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Production, Application, and Performance Evaluation of Eco-Friendly Acrylic Emulsion Paints from Low-Cost Indigenous Raw Materials, A Sustainable and Innovative Green Coating Solution.

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Abstract

The global coatings industry faces mounting pressure to reduce reliance on petroleum-derived, volatile organic compound (VOC)-laden formulations and promote sustainable and innovative, low-toxicity alternatives. This study investigates the production, application, and comprehensive performance evaluation of eco-friendly acrylic emulsion paints formulated from low-cost indigenous raw materials sourced in Nigeria. Three paint formulations (A, B, and C) were systematically developed by partially substituting conventional synthetic extenders with modified cassava starch as modifier and binder, palm kernel shell (PKS) ash as extender and bulk and neem leaf extract as a biocide. Standard physicochemical and performance tests including viscosity, pH, density, fineness of grind, spreading rate, drying time, opacity (contrast ratio), adhesion, scrub resistance, water absorption, VOC content, and heavy metal analysis were conducted in accordance with Nigerian Industrial Standards (NIS), British Standards (BS 3900), and ASTM protocols. Results demonstrated that Formula C, incorporating the highest proportion of bio-based indigenous additives, outperformed commercial-grade paints in scrub resistance (2,430 cycles), adhesion (Grade 0), water resistance, and VOC emission (19 g/L), significantly below the 50 g/L eco-label threshold. Production cost analysis revealed savings of approximately 55–64% compared to equivalent commercial products. The findings confirm that these locally sourced indigenous materials can serve as viable, sustainable, and cost-effective components in green paint synthesis, offering significant economic,

environmental, and technological benefits for the Nigerian coating industry and developing economies at large.

Keywords: Eco-Friendly Paint, Gum Arabic Acrylic Emulsion, Green Synthesis, Indigenous Raw Materials, Cassava Starch, Palm Kernel Shell Ash, Sustainable Coatings, Low-Voc, Biocide

1. Introduction

Paints and surface coatings represent one of the oldest applied chemistry technologies known to human civilisation, serving the dual functions of aesthetic beautification and substrate protection. The global coatings market was valued at approximately USD 177 billion in 2023 and is projected to reach USD 245 billion by 2030, driven largely by growth in the construction, automotive, and industrial sectors (Grand View Research, 2024). However, this remarkable economic growth has come at a significant environmental and public health cost. Conventional solvent-borne paints contain high concentrations of volatile organic compounds (VOCs), heavy metals such as lead and cadmium, and synthetic biocides that contribute to air pollution, ground contamination, and chronic human toxicity (Lambourne & Strivens, 2020).

In response to these concerns, international regulatory frameworks, including the European Union Paints Directive, the US Clean Air Act, and various national environmental protection standards, have increasingly imposed strict limits on VOC emissions and hazardous substance content in coatings. This has accelerated a global paradigm shift towards water-borne, low-VOC, and ultimately bio-based paint formulations. Acrylic emulsion paints represent the dominant category within this transition, owing to their superior water resistance, adhesion, flexibility, and comparatively lower environmental impact relative to alkyd and solvent-borne systems (Wicks et al., 2007).

In developing economies such as Nigeria, the paints and coatings sector is a critical component of the manufacturing industry. Nigeria's paint market was estimated at NGN 150 billion in 2022, with demand driven primarily by the construction boom in urban centres (Lagos, Abuja, Port Harcourt) and rehabilitation of public infrastructure. However, the sector is characterised by near-total dependence on imported raw materials, particularly titanium dioxide (TiO_2), acrylic polymers especially Poly vinyl acetate, synthetic extenders, and chemical biocides, which account for approximately 60–75% of total production costs. This import dependency renders the industry highly vulnerable to foreign exchange fluctuations, global supply chain disruptions, and inflationary pressures, ultimately driving up consumer prices and limiting access to quality coatings for lower-income populations (Okafor et al., 2021).

An urgent opportunity exists; therefore, to harness Nigeria's abundant agricultural wastes and mineral resources as cost-effective, locally sourced inputs for paint production. Materials such as cassava starch (Nigeria is the world's largest cassava producer), palm kernel shell ash (a by-product of the thriving palm oil industry), kaolin and talc (both mined in substantial quantities within the country), calcium carbonate (from extensive limestone deposits), and neem leaf extract (from ubiquitous Azadirachta indica trees) represent largely untapped feedstocks with considerable potential as functional paint components. Their utilisation would simultaneously reduce production costs, minimise waste, and align the coatings industry with national sustainability objectives, including Nigeria's Vision 2050 and commitments under the Paris Agreement.

Despite growing academic interest in bio-based paint components globally, systematic studies integrating multiple indigenous Nigerian raw materials into a single, performance-validated acrylic emulsion paint formulation remain sparse in the literature. Most existing studies focus on single-ingredient substitutions, employ laboratory-scale evaluations without rigorous multi-parameter performance benchmarking, or fail to address cost-effectiveness comprehensively. This study addresses these **gaps** by developing, producing, and rigorously evaluating three eco-friendly acrylic emulsion paint formulations incorporating varying proportions of indigenous bio-based materials, benchmarked against standard commercial paint performance criteria.

1.1. Aims and Objectives

The central aim of this research is to develop eco-friendly, cost-effective, and technically sound acrylic emulsion paint formulations using low-cost indigenous Nigerian raw materials, and to evaluate their performance against established standard requirements for decorative interior and exterior wall coatings.

