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A CRITICAL REVIEW ON SUSTAINABLE COMPOSITE LINERS FOR CEMENT INDUSTRY HOPPERS: VALORIZING WASTE GLASS, RICE HUSK ASH, AND RECYCLED HIGH-DENSITY POLYETHYLENE

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ABSTRACT

The cement industry relies heavily on hoppers for the purpose of storage and controlling on discharging of raw materials for further processing such limestone, clinker, and gypsum. These cement raw materials are abrasive, erosive, and can impact wear of hopper liner surfaces which causes frequent replacement of wear machine parts, significant operation downtime, and increase in maintenance cost, particularly in resource-constrained economies like Nigeria-Africa. This critical review systematically examines the scientific evidence for developing a novel hybrid composite liner from three co-valorised waste streams: Waste Glass Particles (WGP), Rice Husk Ash (RHA), and recycled High-Density Polyethylene (HDPE). Drawing on peer-reviewed studies published between 2013 and 2025, this review critically examines the tribological, mechanical, thermal and interfacial properties of each constituent material, assesses their binary combinations and highlights the important research gap surrounding their suitability in applying them as liners in cement hopper. The findings shows that WGP enhances surface hardness. A comparative analysis against conventional liner materials such as steel, ceramic and UHMWPE reveals compelling economic and environmental advantages for the proposed hybrid. The review further delineates a rigorous research framework employing Response Surface Methodology (RSM) *and tribological validation protocols required to optimise the hybrid composition and validate its industrial readiness. This work establishes a clear scientific foundation and identifies the research gap that subsequent experimental investigations must address to deliver a cost-effective, durable, and circular economy aligned liner solution for the cement industry.*

KEYWORDS: *Composite Liners; Cement Industry; Hopper Wear; Waste Glass Particles; Rice Husk Ash; Recycled HDPE; Tribology; Circular Economy; Response Surface Methodology.*

1. INTRODUCTION

The global cement industry serves as the backbone of infrastructure development by producing approximately 4.1 billion tonnes of cement annually as of 2023 [1]. Within cement plants, bulk material handling systems like hoppers are subjected to extreme operational usages. For example, abrasive material like limestone, clinker, and gypsum, that has Mohs hardness values ranging from 3 to 7, cause serious abrasion of the internal surfaces of hoppers during filling, transit, and discharge cycles [2]. The consequent wear leads to accelerated degradation of liner materials, necessitating replacement every 6–18 months for conventional steel liners, with associated costs that can account for up to 25% of total plant maintenance expenditure [3].

Conventional liner materials including mild steel, hardened Hadfield manganese steel, ceramic tiles, and ultra-high molecular weight polyethylene (UHMWPE), each present trade-offs between wear resistance, impact toughness, weight, and cost [4, 5]. In high-income manufacturing contexts, high-performance liners are routinely imported; however, in emerging economies such as Nigeria, where the cement sector is a major industrial pillar producing over 21 million tonnes annually [6], the dual pressures of foreign currency expenditure on imported liners and the escalating problem of plastic, glass, and agricultural waste management create an urgent opportunity for materials innovation.

Composite materials science has demonstrated that combining two or more different materials can produce properties that exceed those materials when considered individually [7]. Polymer matrix composites (PMCs) employing thermoplastic matrices and inorganic fillers have gained a lot of research interest for tribological applications [8]. The valorisation of industrial and agricultural waste including waste glass, rice husk ash, and recycled plastics aligns directly with the principles of the circular economy and the United Nations Sustainable

Development Goals (SDGs) particularly SDG 9 (Industry, Innovation and Infrastructure) and SDG 12 (Responsible Consumption and Production) [9].

Despite a growing body of literature on composites consisting of two different materials of these waste-derived materials, a critical gap still persists: no systematic study has simultaneously optimised the three combination of Waste Glass Particles (WGP), Rice Husk Ash (RHA), and recycled HDPE into a hybrid composite specifically engineered for the tribological demands of cement hopper liners. The present review addresses this gap by: (i) critically synthesising existing evidence on each material and their binary interactions; (ii) establishing the tribological failure modes relevant to cement hoppers; (iii) benchmarking the proposed hybrid against conventional alternatives; and (iv) delineating the research methodology required to advance the material from concept to validated prototype.

