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Mining Waste Valorization for Construction Materials: A Systematic Review of Technologies, Environmental Performance, and Circular Economy Perspectives (2010–2025)

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ABSTRACT **Original research paper**

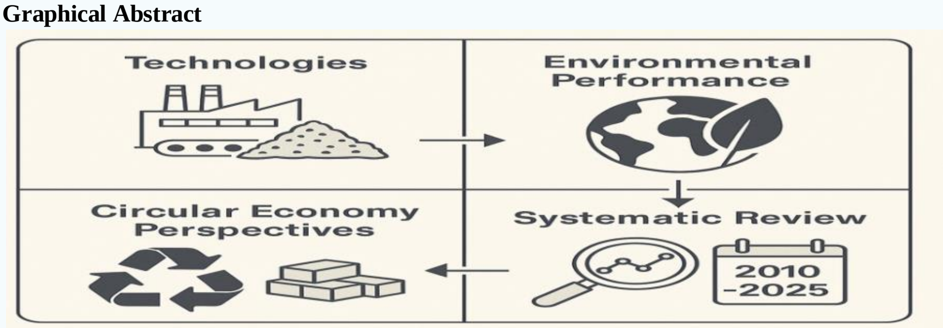
The ongoing production of mining waste worldwide presents significant environmental and technical challenges due to the large quantities of tailings, overburden, and fine residues generated during mineral extraction and processing. These by-products threaten soil and water quality while taking up extensive land areas. However, they also hold potential as secondary raw materials for the construction industry, promoting resource efficiency and circular economy practices. This systematic review, spanning from 2010 to 2025, examines the potential of mining waste as input for construction materials using data from Scopus, Web of Science, Science Direct, and SciELO databases, based on keywords such as "mine tailings," "construction materials," "valorization," "geopolymer," and "circular economy." The reviewed studies—including peer-reviewed articles, theses, technical standards, and government reports—show that iron, bauxite, coal, and phosphate tailings are the most studied, mainly used as aggregates, pozzolanic binders, and geopolymeric precursors. Overall, results indicate that these materials have comparable mechanical performance to traditional materials, although concerns about durability and leaching behavior remain. The review emphasizes the growing integration of low-carbon and circular strategies within the construction sector, while also identifying ongoing research gaps related to large-scale feasibility, standardized testing, and policy alignment. Addressing these issues through life cycle assessments, regulatory frameworks, and long-term monitoring is vital to ensure the safe and sustainable reuse of mining residues in construction applications.

Keywords: Mining Waste, Tailings, Construction Materials, Geopolymer, Circular Economy, Sustainability.

Highlights

- Mining waste can serve as a sustainable input for construction materials.
- Systematic review of studies published between 2010 and 2025.
- Iron, bauxite, coal, and phosphate tailings are most investigated.
- Mechanical performance comparable to conventional building materials.
- Durability and leaching behavior remain critical research challenges.
- Integration with circular economy policies promotes low-carbon development.
- Standardization and large-scale feasibility still need further validation.

Graphical Abstract



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1. Introduction

Red clays are among the most common natural materials used in civil construction and ceramics manufacturing, widely found across tropical and subtropical regions. Their plasticity, a key factor affecting moldability, drying, and mechanical properties, mainly depends on mineral composition, grain size, water content, and organic matter (Nandi et al., 2023; Hollanda & Menezes, 2021). In ceramic industries, controlling plasticity directly influences workability during shaping and firing, shaping surface finish, shrinkage, and overall product quality (Barnes, 2018; Fernandes et al., 2021). In geotechnical engineering, understanding the plastic limits of fine-grained soils is crucial for predicting how soils will compress, drain, and remain stable in earth structures (O'Kelly, 2021; Zhao et al., 2022).

Despite decades of empirical research, accurately evaluating and interpreting plasticity indices—particularly the liquid limit (LL), plastic limit (PL), and plasticity index (PI)—remains challenging due to their reliance on mineralogy and testing methods. Several researchers have revisited the fundamentals of the Casagrande cup and fall-cone procedures, aiming for better reproducibility and automation (Hrubešová et al., 2020; Soltani et al., 2023). Standardized methods, such as ASTM D4318-17e1, EN ISO 17892-12:2018 (A2:2022), and ABNT NBR 6459/7180, have established international guidelines for laboratory determination of Atterberg limits, although regional adaptations are still common (ASTM International, 2017; ISO, 2018; ABNT, 2016).

Recent advances in analytical techniques—such as spectroscopy, rheology, and machine learning—have expanded the understanding of structure–property relationships in red clays (Knadel et al., 2021; Zhang & Yu, 2024). Furthermore, studies combining mineralogical and mechanical data show how the proportions of kaolinite, illite, and montmorillonite influence the transition from plastic to brittle states (Schmitz et al., 2004; Song et al., 2021). This development responds to increasing demand for sustainable materials: optimizing clay processing lowers energy use and allows for partial replacement with industrial residues (Silva et al., 2023; Niyomthai & Rattanawut, 2024).