The specific objectives of the study are:

To identify, characterise, and assess the technical suitability of locally available raw materials — including cassava starch, palm kernel shell ash, neem leaf extract, kaolin, talc, and calcium carbonate as functional components in acrylic emulsion paint production;

To develop three distinct paint formulations (Formulas A, B, and C) with progressively increasing substitution of conventional synthetic extenders and additives with indigenous bio-based alternatives;

To produce pilot-scale batches of each formulation using systematic mixing and homogenisation protocols, ensuring reproducibility and consistency;

To evaluate the physicochemical, performance, and durability properties of the produced paints in accordance with NIS 157, BS 3900, and ASTM D standards;

To assess the environmental credentials of the formulations through VOC content determination and heavy metal analysis;

To conduct a comparative cost analysis between the indigenous formulations and equivalent commercially available acrylic emulsion paints;

To identify the optimal formulation that maximises performance, environmental benefit, and cost savings, and to recommend pathways for scale-up and industrial adoption.

2. Literature Review

2.1. Evolution of Water-Borne Acrylic Emulsion Paints

Acrylic emulsion paints were first commercialised in the 1950s as a less toxic alternative to oil-based alkyd systems. The fundamental formulation comprises four principal categories of ingredients: (1) the binder, typically a Polyvinyl acetate(PVA) or pure acrylic latex copolymer that imparts adhesion, flexibility, and film-forming properties; (2) pigments, primarily titanium dioxide (rutile form) for opacity and colour; (3) extender pigments, minerals such as calcium carbonate, kaolin, talc, and mica that provide bulk, improve rheology, and reduce cost without significantly compromising performance; and (4) additives, comprising dispersants, defoamers, preservatives, coalescents, and rheology modifiers (Kittel, 2016). The transition from solvent-borne to water-borne binders dramatically reduced VOC emissions, making these systems acceptable under increasingly stringent environmental regulations while maintaining technical performance comparable to their solvent-borne counterparts.

Significant advances in polymer chemistry during the 1980s and 1990s enabled the development of 'all-acrylic' latexes with superior exterior durability, chalking resistance, and colour retention compared to earlier VAE-based systems. The introduction of core-shell latex particles, where a hard acrylic core provides film strength while a softer shell promotes film formation at ambient temperatures, further expanded the performance envelope of acrylic emulsion paints (Wicks et al., 2007). More recently, the incorporation of nano-sized additives, including nano-TiO_2 for photocatalytic self-cleaning properties and nano-clay for improved barrier performance has represented the cutting edge of conventional acrylic paint technology (Hashim et al., 2019).

2.2. Bio-Based and Indigenous Components in Paint Formulation

The utilisation of bio-derived materials in coatings has attracted substantial research attention globally. Starch, derived from a variety of botanical sources, has been explored as a thickening agent, rheology modifier, and partial binder supplement. Iji et al. (2020) demonstrated that cassava starch, when gelatinised and functionalised through esterification, exhibited film-forming properties sufficient to partially replace up to 15% of the synthetic polymer binder in emulsion systems, with acceptable consequences for viscosity and adhesion. Similarly, corn starch-based rheology modifiers have been incorporated into latex paint systems with comparable performance to synthetic hydroxyethyl cellulose (HEC) thickeners (Olusegun & Adeyinka, 2019).

Agricultural waste materials have also received considerable attention. Agbo et al. (2018) investigated palm kernel shell (PKS) ash a high-silica, high-calcium waste residue from the palm oil extraction industry as an extender pigment in emulsion paint. Their study reported that PKS ash at 3–5% loading provided improved moisture absorption resistance without significantly compromising opacity or film integrity. The high silica content (SiO_2 >40%) of PKS ash contributes to hardness and abrasion resistance of the dried paint film, a property exploitable in high-traffic areas. Yusuf et al. (2021) corroborated these findings, additionally noting that PKS ash functioned as a partial alkaline pH buffer, contributing to formulation stability.

Neem (*Azadirachta indica*) extract has long been established in ethnobotany as a potent broad-spectrum antimicrobial agent, with active compounds including azadirachtin, nimbin, nimbidin, and gedunin exhibiting documented antifungal and antibacterial activity (Biswas et al., 2002). In paint formulations, synthetic biocides such as isothiazolinones (Kathon CG, MIT, BIT) are routinely employed to prevent microbial degradation of the wet paint and to provide in-can preservation. Ugwu and Ikenna (2022) demonstrated that neem leaf ethanol extract at a 0.5% loading provided equivalent antifungal efficacy against Aspergillus niger and Penicillium citrinum compared to standard synthetic biocide concentrations, while significantly reducing the overall hazard profile of the formulation.

Kaolin, calcium carbonate, and talc have well-documented roles as extender pigments in paint technology. Nigeria possesses substantial deposits of kaolin in Ekiti, Cross River, and Borno States, as well as talc reserves in Osun and Niger States, though exploitation for domestic industrial applications has remained underdeveloped relative to export potential (RMRDC, 2020). Studies by Adesanya and Raheem (2009) demonstrated the technical viability of Nigerian kaolin as a paint extender, achieving acceptable brightness, particle size distribution ($D_{50} \approx 5–10$ µm), and oil absorption values consistent with imported Chinese kaolin specifications. These findings reinforce the economic and technical case for domestic sourcing of mineral extenders.

2.3. Environmental Sustainability in the Coatings Industry

The environmental impact of paint production and application spans the entire product lifecycle from raw material extraction and manufacturing energy consumption, through in-use VOC emissions during application and curing, to end-of-life disposal of paint waste and containers. VOCs from paint formulations contribute to ground-level ozone formation, photochemical smog, and indoor air quality deterioration, with proven links to respiratory illness, neurological damage, and carcinogenesis at elevated exposures (Brown et al., 2021). The WHO has classified several common paint VOCs including benzene, toluene, formaldehyde, and various glycol ethers as Group 1 or Group 2A carcinogens.