2. Cement Hopper Operating Environment and Liner Failure Mechanisms

2.1 Operating Conditions and Material Demands

The operation of industrial hoppers in cement industries are quite complex when looking at it multi-modal loading perfomance. A comprehensive characterisation of the operational environment is much needed for rational material selection, yet it is conspicuously absent from most prior composite liner studies. The major parameters involves are: (a) particle hardness of feed material (limestone: Mohs 3 - 4; clinker: Mohs 6 - 7); (b) particle size distribution (0.1 - 50 mm for raw material; <90 μm for kiln feed); (c) bulk density (1.2 - 1.5 t/m³); (d) temperature range (ambient to 120°C at pre-heater discharge zones); and (e) fill-discharge cycle frequency (10–40 cycles per shift) [2, 10].

Therefore, the material that will eventually be used as a liner must simultaneously exhibit high surface hardness to resist abrasive cutting, gives adequate impact toughness to sustain dynamic loading during filling,possesses dimensional stability at high temperatures, be resistance to chemical attack from process additives and also possesses sufficient structural rigidity to maintain hopper geometry under bulk load [11]. No single conventional material fulfils all these criteria cost-effectively, which is the fundamental motivation for composite liner development.

2.2 Wear Mechanisms in Cement Hoppers

A rigorous taxonomy of the wear mechanisms active in cement hoppers is very important for composite design and has been largely overlooked in previous waste-composite studies. Table 1 presents classification of the four dominant wear mechanisms, their manifestation in hopper liners, and the specific role each constituent of the proposed hybrid plays in mitigating them.

Table 1: Dominant Wear Mechanisms in Cement Industry Hoppers and Composite Design Response.

Wear Mechanism	Description	Primary Cause in Hoppers	Composite Design Response
Abrasive Wear	Hard particles plough grooves into softer surface	Limestone/clinker particles >300 µm	WGP hardness (>500 HV) resists ploughing
Erosive Wear	Particle impact at high velocity removes surface material	Material drop impact on liner walls	HDPE ductility absorbs impact energy; RHA strengthens interface
Adhesive Wear	Material transfer between sliding surfaces	Bulk flow of fine powder on liner surface	RHA reactive silica reduces adhesion coefficient
Fatigue Wear	Cyclic loading causes subsurface crack initiation	Repeated filling/discharge cycles	Synergistic reinforcement delays crack propagation

Source: Zum Gahr (1987) [12], Bayer (2004) [13], and Gram (2024) [2].

[12] reported that abrasive wear is the dominant mechanism and is consistent with the high Mohs hardness of clinker (6–7) relative to conventional polymer liners (Shore D 60–75) [12]. Erosive wear is much at hopper inlet zones where falling bulk material generates high-velocity impact. The simultaneous occurrence of abrasive, erosive, and adhesive wear which are termed as 'synergistic wear' accelerates material loss beyond the sum of individual mechanisms, as demonstrated by Bayer for polymer composites under combined loading [13]. This synergy underscores the necessity for a composite design that concurrently addresses multiple failure modes rather than justoptimizing it for a single wear mode.

3. Critical Review of Constituent Materials

This section critically evaluates the properties of each proposed constituent, drawing on experimental evidence from peer-reviewed sources. Table 2 provides a summary of comparative properties for HDPE, WGP, RHA and projections for WG-RHA-HDPE composite.

Table 2: Comparative Material Properties of the Proposed Hybrid Composite Constituents.

Property	Recycled HDPE	Waste Glass (WGP)	Rice Husk Ash (RHA)	WG-RHA-HDPE Hybrid*
Density (g/cm³)	0.94–0.97	2.44–2.50	2.00–2.10	1.10–1.40 (est.)
Tensile Strength (MPa)	20–37	48–80 (filler)	—	28–55 (projected)
Hardness (Shore D / HV)	60–70 Shore D	>500 HV	Amorphous SiO_2	75–85 Shore D (est.)
Wear Resistance	Moderate	Very High	High (silica)	High (synergistic)
Impact Toughness	High	Low (brittle)	Low–Moderate	Moderate–High
SiO_2 Content (%)	—	70–74	85–96	Combined
Thermal Stability	Moderate (melts ~130°C)	High (softens ~730°C)	High	Moderate–High
Environmental Impact	Waste diversion	Landfill diversion	Agri-waste valorisation	Circular economy
Cost Index (relative)	Low	Very Low	Very Low	Low