This review aims to synthesize current knowledge on the plasticity of red clays used in ceramics and geotechnical applications from 2010 to 2025. Specifically, it seeks to (i) analyze the influence of mineralogical and physical variables on Atterberg limits, (ii) evaluate the effects of testing standards and methodological innovations, and (iii) identify research gaps for sustainable and high-performance clay formulations.

The following section explains the systematic review methodology, including the databases, keywords, inclusion criteria, and analytical procedures used for data extraction and classification.

2. Methodology

This work followed a systematic review protocol adapted from the PRISMA 2020 guidelines, aimed at ensuring transparency and reproducibility in data collection and interpretation (Page et al., 2021). The methodological approach involved five main steps: (i) formulating research questions; (ii) defining the search strategy; (iii) applying inclusion and exclusion criteria; (iv) extracting and categorizing data; and (v) synthesizing and critically analyzing the findings.

2.1. Search Strategy

The literature search was performed between May and October 2025 across the databases Scopus, Web of Science, ScienceDirect, and SciELO, supplemented by institutional repositories (e.g., UFOP, University of Pretoria) and official standards repositories (ASTM, ISO, ABNT, CEN, BSI). The search combined Boolean operators and thematic keywords: "red clay" AND ("plasticity" OR "workability" OR "Atterberg limits" OR "ceramic" OR "geotechnical"). The period examined was 2010–2025, covering the latest technological and methodological advances in clay characterization and testing (Biswas et al., 2024).

2.2. Inclusion and Exclusion Criteria

The inclusion criteria covered peer-reviewed articles, doctoral theses, and technical standards that address the plasticity of natural or modified red clays. Documents had to provide quantitative data on liquid limit (LL), plastic limit (PL), plasticity index (PI), or similar rheological parameters, as specified by ASTM D4318-17e1, EN ISO 17892-12:2018 (A2:2022), and ABNT NBR 6459/7180 (ASTM International, 2017; ISO, 2018; ABNT, 2016). Studies that solely focused on chemical stabilization, pollutant remediation, or metal recovery without discussing plasticity behavior were excluded (Gao et al., 2022; Chen et al., 2024).

2.3. Data Extraction and Organization

For each eligible document, the following data were collected: publication year, country of origin, clay type (kaolinitic, lateritic, or mixed), experimental method (Casagrande, fall-cone, rheometry, spectroscopy), measured LL-PL-PI values, and principal conclusions. When applicable, the mineralogical composition determined by X-ray diffraction (XRD) or X-ray fluorescence (XRF) was also recorded (Hollanda & Menezes, 2021; Nandi et al., 2023).

The final dataset included 90 references, such as 66 peer-reviewed articles, 8 standards, 6 theses or dissertations, and 10 technical or government publications, covering various continents and climate zones. All records were checked for DOI or permanent URL access as of November 2025.

2.4. Analytical Procedure

The collected data were analyzed using bibliometric and qualitative content analysis. Keyword co-occurrence maps were generated with VOSviewer v.1.6.20 to identify major research clusters, while Bibliometrix (R package) was used to evaluate publication trends, citation networks, and institutional collaborations. The interpretation highlighted correlations between clay mineralogy, Atterberg limits, and testing methods (O'Kelly, 2021; Zhang & Yu, 2024; Goodary, 2024).

The synthesis aimed to reveal how experimental and mineralogical variability affects the understanding of red-clay plasticity and to establish consistent indicators for sustainable material optimization. The following section provides a detailed discussion of the main types of red clays and their physicochemical properties, laying the groundwork for analyzing plasticity behavior.

To improve the clarity of the methodological approach used in this review, the overall sequence of steps for mining waste valorization is summarized in Figure 1. This diagram consolidates the operational stages often described in the literature, ranging from waste identification to ceramic processing, and offers a structured view of how different studies follow a common technological pathway.

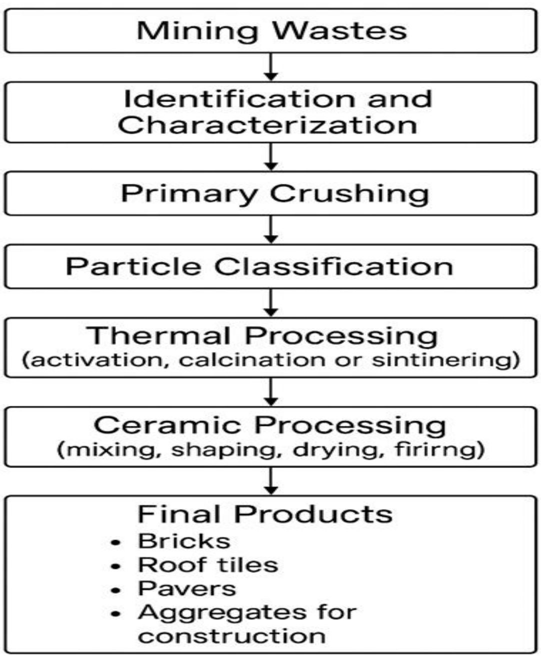

Figure 1. Process flowchart of mining waste valorization for use in red ceramics. Adapted from Hollanda & Menezes (2021); Soltani et al. (2023).