The concept of green chemistry, as articulated through the twelve principles of Anastas and Warner (1998), provides a robust framework for re-engineering paint formulations towards greater sustainability. Key principles applicable to paint production include: (i) prevention of waste through atom-efficient formulation; (ii) design for degradability; (iii) use of renewable feedstocks; (iv) minimisation of auxiliary substances; and (v) inherently safer chemistry. The integration of bio-based indigenous materials aligns directly with these principles, offering a pathway to coatings that are safer in production, application, and disposal, while supporting circular economy goals by valorising agricultural and mining waste streams (Anastas & Eghbali, 2010).

Life cycle assessment (LCA) studies of bio-based versus conventional paint formulations consistently demonstrate environmental advantages for bio-based systems across multiple impact categories, including global warming potential, cumulative energy demand, and eutrophication potential, though human toxicity impact comparisons are more nuanced and depend heavily on the specific bio-sourcing practices employed (Rydberg & Fröling, 2017). These findings provide scientific support for the hypothesis that indigenous bio-based paint formulations can achieve superior environmental performance relative to fully synthetic alternatives, provided raw material extraction and processing are managed sustainably.

2.4. Research Gaps and Justification

A critical review of the existing literature reveals several significant gaps that this study seeks to address. First, while individual indigenous materials (cassava starch, PKS ash, neem extract, Nigeria kaolin) have been studied as single paint additives, no published work has comprehensively integrated multiple indigenous components into a single formulation and evaluated the synergistic effects on paint performance. Second, most prior studies have been limited to qualitative or semi-quantitative assessments, lacking the systematic multi-parameter performance evaluation required for commercial validation against established standards such as NIS 157 and BS 3900. Third, economic analyses comparing the true production cost of indigenous formulations against commercial equivalents are conspicuously absent in the Nigerian paint research literature. Finally, the VOC and heavy metal profiles of bio-based indigenous formulations critical for eco-labelling and regulatory approval have not been systematically documented. This study addresses all four gaps, providing a comprehensive evidence base for the development and commercialisation of eco-friendly indigenous acrylic emulsion paints.

3. Materials and Methodology

3.1. Raw Materials: Sources and Preliminary Characterisation

All raw materials employed in this study were procured from indigenous Nigerian sources wherever possible. Table 1 summarises the primary materials, their sources, roles in the paint formulation, approximate costs, and availability.

Raw Material	Source	Role in Paint	Cost (₦/kg)	Indigenous Availability
Cassava Starch	Local farms	Binder/thickener supplement	500–800	Abundant (Nigeria, W. Africa)

Kaolin Clay	Ebonyi/Borno deposits	Extender pigment	300–800	Widely mined locally
Calcium Carbonate	Limestone quarries	Filler, bulk, opacity	200–500	Extensive deposits
Talc	Osun State mines	Extender, smoothness	100–180	Locally mined
Palm Kernel Shell Ash	Agricultural waste	Functional filler	200–500	Abundant agro-waste
Neem, Zobo, etc Leaf Extract	Local trees	Biocide/preservative	300–600	Ubiquitous in Nigeria
Poly vinyl acetate (PVA)	Chemical supplier	Primary binder	1,200–1,800	Imported; locally procured
Titanium Dioxide (TiO_2)	Chemical supplier	Primary white pigment	6,000–8,000	Imported; locally procured
Oxides (Red, Yellow, Blue)	Chemical supplier	Colour (pigments)	4000-8000	Imported; Locally produced
Gum Arabic	Locally souced from tree sap	Binder	500-1000	Locally sourced
Fomaldehide	Chemical supplier	Preservative	1500-2000	Imported
Ammonia	Chemical supplier	Catalyst	1500-2000	Imported
Biocide	Chemical supplier	Anti microbs surfactant	1000-2000	Imported
Hydroxy propyl cellulose	Chemical supply	Thickener	8000-13,000	Imported

Table 1. *Indigenous and supplementary raw materials used in paint formulations, their sources, functional roles, and costs.*

Cassava starch was obtained from a local processing cooperative in Imo State and modified through acid-catalysed esterification with acetic anhydride to improve compatibility with the acrylic latex binder (gum Arabic) and to enhance water resistance of the derived films. Kaolin sourced from artisanal deposits in Ebonyi State was wet-processed (flotation, drying at 105°C for 24 hours), milled to a target D_{50} of 8 µm, and characterised by X-ray fluorescence (XRF) and FTIR (for elemental composition and functional groups characteristics of the palm kernel shell respectively). Palm kernel shell ash was obtained from a palm oil mill in Delta State, ground in a ball mill for 4 hours, sieved through a 75 µm mesh, and characterised for chemical composition and loss on ignition (LOI). Neem leaf extract was prepared by reflux extraction of air-dried, pulverised neem leaves in 70% ethanol (leaf:solvent ratio 1:10 w/v) for 3 hours, followed by vacuum filtration and rotary evaporation to yield a concentrated extract standardised to 200 mg/mL total phenolic content.

All supplementary materials acrylic/VAE emulsion (MFF <5°C), rutile TiO_2 (Kronos 2190), talc, propylene glycol, dispersant (sodium hexametaphosphate), HPMC thickener, and synthetic biocide (Kathon CG) were sourced from reputable chemical suppliers in Lagos and Kano, with manufacturer certificates of analysis confirming purity and specification compliance.

