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Article

Lead-free alternatives to Nigerian traditional glazes

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Abstract

Over the years, Nigerian potters have used lead-based formulations due to their low melting temperature, excellent luster, and vibrant colors. However, the health and environmental hazards associated with lead have necessitated exploration of safer alternatives. In this paper, the development of lead-free alternatives to traditional Nigerian ceramic glazes was investigated. It looks into various lead-free flux materials like boron, alkaline, and zinc-based compounds, analyzing their potential as substitutes through experimental methodology. It was discovered that borosilicate formulations show particular promise in replicating the desirable properties of traditional lead glazes while maintainning traditional integrity and artistic expression. Sustainable ceramic practices in Nigeria and practical guidance for cottage potters transitioning to safer glaze technologies are the gains of this pilot experimentation, as reported.

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Introduction

Glazed pottery has been an important cultural and artistic heritage of the ceramic traditions in Nigeria, for centuries, (Onuzulike, 2013). Traditional Nigerian glazes have historically relied heavily on lead compounds, particularly lead oxide (PbO), which has been valued for its flux properties, low melting point, and ability to produce vibrant colors and glossy finishes (Agberia, 2005). As opined by Okonkwo (2018), the melting temperatures of traditional lead-based glazes ranges from 750-900°C, thus making them compatible with the wood-firing and other traditional kiln technologies predominant in many Nigerian pottery communities. However, according to Akpomie, Dawodu & Eze (2021) and Ajala (2002), lead poses serious health risks to potters, consumers, and the environment. Neurological damage, developmental delays in children, reproductive issues, and kidney damage among others, have been linked to exposure to and/or consumption of lead-related materials, (Lehman, 2002 and Iwegbue, Overah, Ebigwai, Nwozo, Nwajei, Osa & Eguavoen, 2011). Studies by the World Health Organization (WHO), 2019 also revealed that when lead filters from ceramic containers into food or drinks, particularly acidic substances, it creates exposure passageways for consumers. Moreover, lead released during mining, processing, and firing contributes to environmental contamination of soil and water sources (Adewuyi & Babayemi, 2008 and Ezeh and Chukwu, 2011).

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Globally, ceramics production has progressively moved toward lead-free alternatives in response to these concerns, especially as it relates to regulatory compliance. Serio, Bonvicini, & Mizzoni (2018) reveals that strict regulations on lead content in ceramic glazes have been implemented in USA, Japan and members States of the European Union. Through the National Environmental Standards and Regulations Enforcement Agency (NESREA), Nigeria has also initiate infrastructure to address these issues by establishing guidelines for lead levels in consumer products, though enforcement remains challenging in rural pottery-producing regions (Babayemi, Olafimihan & Nwude, 2017).

Significance of Nigerian Glazed Ceramics

Nigerian glazed ceramics hold immense cultural significance, serving not merely as functional vessels but as expressions of cultural identity, religious practice, and artistic heritage. As noted by Agberia (2005), traditional glazed pottery in Nigeria has historically fulfilled multiple roles, including food storage, ceremonial usage, and social status markers. The distinctive aesthetic qualities achieved through lead glazes—particularly their color range, transparency, and surface qualities—have become defining features of specific regional pottery traditions.

As documented by Onuzulike (2013), various Nigerian ethnic groups developed unique glaze formulations and application techniques. In western Nigeria, glazed ceramics feature prominently in religious rituals dedicated to deities such as Iyemoja and Osun, while in north, particularly among Hausa potters, lead-glazed pottery has been integral to wedding ceremonies and household prestige (Mangut and Mangut, 2012).

The technical knowledge of traditional glaze preparation has typically been transmitted through generational apprenticeship systems, with families guarding proprietary formulations as valuable intellectual property (Ahuwan, 2004 and Ali, 2005). This cultural knowledge represents a significant intangible heritage that must be considered in any transition to alternative materials, Welton, Rodriguez-Lainz, Loza, Brodine, & Fraga, (2018).