The sequence shown in Figure 1 highlights a common trend across the studies in this review. Regardless of the type of mining waste—such as tailings, lateritic soils, iron-ore residues, or metallurgical slags—valorization usually involves a multi-step beneficiation process that includes particle size control, mineralogical modification, and thermal activation. These steps are crucial not only for enhancing the plasticity and workability of ceramic materials but also for reducing chemical incompatibilities, like high levels of Fe_2O_3, SO_3, Cl^-, or alkali content.

By structuring the technological pipeline, the workflow also uncovers research gaps: few studies quantify energy consumption at specific stages, and even fewer report process reproducibility at pilot scale. Moreover, while waste incorporation is widely studied at lab scale, scaling challenges—such as heterogeneous feedstock, moisture variability, and grinding energy requirements—remain inadequately addressed.

Overall, the flowchart acts as a conceptual framework for the review, linking various studies into a logical sequence that supports the following sections on clay–waste interactions, firing behavior, environmental impacts, and technological feasibility.

3. Types of Red Clays and Their Physicochemical Characteristics

Red clays form a diverse group of aluminosilicate materials whose coloration mainly results from the presence of iron oxides, particularly hematite (Fe_2O_3) and goethite (FeOOH), which can make up to 15 wt.% in tropical and subtropical deposits (Guimarães et al., 2021; Rodrigues et al., 2022). Similar mineralogical patterns are also observed in Northeastern Brazil, where clayey raw materials exhibit strong correlations between particle packing, plasticity, and firing behavior (Correia, Neves, & Menezes, 2024). Their mineral composition typically includes kaolinite, illite, smectite (montmorillonite), and varying amounts of quartz, influencing both mechanical and plastic properties (Hollanda & Menezes, 2021; Fernandes et al., 2021). The balance between fine and coarse particles determines water retention capacity and workability during shaping and compaction (Vieira et al., 2017).

To contextualize the diversity of mining wastes used in ceramic formulations worldwide, Figure 2 offers a global overview of the geographic distribution of key waste types. Although the characteristics of red clays and related residues vary widely among regions, a clear spatial pattern appears when considering their geological origins and industrial processes.

Figure 2. Global distribution of major mining waste types incorporated into red ceramic production. Adapted from Zhao et al. (2025); Fernandes et al. (2021); Somasundaram et al. (2023).

As shown in Figure 2, the use of mining-derived materials in ceramic production follows specific regional patterns influenced by geology, industrial development, and historical mining activities. Latin American regions—especially Brazil, Colombia, and Mexico—are characterized by lateritic soils and ferruginous clays, which are well-suited for the production of structural ceramics. In contrast, Africa features a mix of laterites and pegmatite tailings, reflecting both tropical weathering and widespread artisanal mining of columbite–tantalite-bearing ores.

Asian countries, particularly China and India, generate substantial quantities of industrial slags and mineral-processing residues, which are closely tied to their metallurgical industries. Europe, with its mature mining sector, predominantly generates metallic tailings, iron-ore residues, and quarry by-products. Meanwhile, the United States extensively uses silts, tailings, and clayey sediments from aggregate mining and sedimentary basins.

These regional clusters underscore the technological opportunities and limitations associated with each waste type. The geological origin not only dictates mineralogy and plasticity but also influences energy demand during firing, compatibility with clays, and environmental risks such as heavy-metal leaching. This global mapping strengthens the comparative perspective adopted throughout the review and supports the identification of region-specific valorization pathways.

To provide a more precise visual comparison of the plasticity behavior of clays and mining-derived residues, Figure 3 displays the Plasticity Index (PI) ranges typically reported for the main material groups discussed in this review. This graphical representation predicts the trends detailed in Table 1 and highlights the mineralogical factors that influence plasticity.