3.2. Paint Formulation Development

Three paint formulations were developed based on a systematic design-of-experiment approach, with progressive substitution of conventional synthetic components with indigenous bio-based alternatives. Formula A served as the near-baseline formulation, incorporating standard ingredients with minimal indigenous substitution. Formula B represented a moderate substitution level, introducing cassava starch modifier (2%) and PKS ash filler (1.5%). Formula C represented the maximum indigenous substitution level evaluated, incorporating 4% cassava starch modifier and 3% PKS ash filler, while maintaining the neem extract biocide at 0.5% across all formulas. Table 2 presents the complete formulation compositions.

Ingredient	Formula A (%w/w)	Formula B (%w/w)	Formula C (%w/w)
PVA (Emulsion)	35.0	24.0	10.0
TiO_2	15.0	15.0	12.0
Kaolin Clay	8.0	10.0	12.0
Calcium Carbonate	13.0	10.0	12.0
Talc	5.0	5.0	5.0
Cassava Starch Modifier	0.0	7.0	12.0
PKS Ash Filler	0.0	1.5	3.0
Neem Extract (Biocide)	0.5	0.5	0.5
Propylene Glycol	2.0	2.0	2.0

Dispersant (Sodium Hexametaphosphate)	0.5	0.5	0.5
Defoamer	0.3	0.3	0.3
Thickener (Hydroxy Propyl Methyl Cellulose HPMC)	0.5	0.5	0.5
Preservative (Kathon CG)	0.2	0.2	0.2
Gum arabic	0.0	8.0	10
Water	20.0	20.0	20.0
Total	**100.0**	**100.0**	**100.0**

Table 2. *Composition of paint formulations A, B, and C (%w/w basis).*

3.3 Paint Production Procedure

Paint production was conducted under controlled laboratory conditions using a standardised sequence adapted from conventional waterborne emulsion paint manufacturing procedures and designed to simulate pilot-scale production conditions (Patton, 1979; Lambourne & Strivens, 1999; Wicks et al., 2007). The formulation process consisted of five sequential stages.

Stage 1: Dispersion Phase (Grinding)

Kaolin, calcium carbonate, talc, and palm kernel shell (PKS) ash filler (where applicable) were pre-dispersed in approximately 60% of the total deionised water charge containing sodium hexametaphosphate dispersant and a portion of the defoamer. The slurry was introduced into a high-speed Cowles-type disperser operating at 1,500–2,000 rpm for 20–25 min until a fineness of grind of ≤50 µm was attained, as determined using a Hegman gauge according to ISO 1524 (ISO, 2020). The pH was continuously monitored and adjusted to 9.0–9.5 using dilute ammonia solution to maintain optimum electrostatic stabilization and pigment wetting during dispersion (Lambourne & Strivens, 1999; Wicks et al., 2007).

Stage 2: Binder Addition

Following pigment dispersion, the acrylic/vinyl acetate–ethylene (VAE) emulsion binder was gradually introduced under moderate agitation (400–600 rpm) to minimise foam generation and avoid destabilisation of the latex system. For Formulations B and C, cassava starch modifier was incorporated as a pre-gelatinised 10% (w/v) aqueous dispersion immediately before binder addition to promote homogeneous integration into the polymer matrix. Starch modification of emulsion systems has been reported to improve film continuity and rheological stability when incorporated at controlled loading levels (Mali et al., 2005; Nwokocha & Williams, 2011).

Stage 3: Additive Incorporation

Propylene glycol (coalescing aid), hydroxypropyl methylcellulose (HPMC) thickener solution (2% w/v pre-hydrated), and either synthetic biocide or neem (Azadirachta indica) extract were incorporated sequentially under continuous low-speed agitation. A minimum equilibration time of 5 min was allowed between successive additions to ensure adequate dissolution and uniform distribution. Such staged addition procedures are widely adopted in waterborne coating manufacture to optimise rheological behaviour and prevent incompatibility among additives (Patton, 1979; Wicks et al., 2007).

Stage 4: Let-down and Adjustment

The remaining water fraction was added gradually to achieve target density and viscosity. Final pH adjustment was performed using dilute ammonia to obtain values between 8.0 and 9.0. Viscosity was measured using a Brookfield RVT viscometer and adjusted to 95–115 KU by controlled addition of thickener solution. The remaining defoamer portion was subsequently introduced, and the batch was mixed for an additional 5 min to ensure batch uniformity (ASTM D562, 2021).

Stage 5: Quality Check and Packaging

Each formulation underwent in-process quality evaluation including pH, viscosity, density, and fineness of grind measurements before filtration through a 150 µm screen. The paints were packaged in 20 L polyethylene containers and conditioned at ambient laboratory conditions (25 ± 2°C) for 24 h prior to performance testing to permit foam dissipation and system equilibration (NIS 157, 2004; Wicks et al., 2007).

Physicochemical Interpretation

The final formulations maintained an alkaline pH (≈8.4), which is considered favourable for preserving colloidal stability in acrylic-based latex paints and reducing the tendency toward coagulation during storage (Lambourne & Strivens, 1999). Drying behaviour indicated rapid surface drying followed by progressive polymer coalescence and formation of a continuous film network, consistent with established waterborne coating mechanisms (Keddie, 1997).

The contrast ratio (opacity) value of approximately 0.94 suggests effective light-scattering behaviour within the coating film. Fine periwinkle shell particles (≤45 µm) likely acted as extender pigments, improving pigment spacing efficiency and potentially lowering titanium dioxide demand while maintaining optical coverage (Allen, 1993; Patton, 1979).

Flexibility assessment showed that incorporation of modified cassava starch did not significantly impair film integrity during bending tests, indicating adequate compatibility between starch and the emulsion binder phase. Similar observations have been reported for starch-modified coating systems (Mali et al., 2005).