Technical Properties of Traditional Lead Glazes

Primarily for its exceptional technical properties, lead oxide (PbO) has been favored in Nigerian traditional glazes. According to researches by Ndah (2014), lead oxide functions as a powerful flux, lowering the melting point of silica (which plays the role glass-former in glazes) by nearly 300 to 400°C as against alkaline fluxes, (Asaolu, 2002). This property has been particularly valuable given the limited maximum temperatures achievable in traditional Nigerian kilns, which typically operate between 800-950°C (Ibhadode, Dagwa & Oyatogun, 2010).

Beyond its fluxing abilities, lead provides several other desirable characteristics in traditional formulations. Lumpur, Malaysia & Metcalfe (2008) as well as Abiodun (2016) notes that lead glazes exhibit excellent surface tension properties, promoting smooth, even coverage on pottery surfaces. They also demonstrate remarkable tolerance for variations in application thickness as well as a valuable characteristic in hand-applied glazes, (Centers for Disease Control and Prevention, 2013). Furthermore, lead readily forms stable compounds with colorant oxides, producing vibrant, consistent colors that have become signatures of regional styles (Middleton, Kandaswami, & Theoharides, 2000 and Kashim, 2010).

Oke and Umoru (2017) documented how lead glazes typically comprise 40-60% lead oxide (PbO) combined with silica (SiO_2), alumina (Al_2O_3), and various colorants such as copper oxide (CuO) for greens, iron oxide (Fe_2O_3) for browns and reds, and manganese dioxide (MnO_2) for purples and blacks. This compositional flexibility has allowed potters to develop diverse palettes using readily available local materials.

Health and Environmental Concerns of Lead-Based Glazes

The health risks associated with lead glazes have been extensively documented. Research by Ezeh and Chukwu (2011) found elevated blood lead levels in Nigerian pottery workers compared to control populations, with particularly concerning levels among those involved in glaze preparation. Symptoms reported included headaches, abdominal pain, fatigue, and joint pain, consistent with lead exposure.

Environmental contamination presents another significant concern. Babayemi et al. (2017) documented soil lead concentrations up to 1,500 ppm in the vicinity of traditional pottery workshops in southwestern Nigeria, far exceeding the 400 ppm threshold considered safe for residential areas. This contamination extends to water sources, with Akpomie et al. (2021) detecting elevated lead levels in streams near pottery production centers.

Consumer safety represents perhaps the most widespread risk. Studies by Ajala and Onwualu (2013) demonstrated that acidic foods stored in traditionally glazed vessels can leach lead at levels exceeding 5 mg/L, significantly above the 0.01 mg/L maximum contaminant level recommended by the WHO (2019) for drinking water. This leaching creates remote exposure for populations way beyond the immediate pottery production communities, (CDC, 2003).

Motivation for Developing Alternative Glazes

The development of lead-less alternatives to traditional Nigerian glazes addresses several essentials. These includes, but not limited to: (a) health protection, (WHO, 2010); (b) environmental sustainability; (c) regulatory compliance, and (d) cultural preservation. As strongly argued for by Kashim and Adelabu (2020), transitioning to safer materials is not necessarily an abandonment of tradition but rather an evolution to meeting contemporary needs while maintaining cultural integrity, (Chaouali, Mohammed, Aouard, Amira & Hedhill, 2018).

While the economic implications of this transition are considerable, Akintonde and Kalilu (2013) highlight how access to international markets increasingly depends on compliance with safety standards that prohibit lead-containing ceramics, (Mohammed, 2005). Developing viable lead-free alternatives could therefore expand economic opportunities for Nigerian potters while protecting local consumers (Ogbonna, 2021).

Invariably, any successful alternative must be technically feasible within existing infrastructure and economically accessible to traditional pottery communities. As Olatunji (2019) observes, previous attempts to introduce alternative technologies have sometimes failed due to prohibitive costs or requirements for specialized equipment unavailable in rural settings. This paper seeks to prioritizes solutions that can be implemented using locally available materials and existing firing technologies in Nigeria.

Figure 1. Barakatgallery-lead-glazed-jar-with-dish-shaped-mouth

Method

Research Design

This study employed an experimental research design to develop and evaluate lead-free glaze alternatives through three primary phases:

(1) compositional analysis of traditional Nigerian lead glazes to establish baseline properties;
(2) formulation and testing of lead-free alternatives based on different flux systems; and

(3) comparative evaluation of experimental formulations against traditional glazes for technical performance and aesthetic qualities.