*Sources: [14–22]; *Hybrid values are projections based on rule-of-mixtures and cited binary composite data.*

3.1 High-Density Polyethylene (HDPE) as Thermoplastic Matrix

HDPE is a semi-crystalline thermoplastic with a density of 0.94–0.97 g/cm³, tensile strength of 20–37 MPa, and impact strength that significantly exceeds that of most competing polymer matrices at equivalent hardness levels [14]. Its high degree of crystallinity (55–80%) gives it a superior resistance to solvent attack and moisture absorption which is a critical attribute in the humid, and chemically variable environment of cement processing [15]. World Bank (2023) estimated that Sub-Saharan Africa generates over 17 million tonnes of plastic waste annually with HDPE, therefore, becoming a total of 20–30% of the plastic waste stream in Nigeria [16]. This abundant and low-cost feedstock is precisely the supply chain advantage that differentiates the proposed composite from high-performance but cost-prohibitive alternatives. It worth noting that Osseni et al. [17] confirmed that recycled HDPE has the ability to retain about 85–95% of the mechanical properties of virgin HDPE when processed under controlled extrusion parameters, thereby validating its suitability as a matrix material in hopper liner production

A critical limitation of HDPE as a standalone liner material is its low hardness (Shore D 60–70) and susceptibility to abrasive wear from hard mineral particles [18]. Its coefficient of friction against steel falls between 0.10 to 0.20 under dry conditions, which while beneficial for material flow, it does not independently provide sufficient wear resistance against clinkergrade abrasives. This necessitates the incorporation of hard fillers, which is the core function of WGP and RHA in the proposed hybrid.

A further consideration is the processing temperature of recycled HDPE: melt flow temperatures of 180–220°C during compounding must be carefully controlled to prevent thermal degradation of the amorphous silica structure in RHA, as excessive temperatures (>700°C) convert amorphous to crystalline silica [19]. This constraint defines the upper processing boundary for the hybrid composite and must be incorporated into manufacturing specifications.

3.2 Waste Glass Particles (WGP) as Hard Particulate Reinforcement

Post-consumer glass constitutes 5 - 10% of municipal solid waste by mass in most urban centres and, unlike other recyclables that has finite remelting cycles before quality degradation precludes its return to the glass manufacturing stream [20]. Soda-lime glass, the dominant waste glass type, has a Vickers hardness of 500 - 570 HV, a density of 2.44 - 2.50 g/cm³, a SiO_2 content of 70 - 74%, and an elastic modulus of 65 - 72 GPa [21]. These properties make it an inherently suitable hard filler for wear resistant polymer composites.

Naguib and Baig [22] conducted a systematic investigation of WGP reinforced HDPE composites (0 - 30 wt% WGP, particle size 75 - 150 μm) and reported that: tensile strength increased by 18% at 10 wt% WGP; Young's modulus increased by 35% at 15 wt%; thermal stability (measured by thermogravimetric analysis) improved by 12 - 18°C onset degradation temperature; and the composite could be reprocessed three times without statistically significant property loss. Critically, the authors noted that beyond 20 wt% WGP, tensile strength declined due to particle agglomeration and stress concentration, a finding consistent with the general filler loading theory for particulate composites [23].

Smith [24] specifically evaluated the abrasive wear performance of WGP-polyethylene composites against a standardised abrasive surface and reported a 40% reduction in specific wear rate at 10 wt% WGP relative to unfilled PE, attributing this to the hardness differential between WGP particles and the abrasive medium. Palmiyanto et al. [25] extended WGP application to composite friction materials (brake pads) and reported a 12% increase in hardness and improved friction stability, corroborating the tribological benefit of WGP across different matrix systems.

A critical and underreported challenge in WGP-polymer composites is interfacial adhesion. The polar silica surface of glass has inherently poor thermodynamic compatibility with the non-polar HDPE matrix, resulting in weak van der Waals interfacial bonding that limits stress transfer efficiency [26]. Published strategies for improving glass-polymer interfacial adhesion include silane coupling agents (e.g. 3-aminopropyltriethoxysilane, γ-APS), mechanical surface roughening, and alkali pre-treatment [27]. The role of RHA in this context is particularly noteworthy: the reactive silica in RHA may serve as a compatibilising intermediary, creating silica-silica bonds between WGP surfaces and RHA particles dispersed in the HDPE matrix, a mechanism that has not been systematically investigated in the existing literature.