The incorporation of neem (Azadirachta indica) extract contributed antimicrobial functionality without observable microbial deterioration of either stored paint or cured films. The antimicrobial activity of neem constituents has been associated with azadirachtin-rich phytochemicals and broad-spectrum inhibitory effects against bacterial and fungal species (Biswas et al., 2002).

3.4 Performance Testing and Analytical Methods

All tests were conducted in triplicate and results are expressed as mean ± standard deviation. Testing procedures followed recognised national and international coating standards including NIS 157:2004, BS 3900 series, ASTM methods, and ISO specifications.

pH: Determined using a calibrated bench-top pH meter at 25°C (ASTM E70, 2015).

Viscosity: Measured using Brookfield RVT viscometer in Krebs Units (KU) according to ASTM D562 (ASTM, 2021).

Density: Determined using density cup method in accordance with ISO 2811-1 (ISO, 2023).

Fineness of Grind: Measured using Hegman gauge according to ISO 1524 (ISO, 2020).

Spreading Rate: Calculated from measured area coverage at specified wet-film thickness (BS 3900).

Drying Time: Evaluated using thumb-twist and thumb-pressure procedures (BS 3900-C2).

Gloss: Measured at 60° using BYK Gardner gloss meter (ISO 2813, 2014).

Contrast Ratio (Opacity): Determined using cryptometer procedure according to ISO 6504-3 (ISO, 2019).

Adhesion: Cross-cut adhesion test according to ISO 2409:2020.

Scrub Resistance: Measured using ASTM D2486 abrasion procedure.

Water Absorption: Determined from percentage mass gain after 24 h immersion.

VOC Content: Determined using EPA Method 24 and validated by headspace GC–MS.

Heavy Metals (Pb, Cd, Cr, Hg): Determined following acid digestion and ICP-OES analysis.

3.5 Antimicrobial Assessment

The antimicrobial effectiveness of neem (Azadirachta indica) extract at 0.5% loading was assessed using a modified in-can preservation challenge protocol adapted from ISO antimicrobial evaluation procedures (ISO 11731). Paint formulations were inoculated with mixed microbial cultures comprising *Aspergillus niger* (ATCC 16404), *Penicillium citrinum* (ATCC 48898), and *Pseudomonas aeruginosa* (ATCC 9027) at an initial challenge density of approximately 10^6 CFU/mL. Viable microbial populations were enumerated on Days 0, 7, and 28 after inoculation. Biocidal performance was benchmarked against Kathon CG (0.2% loading) and an uninoculated negative control. Reduction in viable count was used as the performance indicator for preservative efficacy (Biswas et al., 2002; CLSI, 2018).

3.6. Cost Analysis

A comparative cost analysis was performed by computing the bill of materials cost for a 20 L batch of each formulation at current (2024) Lagos market prices, incorporating raw material, energy, labour, overhead, and packaging costs. The total production cost was compared against the prevailing retail price range for 20 L of commercial acrylic emulsion paint of equivalent quality specification (spreading rate ≥10 m²/L, contrast ratio ≥ 0.95) in the Nigerian market.

3.7. Statistical Analysis

All experimental data are presented as arithmetic means of triplicate determinations ± standard deviation (SD). One-way analysis of variance (ANOVA) was performed to assess the statistical significance of differences in performance properties across the three formulations, with Tukey's Honestly Significant Difference (HSD) post-hoc test applied where ANOVA indicated significance ($p < 0.05$). All statistical analyses were conducted using IBM SPSS Statistics v26.

4. Results and Discussion

4.1. Characterisation of Indigenous Raw Materials

XRF analysis of the locally sourced kaolin revealed a composition of SiO_2 (55.2%), Al_2O_3 (29.8%), Fe_2O_3 (1.6%), Kaolin (0.9%), and minor oxides (<1% each), which is broadly consistent with published specifications for kaolinitic clays suitable for paint application (Al_2O_3 content >25% preferred for brightness and oil absorption) and comparable to imported Chinese kaolin benchmarks used in the Nigerian paint industry. The Fe_2O_3 content of 1.6%, while slightly elevated compared to high-brightness imported grades (<0.5%), was acceptable for the interior/exterior wall paint formulations targeted in this study, where absolute whiteness is secondary to opacity and film performance. The wet-processed Ebonyi kaolin achieved a Hegman fineness of 6–7 (D_{50} ~7.3 µm after milling), meeting the minimum grind specification for smooth paint films.

The palm kernel shell ash exhibited a chemical composition dominated by SiO_2 (42.3%), CaO (18.7%), Al_2O_3 (9.1%), MgO (6.4%), K_2O (8.2%), and organic carbon equivalents (~9%). Its Blaine specific surface area (SSA) of approximately 1,850 cm^2/g indicates a moderately reactive pozzolanic character, consistent with findings reported by Agbo et al. (2018) for similar agricultural ash materials. Critically, the heavy metal content of PKS ash was confirmed to be below detection limits for Pb, Cd, and Hg, and within acceptable thresholds for Cr (<5 ppm), ensuring it does not compromise the heavy metal compliance profile of the final paint formulations.

The cassava starch esterification process (acetylation with acetic anhydride, 40°C, 2 h, pH 8.5) achieved a degree of substitution (DS) of 0.28, consistent with the target range of 0.2–0.35 for food and industrial starch acetates. At this DS level, the modified starch exhibited significantly improved water dispersibility, reduced retrogradation tendency, and compatibility with the acrylic latex matrix compared to native cassava starch properties essential for maintaining formulation stability and avoiding phase separation during storage. The standardised neem extract contained total azadirachtin equivalents of 210 mg/kg (dry basis), providing a consistent and quantifiable measure of biocidal activity.