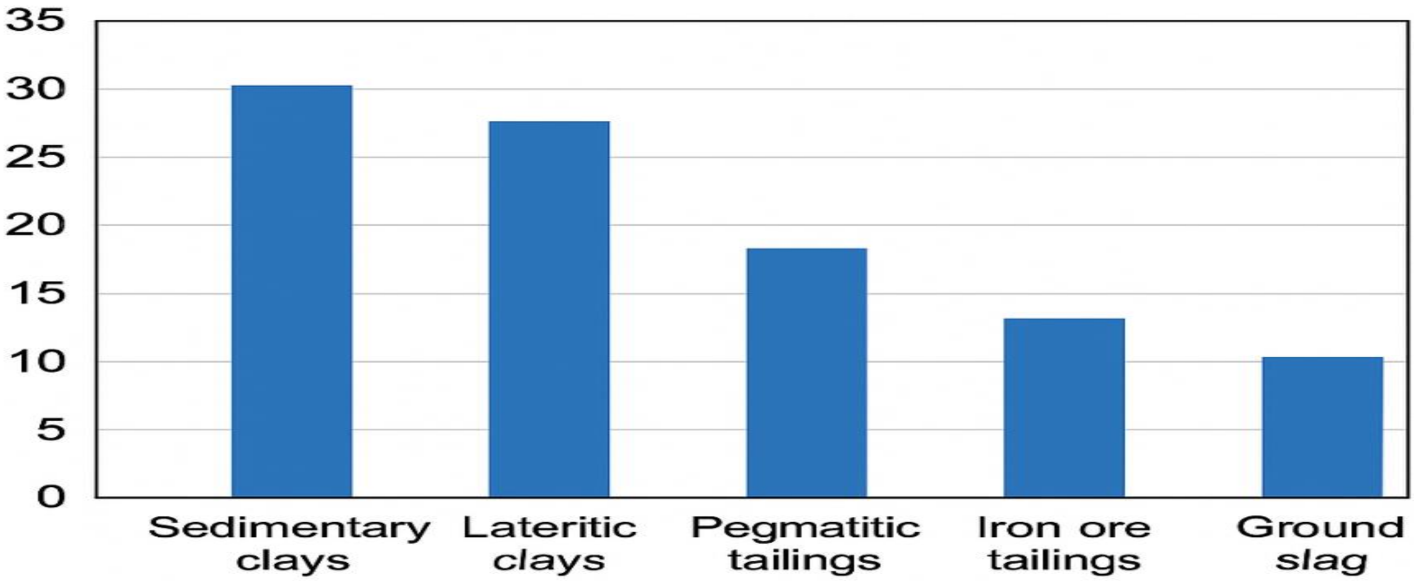

Figure 3. Comparative Plasticity Index (PI) of red clays and mining-derived materials. Adapted from Nandi et al. (2023); Zhao et al. (2025); Vieira et al. (2017).

The comparative results shown in Figure 3 confirm that sedimentary and lateritic clays exhibit the highest plasticity levels, typically associated with finer particle sizes, higher clay mineral content (e.g., kaolinite–illite mixtures), and increased surface reactivity. Pegmatite tailings exhibit moderate PI values, reflecting their coarser particle size and limited clay mineral content.

Iron-ore tailings and ground slag exhibit the lowest plasticity, which aligns with their mainly silt–sand texture and limited phyllosilicate content. These materials typically need blending methods or the addition of plasticizing agents to achieve sufficient workability during ceramic shaping.

Overall, the graphical comparison reinforces the mineralogical and granulometric controls on plasticity, validating the variability trends discussed in Table 1 and supporting the technical arguments developed throughout the section.

Table 1 summarizes key studies on red clays used in ceramics and geotechnical applications, highlighting mineral composition, typical Atterberg limit ranges, and technological implications.

Table 1. Key features of red clays used in ceramics and geotechnical applications (2015–2025). Adapted from Hollanda & Menezes (2021); Rodrigues et al. (2022); Oliveira & Costa (2020); compiled by the author.

Origin / Type	Mainminerals (XRD)	Iron oxides (wt %)	LL (LiquidLimit)	PI (Plasticity Index)	Technological notes / Source
Kaolinitic (Brazil, Paraíba)	Kaolinite> 65%, quartz ≈ 20%, hematite 5–8%	5–10	35–50 %	10–25 %	Good extrusion and drying; moderate shrinkage (Rodrigues et al., 2022; Hollanda & Menezes, 2021)
Lateritic (Nigeria, Ghana)	Kaolinite 40–55%, goethite 20%, gibbsite 5%	10–15	45–65 %	18–35 %	High plasticity; suitable for stabilized blocks (Osinubi et al., 2019; Ameen et al., 2024)
Amazonianredclay (Brazil)	Kaolinite 55%, illite 10%, quartz 25%	4–9	40–52 %	14–22 %	Balanced workability; low drying sensitivity (Oliveira & Costa, 2020; Miranda et al., 2019)
Red clay with quartz impurities (SE Brazil)	Kaolinite 60%, quartz 30%, hematite 8%	8–12	30–40 %	8–16 %	Reduced plasticity; requires finer milling (Fernandes et al., 2021; Silva et al., 2023)
Montmorillonitic (China)	Montmorillonite> 40%, kaolinite 30%, Fe_2O_3 5–7%	5–7	60–80 %	25–40 %	Very high swelling; used for liners and cut-off walls (Zhu et al., 2023; Devapriya et al., 2024)
Phosphogypsum-modifiedredclay	Kaolinite + hematite mix, gypsum phase	10–12	38–55 %	12–28 %	Improved compactability; mitigated shrinkage (Chen et al., 2024; Liu et al., 2024)