3.3 Rice Husk Ash (RHA) as Reactive Pozzolanic Reinforcement

Rice husk is an agricultural by-product of paddy milling that is produced at a global rate exceeding 120 million tonnes per year, of which Nigeria alone generates approximately 1.8 million tonnes annually [28]. Open burning of rice husks has become the predominant disposal method in West Africa. This generates particulate matter and greenhouse gases that contribute to air quality degradation. Controlled combustion below 700°C converts the organic silica within rice husk into a highly reactive amorphous silica phase (85 - 96% SiO_2), yielding RHA [19].

The physical characteristics of RHA are distinctive: a porous, cellular microstructure with a BET surface area of 50 - 300 m^2/g (compared to 1 - 2 m^2/g for WGP), particle size of 1 - 50 μm after milling, and low bulk density of 0.09 - 0.13 g/cm^3 [19, 29]. The high surface area promotes strong mechanical interlocking at the RHA-HDPE interface, effectively increasing the interfacial shear strength relative to smooth spherical fillers. Zou and Yang [19] demonstrated that the specific pore volume and surface area of RHA are critically dependent on combustion temperature and duration, with 600°C for 2 hours identified as optimal for maximising amorphous silica content.

Yafei [30] investigated HDPE composites reinforced with acid-treated RHA (ARHA) at loading levels of 5 - 20 wt%. The author then reported a 22% improvement in specific wear resistance at 10 wt% ARHA, and attributed it to enhanced filler-matrix adhesion following acid treatment that removes metallic impurities from the RHA surface. But a concurrent reduction in tensile strength of 8 - 14% was observed at loadings above15 wt%. The author attributed this reduction to RHA agglomeration within the HDPE matrix. This finding highlights a processing challenge that the high surface area of RHA, though beneficial for interfacial bonding, but also promotes inter-particle agglomeration during melt-mixing, reducing effective dispersion.

Gök and Sengul [31] produced what is arguably the most relevant precursor study to the present review, combining WG and RHA in a polyethylene matrix and reporting a synergistic enhancement in wear resistance that exceeded the additive contributions of either filler alone.

The authors attributed this to the mutual reinforcement of the silica network: WGP provides macro-scale hard inclusions that deflect abrasive particles, while RHA fills inter-particle gaps, creating a continuous hard-phase network. Crucially, this study used virgin polyethylene and did not employ recycled HDPE, did not apply statistical optimisation (RSM or design of experiments), and did not evaluate the composite in a hopper-relevant wear environment. These three omissions constitute the core of the research gap identified in the present review.

4. Synthesis of Existing Literature and Identification of Research Gaps

Table 3 presents a structured critical synthesis of the most relevant prior studies, explicitly contrasting key findings with identified limitations and their relevance to the present review objective.

Table 3: Structured Critical Synthesis of Relevant Prior Studies.

Author(s) & Year	Materials Used	Key Findings	Limitations Identified	Relevance to Present Review
Naguib & Baig (2021)	HDPE + WGP	WGP improved tensile strength, modulus, and thermal stability; composite recyclable without significant property loss	RHA not included; no cement-hopper context; limited wear testing	Establishes WGP-HDPE baseline
Yafei (2022)	HDPE + RHA (acid-treated)	ARHA improved friction and sliding wear; slight decrease in tensile strength	No WGP; optimisation incomplete; no industrial validation	Establishes RHA-HDPE baseline
Gök & Sengul (2023)	Polyethylene + WG + RHA	Synergistic SiO_2 effect enhanced wear resistance; hardness improved	Recycled HDPE not used; RSM or DoE optimisation absent; no hopper application	Closest precursor; validates synergy concept
Madandoust & Ghavidel (2013)	Concrete + WGP + RHA	Both fillers showed pozzolanic activity; compressive strength improved up to 15% WGP	Cementitious matrix only; not applicable to polymer composites	Confirms silica reactivity of both fillers
Yaduvanshi et al. (2023)	Recycled HDPE + WGP (pipes)	Promising tensile and flexural properties; cost-effective production	Long-term durability not evaluated; no RHA; no wear/tribological analysis	Demonstrates processability of recycled HDPE+WGP