4.2. Physicochemical Properties of Paint Formulations

Table 3 presents the complete performance evaluation results for all three formulations, alongside the applicable standard requirements and interpretive remarks.

Property	Formula A	Formula B	Formula C	Std. Requirement (NIS/BS)	Remarks
pH	8.1	8.3	8.5	7.5–9.5	All within acceptable alkaline range
Viscosity (KU)	98	104	112	90–120 KU	Increasing with bio-fillers; all acceptable
Density (g/mL)	1.38	1.41	1.44	1.3–1.5	Consistent with standard emulsion paints

Fineness of Grind (µm)	45	42	40	≤50 µm	Good pigment dispersion in all formulas
Spreading Rate (m^2/L)	12.8	12.1	11.5	≥10 m^2/L	All exceed minimum requirement
Drying Time – Touch (min)	28	25	22	≤30 min	Bio-fillers accelerate drying slightly
Drying Time – Hard (hr)	3.2	2.9	2.6	≤4 hr	All satisfactory
Gloss (60°, GU)	18	15	12	5–25 (matt–mid)	Matt-finish range; suitable for walls
Contrast Ratio (Opacity)	0.960	0.965	0.972	≥0.95	Excellent hiding power in all formulas
Adhesion (cross-cut, ISO 2409)	1	1	0	0–1	Formula C: superior adhesion
Scrub Resistance (cycles)	1,820	2,150	2,430	≥1,000	All exceed standard; C best
Water Absorption (%)	3.8	3.1	2.6	≤5%	Improved moisture resistance with PKS ash
VOC Content (g/L)	28	24	19	≤50 (eco-label)	All qualify as low-VOC green paints
Heavy Metal (Pb, ppm)	<5	<5	<5	<90 ppm (BS)	Well within safety limit

Table 3. *Performance evaluation results for paint Formulas A, B, and C, with standard requirements and remarks.*

4.2.1. pH and Viscosity

All three formulations exhibited pH values within the recommended alkaline range of 7.5–9.5 (NIS 157). The progressive increase in pH from Formula A (8.1) through B (8.3) to C (8.5) is attributable to the alkaline nature of PKS ash, which contains significant quantities of CaO and K_2O that hydrolyse to generate hydroxide ions in the aqueous paint matrix. This mild alkalinity is technically beneficial, as it maintains the negative surface charge (zeta potential) on pigment particles that underpins colloidal stability and prevents flocculation during storage (Lambourne & Strivens, 2020). Importantly, the pH values remained below 9.5, above which the zinc and ammonia components of conventional HPMC thickeners can begin to degrade, causing viscosity loss.

Viscosity exhibited a consistent upward trend with increasing indigenous additive content, rising from 98 KU (Formula A) to 104 KU (Formula B) and 112 KU (Formula C). The contribution of acetylated cassava starch as a secondary rheology modifier supplements the primary HPMC thickener, generating additional associative thickening through hydrogen bonding interactions in the aqueous phase. The PKS ash, with its high specific surface area, also contributes to the overall paint structure through physical thixotropy. All formulations fell within the target viscosity range of 90–120 KU, ensuring acceptable brushability, rollability, and flow/levelling characteristics for application by brush, roller, and spray methods.

4.2.2. Spreading Rate, Opacity, and Drying Time

The spreading rate exhibited a modest decline from 12.8 m^2/L (Formula A) to 11.5 m^2/L (Formula C), which is consistent with the higher density arising from increased loading of mineral and bio-fillers. Nevertheless, all three formulations substantially exceeded the minimum NIS requirement of 10 m^2/L for a single coat, confirming their commercial adequacy in this respect. Opacity (contrast ratio) improved marginally from 0.960 (Formula A) to 0.972 (Formula C), remaining above the mandatory threshold of 0.95. This improvement can be attributed to the light-scattering contribution of fine kaolin and PKS ash particles, which act as secondary opacity contributors by creating additional air-polymer and polymer-particle interfaces within the dried film (Wicks et al., 2007). The slight improvement in opacity despite the reduction in binder content further demonstrates the efficiency of the indigenous fillers.

Touch-dry and hard-dry times improved monotonically with increasing bio-filler content. Formula C achieved touch-dry in 22 minutes and hard-dry in 2.6 hours, compared to 28 minutes and 3.2 hours for Formula A, respectively. This acceleration is attributable to the hydrophilic hygroscopic character of the acetylated cassava starch and the porous structure of PKS ash particles, which collectively increase the rate of water evaporation from the wet film surface. All formulations comfortably met the standard requirements of ≤30 minutes (touch-dry) and ≤4 hours (hard-dry).

4.2.3. Adhesion and Scrub Resistance

Adhesion: as measured by the ISO 2409 cross-cut tape test, was excellent for all formulations, with Formulas A and B both achieving Grade 1 (minor detachment at grid intersections) and Formula C achieving the maximum Grade 0 (perfect adhesion, no detachment). The superior adhesion of Formula C is attributed to the film-forming contribution of the acetylated cassava starch, which appears to enhance interfacial bonding between the paint film and the concrete and plaster substrates tested. This finding is consistent with the results of Iji et al. (2020), who attributed improved adhesion in starch-modified latex films to increased hydroxyl group density at the film-substrate interface, promoting hydrogen bonding.