Quantitative analytical techniques and qualitative assessments by practicing Nigerian potters were employed. This aligns with what Nwankwo (2020) describes as "culturally responsive materials science," which acknowledges the importance of both empirical data and traditional knowledge systems.

Materials Selection

Materials selection prioritized compounds that are both safely handled and locally available or economically viable to import, (Rhodes, 1977). Following guidelines established by Olusegun, Olatunji & Oguntoye. (2013), materials were selected based on their potential to replicate the key functional properties of lead oxide: flux activity, color development, surface tension, and compatibility with traditional forming and firing methods.

Primary materials selected included:

1. Flux components: Borax ($Na_2B_4O_7{\cdot}10H_2O$), boric acid (H_3BO_3), soda ash (Na_2CO_3), potash (K_2CO_3), lithium carbonate (Li_2CO_3), calcium carbonate ($CaCO_3$), zinc oxide (ZnO), and strontium carbonate ($SrCO_3$), (Speight & Toki, 2004).

2. Glass formers: Silica (SiO_2) sourced from local quartz deposits and feldspar from Nigerian mines, as characterized by Adamu and Abdullahi (2019).

3. Stabilizers: Kaolin ($Al_2Si_2O_5(OH)_4$) from deposits in Kankara, Nigeria, which Odo et al. (2009) identified as having suitable mineralogical composition for ceramic applications.

4. Colorants: Iron oxide (Fe_2O_3), copper oxide (CuO), cobalt oxide (Co_3O_4), manganese dioxide (MnO_2), and rutile (TiO_2), selected based on their traditional use as documented by Kashim (2010).

Materials were sourced primarily from Nigerian suppliers, with specialty chemicals obtained from laboratory supply companies. All materials were characterized for purity using X-ray fluorescence (XRF) analysis prior to use in formulations.

Formulation Development

Three primary flux systems were investigated as potential lead replacements, following the classification system proposed by Eppler and Eppler (2000):

1. Boron-based formulations: These utilized borax and boric acid as primary fluxes, which Olusegun et al. (2013) identified as having melting behavior similar to lead oxide at traditional firing temperatures.

2. Alkaline formulations: Based on combinations of sodium, potassium, and lithium compounds, which Augustin (2014) found effective in lowering the melting point of silica, though typically requiring higher concentrations than lead.

3. Zinc-based formulations: Incorporating zinc oxide as a secondary flux alongside alkaline components, an approach that Ndah (2014) demonstrated could improve glaze surface quality and durability.

Initial formulations were developed using the Seger formula methodology, which expresses glaze compositions as molecular ratios rather than percentages by weight. This approach, recommended by Olatunji (2019) for systematic glaze development, facilitates meaningful comparison between different flux systems.

The following general molecular formula ranges were investigated:

0.2 to 0.4 R_2O (Na_2O, K_2O, Li_2O)

0.6 to 0.8 RO (CaO, MgO, ZnO, SrO)

0.3 to 0.5 B_2O_3

2.0 to 3.0 SiO_2

0.3 to 0.5 Al_2O_3

Control formulations based on traditional lead glazes were prepared following recipes documented by Kashim and Adelabu (2020), typically containing 45 to 55% PbO.

Sample Preparation and Firing

Test tiles were produced using traditional Nigerian clay bodies from three regions:

Abuja clay (central Nigeria),

Ipetumodu clay (southwestern Nigeria), and

Ilorin clay (west-central Nigeria).

These clays were selected based on their historical use in glazed pottery production and their diverse mineralogical compositions as analyzed by Odo, Okonkwo, & Aka (2009).

Clay preparation followed traditional methods documented by Onuzulike (2013), including aging, wedging, and hand-forming. Standardized test tiles measuring 10cm × 10cm × 0.8cm were pressed in plaster molds and bisque fired to 800°C in an electric kiln. Glaze slurries were prepared by ball milling raw materials with water and carboxymethyl cellulose (CMC) as a suspending agent. Application method of dipping, was employed. Glazed tiles were allowed to dry for 24 hours before firing. Firing trials were conducted in Gas-fired kiln reaching 1050°C. Temperature profiles were monitored using pyrometric cones and digital pyrometers to ensure consistency across firing cycles, Nwankwo (2020).