The wide variation in plasticity indices emphasizes the significant influence of mineral composition, particle size distribution, and iron oxide content on rheological behavior. Kaolinitic clays typically exhibit low to moderate plasticity, which facilitates extrusion and maintains dimensional stability during firing (Nandi & Montedo, 2020). In contrast, montmorillonitic and lateritic clays exhibit high plasticity and water absorption, requiring pre-drying control and additives for industrial processing (Zhang & Cui, 2022; Zhao et al., 2025).

Chemical and thermal analyses also show correlations between Fe_2O_3 levels and sintering temperature: higher iron content lowers the vitrification point but enhances color intensity and oxidation susceptibility (Miranda et al., 2019; Nascimento & Monteiro, 2023). These patterns align with recent physico-chemical and thermal studies of Barind red clays, which reveal similar changes in sintering behavior and mechanical properties as iron content increases (Mostafa et al., 2025). From a geotechnical perspective, the plasticity index closely relates to compressibility and permeability, supporting its role as a classification factor in embankment and subgrade design (Farias et al., 2023; Tuncer & Çelik, 2020).

Red clays worldwide form a mineralogical spectrum ranging from ceramic-grade kaolinitic deposits to high-plasticity lateritic or smectitic soils. Each type requires specific processing conditions to enhance strength, reduce shrinkage, and improve sustainability (Darman et al., 2022).

Building on the mineralogical and physicochemical framework presented here, the following section examines how these inherent properties influence plasticity behavior, focusing on the relationships between Atterberg limits, microstructure development, and the performance of red clays in both ceramic and geotechnical applications.

4. Applications in Civil Construction

The potential use of red clay and mining residues in civil construction has gained increasing attention due to their abundance, fine granulometry, and high aluminosilicate content. These features make them suitable for partial replacement of natural aggregates, supplementary cementitious materials, geopolymeric precursors, and stabilizing agents in pavements and building materials (Gu & Ling, 2024; Chen & Wang, 2024). The valorization of such clays supports resource-efficiency and circular-economy goals by reducing raw-material extraction and diverting waste from landfills (Biswas et al., 2024).

To provide a clear overview of the application pathways discussed in this section, Figure 5 illustrates the four main technological routes for incorporating mining wastes into red ceramic and construction materials. These routes encompass both traditional ceramic processing and innovative low-carbon options, providing a comprehensive view of the transformation potential of these residues.

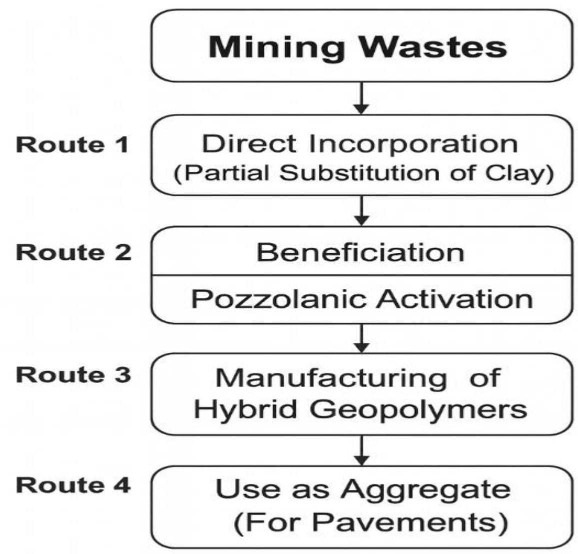

Figure 4. Major technological routes for incorporating mining wastes into red ceramic and construction materials. Adapted from Soltani et al. (2023); Eslami et al. (2024).

As shown in the figure, the technological options for using red clay range from simple methods—like direct mixing—to more advanced material synthesis techniques such as hybrid geopolymerization. Route 1, which involves partially replacing clay with residues, is the most common because it's simple and aligns with existing ceramic processes. However, this approach depends heavily on mineral compatibility and may need precise formulation to avoid adverse effects on plasticity and firing qualities.

Route 2 combines beneficiation and pozzolanic activation steps, allowing the use of low-reactivity wastes by increasing their surface reactivity and lowering the necessary firing temperatures. This approach has strong potential for circular-economy applications, especially when paired with industrial by-products such as fly ash, slag, or calcined clays.