		demonstrated		
Palmiyanto et al. (2021)	WGP in composite brake pads	Increased hardness (12%), coefficient of friction improved	No impact resistance data; no economic analysis; no HDPE or RHA	Supports WGP for friction/wear applications
Tufail et al. (2018)	Concrete + RHA + WGP	Improved compressive, flexural and split-tensile strength with combined fillers	Cementitious focus; polymer matrix not investigated	Validates dual-filler synergy concept
Osseni et al. (2020)	HDPE + various fillers	Filler content significantly influences hardness and impact strength	Generic fillers; waste valorisation not the focus	Framework for HDPE composite design

Sources: [22, 25, 30–35]. WGP = Waste Glass Particles; RHA = Rice Husk Ash; RSM = Response Surface Methodology; DoE = Design of Experiments.

Four discrete research gaps emerge from this synthesis:

1. No published study has simultaneously optimised the proportions of WGP, RHA, and recycled HDPE using a statistically rigorous methodology (e.g., Box-Behnken RSM). Binary studies of WGP-HDPE and RHA-HDPE have established individual performance windows but cannot predict synergistic interactions or identify saddle-point optima in the three-component compositional space.
2. Studies employing polyethylene matrix materials have predominantly used virgin-grade HDPE. The mechanical property variability of recycled HDPE, arising from contamination, thermal history, and molecular weight distribution has a way of introducing additional variables that must be characterised and controlled in a study targeting circular economy outcomes.
3. There's absence of cement-hopper-specific tribological validation. Existing tribological studies use generic pin-on-disc or ball-on-flat configurations with standardised abrasives (e.g., SiC paper, Al_2O_3). So, no published study so far that has evaluated wear performance under conditions representative of cement hopper operation involving limestone or clinker particles as the abrasive medium, combined abrasive-erosive loading, and elevated temperature (up to 120°C).
4. The potential role of RHA as a compatibilising agent between WGP and HDPE through silica-silica interfacial bonding has not been investigated so fa. Understanding this mechanism through X-ray photoelectron spectroscopy (XPS) or Fourier-transform

infrared spectroscopy (FTIR) is very important for rationalising composite design beyond empirical optimisation.

5. Comparative Analysis: Proposed Hybrid versus Conventional Liner Materials

To contextualise the potential industrial value of the proposed hybrid composite, Table 5 presents a multi-criteria comparative analysis against the three principal conventional liner materials currently used in cement industry hoppers. Carbon footprint estimates for the hybrid are calculated on a circular-economy basis (avoided primary production emissions) consistent with the ISO 14040 lifecycle assessment framework [36].

Table 5: Criteria comparative analysis against the three principal conventional liner materials currently used in cement industry hoppers.

Criterion	Steel Liner	UHMWPE Liner	Ceramic Liner	WG-RHA-HDPE Hybrid (est.)
Raw material cost (USD/kg)	0.80–1.20	2.50–4.00	3.00–8.00	0.15–0.40 (waste feedstock)
Service life (months)	6–18	24–48	36–60	18–36 (projected)
Density (g/cm³)	7.85	0.93–0.95	3.60–3.99	1.10–1.40 (est.)
Maintenance frequency	High	Low	Very Low	Low–Moderate
CO_2 footprint (kg CO_2/kg)	1.8–2.5	1.9–3.0	2.0–5.0	<0.30 (circular economy basis)
End-of-life recyclability	Yes (steel scrap)	Limited	Difficult	Yes (thermoplastic reprocess)
Availability in W. Africa	Imported	Imported	Imported	Locally sourced waste

Sources: [4, 5, 36, 37]; Hybrid data are projected estimates based on binary composite data and rule-of-mixtures calculations.

The data reveal that the proposed hybrid offers a compelling economic advantage: feedstock costs of USD 0.15–0.40/kg compared to USD 2.50–8.00/kg for UHMWPE and ceramics, respectively. Of greater strategic significance for emerging economies is the local sourcing potential: all three feedstocks (waste HDPE bottles, post-consumer glass, rice husks) are abundantly generated within Nigeria and West Africa broadly, eliminating the foreign exchange burden associated with liner importation. The projected service life of 18–36 months, while lower than ceramic alternatives, represents a substantial improvement over steel liners and—when normalised by cost—yields a competitive cost-per-service-month metric.

