaian feldspar is scarce or imported.

6.3 Geopolymers and stabilised earth

Potash leached from cocoa pods, dosed at 100–150 g/L and cured at 100–150 °C, yields water-stable blocks above the 4 MPa load-bearing threshold [20]. Blends of cassava peel with coal ash in stabilised earth remain weaker (~ 2.6 MPa) and wetter, so they belong in non-structural walls unless further activated [30].

6.4 Cementitious and tile systems

RHA and oil-palm residues meeting ASTM C618 Class N can replace part of Portland cement in laterised concretes and pozzolan blends [10], [17], [31]. Pressed PET–POFA tiles have reported compressive strength 8.37 MPa with water absorption 0.12% [32]. RHA plus eggshell has been used to form bioactive Ca-silicate scaffolds that grow hydroxyapatite in SBF [28].

6.5 Glass-ceramics

Silica-rich husk and stalk ashes, fluxed by inherent K₂O/CaO, produce low-dielectric glass-ceramics and insulating foams [23], [34]. These remain less industrially mature in West Africa than brick and stoneware routes, but they are the logical destination for the cleanest, highest-silica RHA fractions.

7. Environmental and Economic Considerations

Open-field burning of West-African cocoa pods alone has been estimated at ~17 Mt CO₂-eq/yr [13]. Conversion to biochar or ceramic ash could avoid more than 18 Mt CO₂-eq/yr [13], [22]. Fluxing cuts kiln temperature by 50–200 °C, which is a 10–25% fuel saving in diesel-fired West-African kilns [2], [19]. Residual biomass carbon can supply part of the firing heat, as shown by related biomass-in-clay studies [36].

Avoided Portland cement (USD 100–140/t in the region) and imported feldspar or K₂CO₃ (USD 200–400/t) dominate the project economics. Local FA-class ash often trades below USD 20/t. Yet current practice still leaves the bulk of CPH to rot on-farm, with less than 1% taken as soap feedstock in Ghana and Côte d'Ivoire [14], and cassava peel only marginally digested or composted [12].

8. Conclusions and Recommendations

Over 2015–2025 cocoa-pod husk scaled most dramatically (>5 Mt/yr product-linked residue), followed by cassava peels and rice husk. Together they represent more than 4–6 Mt/yr of ceramic-grade ash at conservative residue-to-product ratios. Flexural strengths of 16.5–32 MPa, water absorption as low as 0.12%, ISO 13006 stoneware, >4 MPa stabilised blocks, and ASTM C618 Class N compliance show that this stream is a raw material, not a liability. Valorization offers a triple dividend: lower agricultural methane and particulates, cheaper ceramic bodies that displace imported feldspar and cement, and kiln decarbonisation through cooler firing.

- Map trace-element effects (especially phosphorus) on glass-ceramic nucleation.
- Quantify processing–microstructure–property relations so bodies can be designed rather than trialled.
- Measure sintering and interfacial kinetics under West-African firing schedules.
- Write regional standards that recognise AWA bricks, tiles and stoneware as structural-grade products.
- Connect cocoa, palm-oil and rice processors to ceramic plants so the documented ~50 Mt/yr residue base becomes a year-round ash supply chain.

Declarations

Conflict of interest

The authors declare no competing interests.

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