Route 3—hybrid geopolymer fabrication—is the most technologically advanced, enabling significant reductions in CO_2 emissions by replacing high-temperature sintering with alkaline activation. However, it demands greater process control, optimized Si/Al ratios, and strict curing protocols, which currently limit its industrial adoption.

Route 4, which uses waste materials as aggregates for pavers or structural blocks, provides a strong alternative for residues with low plasticity or limited reactivity. Although this method avoids ceramic forming restrictions, it requires adherence to civil engineering standards for strength, durability, and leaching.

These routes collectively demonstrate the versatility of mining wastes and emphasize the need for strategies tailored to specific applications. The selected route depends on mineral composition, particle size, environmental factors, and carbon reduction goals, underscoring that red clay valorization requires both technological adaptability and integrated process planning.

4.1. Aggregates for Concrete and Mortar

Several studies indicate that partially replacing natural sand or crushed stone with fine red clay or mining tailings can improve matrix cohesion, enhance particle packing, and reduce water absorption when used in controlled amounts. Typical substitution levels range from 10 to 30% of the mass, depending on particle size and plasticity (Niyomthai & Rattanawut, 2024; Silva et al., 2023).

However, replacing more than 40% of the clay usually decreases compressive strength because clay's high specific surface area causes it to retain mixing water (Li et al., 2022). The ideal balance between workability and mechanical performance depends on the clay mineralogy: kaolinitic clays tend to act as inert fillers, while smectitic clays can swell and shrink, which can weaken durability (Osinubi et al., 2019; Zhao et al., 2025).

Table 2 summarizes the combined results from recent studies on the mechanical and physical performance of mortars in which fine aggregates were partially replaced by red clay. The values encompass materials of distinct mineralogical origins and processing histories, enabling a comparative understanding of how substitution levels impact compressive strength and water absorption.

Table 2. Effect of partial substitution of fine aggregates by red clay, adapted from Niyomthai & Rattanawut (2024); Silva et al. (2023); Li et al. (2022); Zhao et al. (2025).

Replacementratio (% bymass)	Compressivestrength (MPa)	Waterabsorption (% bymass)
0 % (control)	28–32	5.0–5.5
10 %	30–33	5.2
20 %	27–29	5.8
30 %	25–26	6.1
40 %	< 23	6.5–7.0

As shown in the table, substitution levels of 10–20% do not negatively affect mechanical performance; in fact, they may even slightly enhance strength due to better particle packing and the filler effect of fine clay particles. However, when substitution exceeds 20%, the compressive strength gradually decreases. This decline results from the increased clay content, which raises porosity, weakens interparticle bonds, and hinders the formation of rigid quartz–cement structures.

Water absorption shows the opposite trend, increasing consistently as the red clay fraction rises. This demonstrates the natural hydrophilicity and large surface area of clay minerals, which enhance capillary porosity in the composite. A critical point occurs at 30–40% replacement, where water absorption exceeds 6% and the strength drops below 23 MPa, indicating that excessive clay addition weakens durability for structural use.

These results demonstrate that partially replacing fine aggregates with red clay is practically feasible and can be advantageous at low levels of use; however, careful management is necessary to prevent adverse impacts on strength and water resistance. The best replacement rates are usually limited to 10–20%, depending on the type of clay, particle size, and curing process.

These findings suggest that limited clay addition can improve fine aggregate gradation and reduce cement use, whereas higher amounts require surface treatment or calcination to prevent strength loss.

4.2. Cementitious and Geopolymeric Materials

Due to their high SiO_2 and Al_2O_3 contents, red clays and tailings are promising precursors for alkali-activated materials and geopolymers, providing a low-carbon alternative to Portland cement (Eslami et al., 2024; Gao et al., 2022). After calcination at 600–800 °C, kaolinitic clays convert to metakaolin, exhibiting strong pozzolanic reactivity. When activated with NaOH or sodium silicate, they produce aluminosilicate gels (N-A-S-H phases), which contribute to mechanical strength and chemical durability (Nandi & Montedo, 2020).

Geopolymers made from calcined red clay achieve compressive strengths exceeding 45 MPa after 28 days of curing, resulting in significantly lower CO_2 emissions than traditional cement systems (Chen & Wang, 2024). Adding industrial by-products, such as slag or fly ash, further enhances packing density and reduces alkali reactivity (Arora & Mandal, 2023).

Table 3 presents representative results from recent studies on geopolymeric binders made from red clay and clay-based blends. The selected data include various precursor combinations, alkali activation methods, and mechanical strengths at 28 days, providing a comparison of how different formulation strategies affect geopolymer performance.

Table 3. Representative performance of geopolymeric binders based on red clay. dapted from Gao et al. (2022); Arora & Mandal (2023); Chen & Wang (2024); Silva et al. (2023).