Scrub resistance: a critical durability indicator for decorative emulsion paints applied in high-traffic areas showed the most dramatic and statistically significant ($p < 0.001$) improvement with indigenous additive incorporation. Formula C withstood 2,430 scrub cycles before substrate exposure, compared to 2,150 (Formula B) and 1,820 (Formula A). All formulations markedly exceeded the standard minimum of 1,000 cycles. The enhancement in scrub resistance with increased PKS ash loading is particularly noteworthy and is mechanistically explained by the abrasion resistance contributed by the hard siliceous PKS ash particles embedded within the dried film matrix, analogous to the role of silica in reinforced rubber compounds. The acetylated cassava starch additionally contributes to film cohesion, reducing the tendency for binder matrix fatigue under cyclic mechanical stress from scrubbing action.

4.2.4. Water Absorption and Weather Resistance

Water absorption after 24-hour immersion decreased significantly from 3.8% (Formula A) to 2.6% (Formula C), all values remaining below the 5% threshold specified in NIS 157. The reduction in water absorption with increasing PKS ash and acetylated starch content is explained by two complementary mechanisms. First, the dense packing of multi-modal particle size distributions (coarse calcium carbonate, medium kaolin and talc, fine TiO_2, and very fine PKS ash) reduces porosity and tortuosity of diffusion pathways in the dried film. Second, the hydrophobic ester groups introduced by acetylation of the cassava starch reduce the overall hygroscopicity of the bio-based additive fraction. These improvements in water absorption resistance are particularly significant for exterior applications where paint films are subjected to tropical rainfall patterns prevalent in southern Nigeria, characterised by intense, prolonged precipitation during the March–November wet season.

4.3. Environmental Performance

4.3.1. VOC Content

VOC content, determined by EPA Method 24 mass balance and confirmed by headspace GC-MS, was 28 g/L for Formula A, 24 g/L for Formula B, and 19 g/L for Formula C. All three formulations comfortably qualified as low-VOC paints under the EU Ecolabel criterion (≤50 g/L for interior matt paints) and the US EPA Architectural Coatings rule (≤100 g/L for flat coatings). The progressive reduction in VOC from A to C reflects the decreasing proportion of synthetic coalescent (propylene glycol), dispersant, and synthetic biocide relative to the increasing volume fraction of low-VOC indigenous components. Formula C's VOC of 19 g/L approaches the threshold for 'ultra-low VOC' classification (<10 g/L), suggesting that further optimisation — particularly through complete replacement of the synthetic biocide with neem extract and reduction of the propylene glycol coalescent — could achieve this benchmark. The dominant VOC contributors identified by GC-MS were propylene glycol (coalescent), 2-amino-2-methyl-1-propanol (pH adjuster), and trace quantities of residual acrylic monomer (methyl acrylate, <0.5 ppm). No formaldehyde, benzene, toluene, or xylene was detected in any formulation, consistent with the non-aromatic chemistry of the acrylic/VAE binder system. The VOC profiles of all three formulas compared favourably against a market-standard commercial acrylic emulsion paint (Formula D, control) which recorded 38 g/L under identical test conditions.

4.3.2. Heavy Metal Analysis

ICP-OES analysis of acid-digested dried paint films confirmed that all three formulations contained lead (Pb) at levels below the instrument detection limit of 5 ppm, well within the British Standard BS 3900 E10 requirement of <90 ppm and the Consumer Products Safety Commission (CPSC) limit of <90 ppm for architectural paints accessible to children. Cadmium (Cd) and mercury (Hg) were undetected (<2 ppm), and chromium (Cr) was present only as trivalent Cr (III) at <3 ppm, posing no hexavalent chromium toxicity concern. These results confirm that the bio-based indigenous additives do not introduce problematic heavy metal contamination into the formulations, a potential concern given the wide variability in mineral composition of agricultural ash materials. The comprehensive heavy metal compliance profile qualifies these formulations for consideration under international eco-labelling schemes, including the EU Ecolabel, the Nordic Swan, and potential future Nigerian Green Label standards.

4.3.3. Antimicrobial Efficacy

The in-can preservation challenge results demonstrated that neem extract at 0.5% loading achieved greater than 4-$\log_{10}$ reduction in viable counts of both fungal (Aspergillus niger, Penicillium citrinum) and bacterial (Pseudomonas aeruginosa) test organisms by Day 7, with no recovery observed at Day 28 for any organism tested. This performance was statistically equivalent ($p > 0.05$) to the synthetic Kathon CG biocide benchmark at 0.2% loading. The uninoculated negative control confirmed the sterility of non-inoculated paint samples throughout the 28-day test period. These results corroborate the findings of Ugwu and Ikenna (2022) regarding the biocidal equivalence of neem extract in coating systems, and provide the first quantitative in-can preservation validation specifically for neem extract in acrylic emulsion paint at pilot production scale. The multi-mechanistic mode of action of neem's active constituents including cell membrane disruption by nimbin, inhibition of chitin synthesis by azadirachtin, and protein denaturation by gedunin is considered advantageous from a resistance management perspective compared to single-target synthetic biocides.

4.4. Cost Analysis

Table 4 presents the comparative production cost analysis for a 10L batch of Formula A (lowest indigenous substitution) and Formula C (highest indigenous substitution), alongside the prevailing commercial retail price for equivalent-specification paint.

Cost Component	**Formula A (₦/10L)**	**Formula C (₦/10L)**
Raw Materials	2,840	2,210
Energy (milling, mixing)	320	320
Labour & Overhead	480	480
Packaging (10L bucket)	350	350
Total Cost of Production	3,990	3,360
Market Price Equivalent (commercial)	7,500–9,500	7,500–9,500
Estimated Cost Savings vs. Commercial Paint	**~48–58%**	**~55–64%**

Table 4. *Production cost analysis for a 20 L batch of Formulas A and C versus commercial equivalent (2024 prices, ₦).*

Formula C demonstrated a raw material cost reduction of approximately ₦630 per 10L compared to Formula A, primarily driven by the partial substitution of imported acrylic emulsion binder and synthetic biocide with indigenous cassava starch modifier, PKS ash, and neem extract, which collectively cost an order of magnitude less per kilogram. The total production cost of Formula C (₦3,360 per 10L) represents a 55–64% cost saving relative to commercial retail prices for equivalent paint (₦7,500–₦9,500 per 10L), demonstrating compelling economic viability. Even accounting for profit margins, regulatory compliance costs, and the formational efficiencies of large-scale industrial production, it is conservative to project that indigenous formulations could be profitably marketed at 30–40% below prevailing retail prices, enhancing accessibility for low- and middle-income consumers while maintaining manufacturer profitability.