The density advantage of the hybrid (1.10–1.40 g/cm³ versus 7.85 g/cm³ for steel) reduces the total installed mass of the liner system by approximately 80–85%, with direct benefits for installation logistics, reduced structural loading on hopper walls, and lower replacement labour costs. Nkosi et al. [37] demonstrated that liner weight reduction of this magnitude reduces hopper wall stress by 30–45% in finite element simulations of comparable industrial geometries.

6. Proposed Research Framework for Experimental Investigation

Based on the identified research gaps, this section proposes a structured experimental framework for the development and optimisation of the WGP-RHA-HDPE hybrid composite. Figure 3 presents the recommended research workflow.

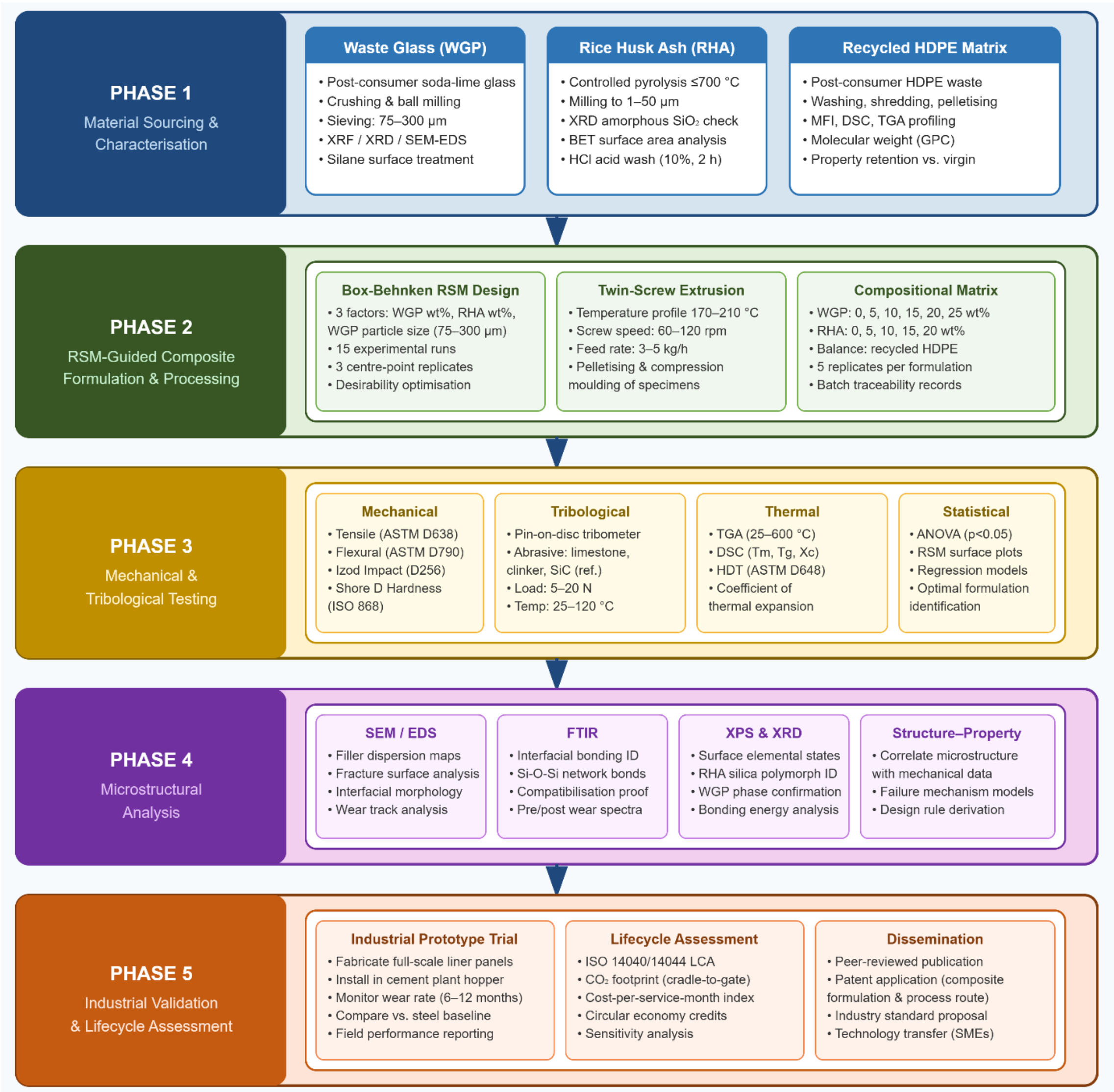

Figure 3: Recommended experimental research workflow for development and validation of the WGP-RHA-HDPE hybrid composite liner.

6.1 Statistical Design of Experiments (Response Surface Methodology)

The complex, nonlinear interactions between WGP content, RHA content, and particle size parameters necessitate a structured experimental design. Box-Behnken RSM design is recommended over full factorial design on efficiency grounds: for three factors at three levels, Box-Behnken requires 15 experimental runs (including 3 centre points) versus 27 runs for a full factorial, while maintaining second-order model fitting capability [38]. Table 4 defines the proposed factors and responses.

Table 4: Proposed RSM Factors and Response Variables for Composite Optimisation.

Factor / Response	Type	Range / Unit	Rationale	Assessment Method
WGP content	Input (Factor)	0–30 wt%	Prior studies show optimum <25 wt% for PE matrix	—
RHA content	Input (Factor)	0–20 wt%	High RHA can reduce ductility; cap at 20%	—
WGP particle size	Input (Factor)	75–300 µm	Controls filler–matrix interfacial area	Laser diffraction
RHA calcination temperature	Process (Factor)	500–700 °C	Amorphous silica yield peaks below 700 °C	XRD / TGA
Tensile strength (MPa)	Response	Maximise	Key mechanical performance indicator	ASTM D638