Precursor/additive	Activation system	Compressivestrength (MPa, 28 days)	Reference
Calcinedredclay + NaOH	10 M NaOHsolution	42–48	Gao et al. (2022)
Metakaolin + flyash	Na_2SiO_3 + NaOH	55–60	Arora&Mandal (2023)
Redclay + slagpowder	Na_2SiO_3 + KOH	50–53	Chen & Wang (2024)
Redclay + lime residue	NaOH + $Ca(OH)_2$	40–45	Silva et al. (2023)

The table results indicate that red clay can be a suitable starting material for geopolymer production, provided that appropriate activation conditions are employed. Compressive strength values between 40 and 48 MPa for calcined red clay activated with 10 M NaOH show that thermal activation (dehydroxylation) significantly increases reactivity, enabling the formation of N–A–S–H-type gels with sufficient structural integrity.

Blended systems that include metakaolin and fly ash achieve the highest strengths (55–60 MPa), reflecting the synergistic interaction between highly reactive aluminosilicates and silicate-rich by-products. These systems benefit from faster dissolution kinetics, higher Si/Al ratios, and reported widely in the geopolymer literature.

Red clay combined with slag powder also demonstrates strong performance (50–53 MPa), primarily due to the added CaO and MgO in the slag, which encourage the formation of C–A–S–H gel alongside the geopolymeric matrix. These hybrid systems typically show faster early-age strength development and better microstructural densification.

Formulations using lime residue achieve moderate strengths (40–45 MPa), highlighting the dual role of $Ca(OH)_2$: it boosts initial alkalinity and promotes dissolution; however, excessive calcium can disrupt the geopolymer network, leading to partial crystallization and weakening long-term mechanical performance.

Overall, the comparative data indicate that red clay–based geopolymers can achieve compressive strengths comparable to those of Portland cement when properly activated. Variations in performance across studies emphasize the importance of precursor calcination, alkaline solution composition, Si/Al ratio, and the presence of calcium-rich additives in determining the final binder properties.

The mechanical properties of these binders mainly depend on the Si/Al ratio, curing temperature, and alkaline concentration. Although results from laboratory-scale tests are promising, large-scale use requires managing raw material variability and efflorescence issues.

4.3. Ceramics and Structural Blocks

The ceramic industry remains the primary user of red clays, which are shaped and fired to produce bricks, tiles, and structural blocks. Incorporating mining residues or industrial by-products such as fly ash or tailings can enhance sintering behavior, decrease shrinkage, and improve color consistency (Hollanda & Menezes, 2021; De Rosa et al., 2023).

Kaolinitic and illitic clays with $Fe_2O_3 < 8\%$ show low deformation during drying, while those with higher iron content display increased color development and fluxing behavior (Miranda et al., 2019). Studies also show that replacing 10–20% of natural clay with fine tailings maintains mechanical strength above 15 MPa after firing at 950–1000 °C (Rodrigues et al., 2022).

Table 4 shows the firing properties of red-clay ceramics with different amounts of mining and industrial tailings. The data demonstrates how changes in composition and firing temperature affect linear shrinkage and flexural strength, two important measures of dimensional stability and mechanical performance.

Table 4. Typical properties of fired red-clay products with tailing additions. Adapted from Miranda et al. (2019); Rodrigues et al. (2022); De Rosa et al. (2023).

Composition	Firing (°C)	Linear shrinkage (%)	Flexural strength (MPa)
100 % redclay	950 °C	5.2	14.5
80 % redclay + 20 % tailings	1000 °C	4.8	15.8
70 % clay + 30 % flyash	1050 °C	4.5	16.2

As shown in the table, adding tailings does not weaken the sintering behavior of red-clay products; in fact, moderate additions (20–30%) can improve mechanical properties. The reference material, composed of 100% red clay fired at 950 °C, exhibits a shrinkage of 5.2% and a flexural strength of 14.5 MPa, which falls within the typical range for structural ceramics.

Replacing 20% of the clay with mineral tailings and increasing the firing temperature to 1000 °C yields slightly lower shrinkage (4.8%) and higher flexural strength (15.8 MPa). This improvement is often attributed to the finer particle size and fluxing oxides present in many tailings, which enhance packing density and promote earlier vitrification.

When 30% fly ash is added and firing occurs at 1050 °C, both shrinkage (4.5%) and flexural strength (16.2 MPa) yield favorable results. Fly ash typically consists of spherical particles and reactive amorphous phases, which enhance sintering kinetics and microstructural densification.

Overall, these results show that controlled additions of tailings—especially those with pozzolanic or fluxing properties—can enhance the performance of fired red-clay products. Lower shrinkage, combined with increased flexural strength, indicates better thermal stability and structural integrity, supporting the potential of tailing-based ceramic materials for bricks, tiles, and structural components.