The cost advantage is reinforced when life-cycle economics are considered. The use of agricultural waste (PKS ash) and tree-derived biocide (neem) reduces the waste disposal burden on processing industries, potentially allowing procurement of these materials at zero or near-zero direct cost when sourced through waste valorisation partnerships with palm oil mills and agricultural cooperatives. Furthermore, local procurement of kaolin, talc, and calcium carbonate eliminates import costs and foreign exchange exposure for these components, providing additional production cost stability in the volatile Nigerian economic environment.

4.5. Comparative Assessment against Commercial Paint

Taken together, the performance evaluation results indicate that Formula C, the indigenous-optimised formulation achieved superior or equivalent performance to the commercial control in 11 of 14 test parameters evaluated. The only parameters where Formula A marginally outperformed Formula C were spreading rate (12.8 vs. 11.5 m^2/L) and gloss (18 vs. 12 GU), both of which remained within the respective standard ranges. The comparatively lower spreading rate of Formula C reflects its marginally higher density, which is practically compensated by improved scrub resistance (meaning fewer repainting cycles over the coating's service life). The lower gloss of Formula C is consistent with the increased filler loading and is entirely appropriate for the matt interior and exterior decorative paint classification targeted in this study.

The most significant performance advantages of Formula cover the commercial control were in scrub resistance (2,430 vs. ~1,800 cycles for commercial benchmark), water absorption (2.6% vs. 3.5% for commercial), and VOC content (19 vs. 38 g/L for commercial). These attributes position the indigenous formulation as a technically superior product in the dimensions most critical for tropical climates with high rainfall, humidity, and mechanical wear on painted surfaces.

5. Conclusions

This study has successfully demonstrated the production, application, and comprehensive performance evaluation of eco-friendly acrylic emulsion paints formulated from low-cost indigenous Nigerian raw materials. The principal findings and conclusions are as follows:

Three paint formulations (A, B, and C) incorporating progressively increasing levels of acetylated cassava starch, palm kernel shell ash, kaolin, talc, calcium carbonate, and neem extract were successfully produced at pilot scale using standard manufacturing protocols, yielding stable, homogeneous, and reproducible products.

All three formulations met or exceeded the requirements of NIS 157:2004 and BS 3900 standards across all 14 physicochemical and performance parameters evaluated, including pH, viscosity, spreading rate, opacity, adhesion, scrub resistance, water absorption, VOC content, and heavy metal limits.

Formula C, incorporating the highest proportion of indigenous bio-based additives, achieved the best overall performance profile, particularly demonstrating superior scrub resistance (2,430 cycles), adhesion (Grade 0), water absorption resistance (2.6%), and the lowest VOC content (19 g/L) of all formulations tested.

Neem leaf extract at 0.5% concentration provided biocidal efficacy statistically equivalent to the synthetic Kathon CG biocide benchmark against standard fungal and bacterial challenge organisms, supporting its viability as a natural preservative in acrylic emulsion paint systems.

A production cost analysis confirmed savings of 55–64% per 20 L compared to equivalent commercial products, establishing a compelling economic case for the commercialisation of indigenous-formulated paints in the Nigerian and West African markets.

The VOC and heavy metal profiles of all formulations fully complied with international eco-labelling standards (EU Ecolabel, Nordic Swan), qualifying these paints as genuinely green coating solutions with strong export potential.

The research provides a robust scientific foundation for the scale-up and commercialisation of indigenous eco-friendly acrylic emulsion paints in Nigeria, with broader applicability across developing economies that share comparable agricultural resource bases and raw material challenges. Future work should address long-term outdoor exposure durability, optimisation of the acetylation process for maximum starch compatibility, investigation of additional indigenous pigment sources, and full life cycle assessment of the formulations from cradle to grave.

6. Recommendations

Based on the findings of this study, the following recommendations are advanced:

The Federal Government of Nigeria, through the Standards Organisation of Nigeria (SON) and the Raw Materials Research and Development Council (RMRDC), should fund pilot industrial-scale production and market trials of Formula C, with a view to establishing it as a standardised indigenous paint formulation eligible for public procurement preference.

Paint manufacturers in Nigeria should invest in domestic kaolin and talc processing infrastructure to reduce dependence on imported mineral extenders and capture the substantial cost advantages demonstrated in this study.

The development of a Nigerian Green Coating Label — analogous to the EU Ecolabel — incorporating VOC thresholds, heavy metal limits, and indigenous content quotas should be prioritised by regulatory bodies, creating a market incentive for eco-friendly indigenous formulations.

Further research should be directed at nano-modification of indigenous fillers (e.g., nano-kaolin, nano-PKS ash) to further enhance barrier and mechanical performance, and at the development of coloured eco-paints using natural mineral pigments (ochre, red mud) to expand the indigenous formulation product range.

Cassava starch processing cooperatives and palm oil mills should be engaged as strategic supply chain partners under waste valorisation frameworks, establishing a sustainable, circular raw material procurement model for the indigenous paint industry.

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Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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