Analytical Methods

Fired samples underwent systematic evaluation using both quantitative and qualitative methods:

1. Melting behavior: Fusion tests were conducted following the methodology of Oke and Umoru (2017), with glaze cones fired on an inclined plane to measure melt flow relative to traditional lead formulations.

2. Surface characteristics: Gloss, texture, and visual appearance were assessed through reflection spectrophotometry using methods adapted from Serio et al. (2018).

3. Thermal expansion compatibility: Compatibility with clay bodies was determined by measuring fit and crazing using the strain test method described by Eppler and Eppler (2000).

4. Chemical durability: Acid resistance testing was performed using 4% acetic acid solution for 24 hours at room temperature, following the methodology of Ajala and Onwualu (2013). Leaching of constituent elements was analyzed using atomic absorption spectroscopy (AAS).

5. Color development: Colorant response was evaluated using direct color measurement system as implemented by Speight & Toki, 2004 and Augustin 2014 for systematic color comparison.

Comparative Performances of Various Nigerian Lead-Free Glaze Formulations

Compositional Analysis of Traditional Nigerian Glazes

Analysis of traditional Nigerian lead glazes revealed significant regional variations in composition. Samples collected from the Southwestaern region contained an average of 48.3% PbO, 39.1% SiO_2, 5.7% Al_2O_3, with remaining components comprising alkali and colorant oxides. Northern Nigerian samples from Kano and Sokoto displayed higher lead content, averaging 53.6% PbO, with correspondingly lower silica content (35.2% SiO_2).

XRF analysis confirmed earlier findings by Kashim (2010) regarding the compositional basis of regional color variations. Distinctive green-blue glazes from Ilorin contained 2.3-3.1% CuO, while the characteristic yellow-amber glazes of Abuja incorporated 1.8-2.5% Fe_2O_3. These relationships between composition and color provided essential baseline targets for alternative formulations. Thermal analysis demonstrated melting points between 750-830°C for traditional formulations, significantly lower than most commercial lead-free alternatives, which typically melt between 1000-1200°C as noted by Eppler and Eppler (2000). This finding underscored the technical challenge of developing alternatives compatible with traditional firing methods.

Performance of Boron-Based Formulations

Boron-based formulations demonstrated the most promising performance as lead substitutes across multiple criteria. Formulation B-3, containing 15% borax, 10% boric acid, 40% feldspar, 20% silica, 10% calcium carbonate, and 5% kaolin (percentages by weight), achieved complete maturation at 880°C, closely matching the melting behavior of traditional formulations. Surface gloss measurements showed that boron-based glazes achieved 85-92% of the reflectivity of lead controls, representing the closest match among alternatives tested. Microscopic examination revealed similar surface morphology, with comparable wetting characteristics and minimal pinholing.

Color development in boron-based formulations closely approximated traditional results, particularly with copper and iron colorants. As demonstrated by Olusegun et al. (2013), boron acts as an effective flux for these colorants, producing the vibrant greens, blues, and ambers characteristic of regional traditions. Cobalt and manganese required slightly higher concentrations (approximately 15-20% more) to achieve comparable color intensity to lead-based controls as opined by Commission of European Communities (2008). Durability testing showed superior acid resistance compared to traditional formulations. Leaching tests using 4% acetic acid resulted in negligible detection of constituent elements, well below WHO (2019) safety thresholds. This represents a significant improvement over traditional glazes, which Ajala and Onwualu (2013) found could leach lead at concentrations exceeding 5 mg/L under similar test conditions.

Performance of Alkaline Formulations

Alkaline formulations based on sodium, potassium, and lithium compounds demonstrated mixed results. These glazes required higher firing temperatures (minimum 950°C) to achieve full maturation, exceeding the capabilities of many traditional kilns as documented by Ibhadode et al. (2010). Surface quality in alkaline formulations showed greater variability than boron-based alternatives. Formulation A-2, containing 15% soda ash, 10% potash, 5% lithium carbonate, 45% feldspar, 20% silica, and 5% kaolin, achieved acceptable surface quality but demonstrated a narrower firing range with increased tendency toward pinholing and crawling defects.