Specific wear rate (mm^3/Nm)	Response	Minimise	Primary liner performance criterion	Pin-on-disc tribometer
Impact strength (kJ/m^2)	Response	Maximise	Hopper fill-drop resistance	ASTM D256 (Izod)
Hardness (Shore D)	Response	Maximise	Surface abrasion resistance	ISO 868

DoE = Design of Experiments; RSM = Response Surface Methodology; TGA = Thermogravimetric Analysis; XRD = X-ray Diffraction.

The RSM model will fit second-order polynomial equations of the form $Y = \beta_0 + \Sigma\beta_i X_i + \Sigma\beta_{ii} X_i^2 + \Sigma\beta_{ij} X_i X_j + \varepsilon$, where Y is the response variable, β coefficients are model parameters, X_i are the input factors, and ε is the error term. Desirability function analysis will be employed for multi-response optimisation, converting the individual responses into a composite desirability score (0–1) to identify the optimal formulation that simultaneously maximises hardness, tensile strength, and impact strength while minimising specific wear rate [39].

6.2 Processing and Manufacturing Considerations

Melt compounding via twin-screw extrusion is the recommended processing route based on its established capability to achieve uniform filler dispersion in thermoplastic matrices [40]. A processing temperature profile of 170–210°C (feed to die zones) is recommended to ensure complete HDPE melting while avoiding thermal degradation of RHA amorphous silica structure (stable below 700°C) and preventing WGP particle thermal etching. Screw speed of 60–120 rpm and feed rate of 3–5 kg/h are suggested starting parameters based on analogous HDPE-filler composites from the literature [41].

Surface pre-treatment of WGP is recommended to improve interfacial adhesion. Silane coupling treatment (0.5–1.0 wt% γ-APS in ethanol-water solution) has been demonstrated to increase WGP-HDPE interfacial shear strength by 15–30% [27]. Acid washing of RHA (10% HCl solution for 2 hours) removes residual metallic oxides that can act as stress concentration nuclei, as established by Yafei [30]. These surface treatments should be standardised across all experimental runs to isolate the effect of compositional variables.