Color development in alkaline systems proved problematic for certain traditional hues. While iron and manganese performed adequately, copper colorants produced inconsistent results, failing to achieve the characteristic turquoise blues documented by Kashim (2010) as significant in Yoruba traditions. This limitation aligns with findings by Augustin (2014) regarding the influence of flux type on colorant behavior. Thermal expansion compatibility presented challenges with alkaline formulations, resulting in increased incidence of crazing (41% of test tiles) compared to boron-based formulations (12%) and traditional lead glazes (8%). This finding supports observations by Eppler and Eppler (2000) regarding the typically higher expansion coefficients of high-alkali glazes.

Performance of Zinc-Based Formulations

Zinc-based formulations occupied an intermediate position between boron and alkaline systems in terms of overall performance. Formulation Z-4, containing 10% zinc oxide, 5% soda ash, 5% potash, 45% feldspar, 25% silica, 5% kaolin, and 5% calcium carbonate, matured at approximately 930°C. Surface quality in zinc formulations was superior to purely alkaline systems, displaying improved gloss and reduced defects. This aligns with findings by Ndah (2014) regarding the positive influence of zinc oxide on surface tension and melt viscosity.

Color response in zinc-containing glazes showed mixed results. While these formulations produced excellent earth tones with iron oxide, achieving the red-browns significant in northern Nigerian traditions, they demonstrated inconsistent results with copper colorants. This limitation reflects zinc's known interaction with copper, which Kashim and Adelabu (2020) note can produce muted greens rather than the vibrant blues characteristic of traditional formulations. Durability testing indicated excellent chemical stability, with minimal leaching of constituent elements. However, mechanical durability testing revealed increased susceptibility to abrasion compared to both lead and boron-based formulations.

Feedback from Traditional Potters

Master potters' evaluations provided crucial perspectives on the practical applicability of experimental formulations. Boron-based formulations received the highest overall ratings (average 4.2/5) for compatibility with traditional practices, with particular approval for application characteristics and firing behavior. Qualitative feedback highlighted several important considerations. As one potter from Ilorin noted: "The [boron] glaze flows similarly to our traditional recipes, covering the surface evenly without requiring special techniques." Another participant observed that "colors appear familiar but slightly less intense, requiring some adjustment to our usual formulations."

Concerns were expressed regarding material accessibility and cost. Multiple participants noted that while local feldspars and colorants were readily available, boron compounds would need to be imported, potentially increasing production costs. This feedback aligns with Olatunji's (2019) emphasis on economic feasibility as a critical factor in technology adoption. Several potters expressed interest in hybrid approaches, suggesting the gradual reduction rather than elimination of lead through progressive substitution with alternative fluxes. This perspective reflects the pragmatic, incremental approach to innovation often documented in traditional craft communities (Nwankwo, 2020).

Conclusion

This research demonstrates that viable lead-free alternatives to traditional Nigerian glazes can be developed using primarily boron-based flux systems. It represents the most promising alternative, offering comparable melting behavior, surface quality, and aesthetic properties to traditional lead glazes while eliminating health and environmental hazards. The findings support earlier work by Olusegun et al. (2013) regarding the potential of boron compounds as lead substitutes in low-temperature glaze applications, while extending this knowledge specifically to Nigerian cultural contexts and traditional firing methods. The relationship between flux composition and color development in culturally significant ceramic traditions is significant.

Recommendations

This research recommends phased implementation that is, a graduated approach to lead reduction, beginning with hybrid formulations containing reduced lead percentages alongside increasing boron content, may facilitate transition while allowing for technical adjustments. A supply chain development which will establish reliable, affordable access to boron compounds, for the production of alternative lead glazes is a critical need. Collaboration with academic institutions, government agencies, and NGOs could support bulk purchasing and distribution networks to reduce costs.

Workshops demonstrating preparation and application techniques for alternative glazes should be developed in collaboration with master potters, building on existing knowledge systems rather than replacing them. Also, kiln modifications such as minor adaptations to traditional kilns, in the area of improved insulation and airflow control could enhance temperature consistency and expand the range of viable lead-free formulations. Further investigation into locally available materials as potential flux components could enhance sustainability and reduce dependence on imported materials. By prioritizing both technical performance and cultural compatibility, the study offers a model for addressing environmental and health concerns while respecting and preserving valuable cultural heritage.

Declarations

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