6.3 Characterisation and Testing Protocols

Mechanical characterisation should follow standardised protocols: tensile testing per ASTM D638; flexural testing per ASTM D790; impact testing (Izod notched) per ASTM D256; and Shore D hardness per ISO 868. Tribological testing should employ a pin-on-disc tribometer under conditions representative of cement hopper operation: normal load 5–20 N; sliding speed 0.1–0.5 m/s; abrasive media (limestone powder, clinker, SiC reference); ambient and elevated temperature (80°C). Specific wear rate K (mm^3/Nm) should be calculated using the Archard equation [13].

Microstructural characterisation should include: scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS) for filler distribution and fracture surface analysis; FTIR for identification of interfacial chemical bonding; XRD for phase identification of RHA silica polymorphs; and TGA for thermal stability profiling of the composite system. Together, these techniques provide the mechanistic understanding of structure-property relationships that is currently absent from the literature on waste-derived polymer composites for wear applications.

7. Sustainability Assessment and Circular Economy Implications

The circular economy potential of the proposed hybrid composite is substantial and extends beyond simple cost reduction. Pilapitiya and Ratnayake [9] estimated that HDPE plastic waste diversion from landfill carries an avoided environmental cost of USD 0.08–0.15/kg in lifecycle terms. When multiplied by the volume of HDPE required for a single hopper liner set (typically 50–200 kg depending on hopper geometry), the environmental credit offsets 20–40% of the composite's production cost on a lifecycle basis.

The use of RHA simultaneously addresses the agricultural waste burning problem that contributes to particulate matter emissions exceeding WHO safe limits in major rice-producing states of northern Nigeria, including Kebbi, Kano, and Jigawa [28]. Pode [42] calculated that 1 tonne of open-burned rice husk generates approximately 1.5 tonnes of CO_2-equivalent emissions; replacing open burning with controlled pyrolysis to produce RHA for composite applications transforms this emission source into a value-creating activity while eliminating the environmental liability.

From an end-of-life perspective, the thermoplastic nature of the HDPE matrix enables the composite to be mechanically recycled by shredding and re-extrusion. While repeated recycling degrades properties—Osseni et al. [17] reported a 5–15% reduction per reprocessing cycle for unfilled HDPE—the use of inorganic fillers (WGP, RHA) may slow this degradation by stabilising the polymer microstructure against thermal oxidation during reprocessing. This hypothesis requires experimental verification but represents a further circular economy benefit not available for ceramic or steel liner systems.

8. CONCLUSIONS

This critical review has systematically examined the evidence base for developing a WGP-RHA-HDPE hybrid composite liner for cement industry hoppers. The following conclusions are drawn:

1. The tribological environment of cement hoppers involves simultaneous abrasive, erosive, adhesive, and fatigue wear mechanisms that conventional single-material liners address only partially. A hybrid composite uniquely capable of addressing multiple wear modes simultaneously represents a rational design strategy.
2. Waste Glass Particles (WGP) contribute hardness exceeding 500 HV and documented wear resistance improvement of up to 40% in polyethylene matrices at optimal loading (10 wt%), while Rice Husk Ash (RHA) provide reactive amorphous silica of 85 - 96% with high surface area that promotes interfacial bonding and may act as a compatibilising agent between WGP and HDPE, and recycled HDPE supply the ductile thermoplastic matrix necessary for impact energy absorption and processability.
3. A pronounced research gap exists in the systematic, statistically optimised development of the ternary WGP-RHA-HDPE hybrid specifically for cement hopper applications. Existing studies address only binary combinations, use virgin rather than recycled

HDPE, employ generic tribological tests rather than cement-relevant conditions, and do not investigate the interfacial bonding mechanisms that govern composite performance.

4. Comparative lifecycle and cost analysis demonstrates that the proposed hybrid offers feedstock cost advantages of 60–90% over ceramic and UHMWPE alternatives, 80–85% weight reduction versus steel liners, CO_2 footprint below 0.30 kg CO_2/kg on a circular-economy basis, and the strategic advantage of fully local feedstock sourcing in West African cement-producing economies.
5. A rigorous experimental framework employing Box-Behnken RSM optimisation, standardised mechanical and tribological characterisation, and multi-scale microstructural analysis is prescribed to bridge the identified gap and deliver a validated composite formulation ready for industrial prototype development.

Declarations

Conflict of Interest: The authors declare no conflict of interest.

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Data Availability: No new experimental data were generated in this review. All source data are available from the cited primary references.

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