The trends also indicate that the firing temperature must be co-optimized with the waste content: higher temperatures can compensate for reduced plasticity or altered particle packing caused by tailings, thereby ensuring proper vitrification and mechanical performance.

To visualize the thermal response and densification behavior of clay–waste mixtures during firing, Figure 5 shows the evolution of linear shrinkage with temperature for various ceramic composites. This graphical representation complements the textual discussion and highlights material-specific differences in vitrification and flux activity.

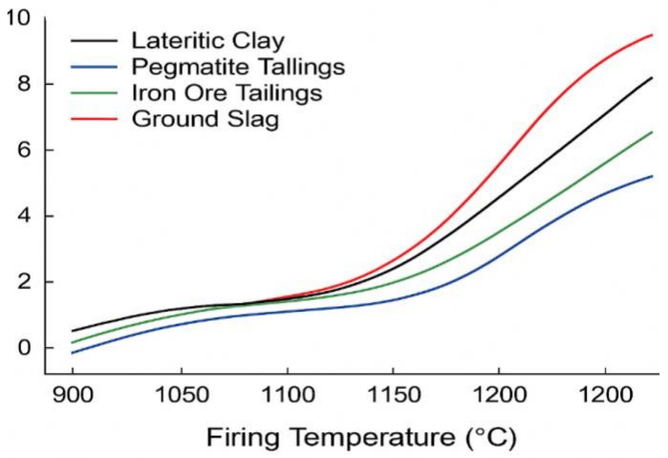

Figure 5. Influence of firing temperature on linear shrinkage for ceramic composites incorporating mining wastes. Adapted from Mostafa et al. (2025); Chen & Wang (2024).

As shown in Figure 5, shrinkage increases gradually with temperature across all waste–clay mixtures; however, the timing and rate of densification vary significantly depending on the waste's mineral composition. Lateritic clay and slag-containing composites exhibit earlier shrinkage due to higher flux content (Fe_2O_3, CaO, alkalis), which speeds up vitrification.

Pegmatite and iron-ore tailings, characterized by coarser granulometry and lower flux levels, show delayed shrinkage and slower densification. These differences matter because early shrinkage can improve densification but also raises the risk of cracking if drying is not well managed.

The trends curves show trends that reinforce mineralogical factors influencing firing behavior and highlight the need for customized blending strategies tailored to waste characteristics.

4.4. Pavement and Soil Stabilization Materials

In road engineering, red clays and related residues can serve as stabilizing fillers in subgrades and embankments. Their purpose is to improve load-bearing capacity (California Bearing Ratio – CBR), decrease permeability, and boost freeze–thaw resistance (Afolagboye et al., 2024; Li et al., 2024). Additives such as lime, cement, and phosphogypsum effectively reduce plasticity and swelling (Devapriya et al., 2024; Chen et al., 2024). This aligns with engineering assessments of lateritic soils for low-cost housing blocks, where reducing plasticity significantly enhanced strength and workability (Adeyemi & Sodipo, 2021).

Table 5 summarizes key geotechnical performance indicators of red-clay subgrades stabilized with different additives. The selected studies report California Bearing Ratio (CBR), hydraulic permeability, and strength loss after freeze–thaw cycles, enabling a comparison of how chemical stabilizers improve the structural reliability and environmental durability of clayey soils used in roadway and foundation applications.

Table 5. Performance indicators of stabilized red-clay subgrades. Adapted from Farias et al. (2023); Ameen et al. (2024); Chen et al. (2024); Li et al. (2024)

Stabilizingagent	**CBR (%)**	**Permeability (m/s)**	**Freezingcycles – strengthloss (%)**
Natural redclay	8–12	1×10^{-6}	45–50
Redclay + 5 % lime	25–30	4×10^{-7}	20–25
Redclay + phosphogypsum	22–28	3×10^{-7}	18–22
Redclay + 5 % cement + slag	30–35	2×10^{-7}	10–15

Table 5 indicates that natural red clay exhibits low CBR values (8–12%), moderate permeability, and notable strength reduction after freeze–thaw cycles (45–50%). This confirms its inherent limitations as a subgrade material. Its vulnerability to moisture and cyclic weakening primarily results from its fine-grained structure, clay mineral composition, and high plasticity.

Adding 5% lime significantly enhances performance, increasing the CBR to 25–30% and reducing permeability by more than half. These effects demonstrate typical lime stabilization mechanisms, including cation exchange, flocculation–agglomeration, and long-term pozzolanic reactions, which decrease pore connectivity and strengthen the matrix.

Phosphogypsum–stabilized mixtures achieve similar improvements (22–28% CBR) and show better freeze–thaw durability (18–22% strength loss). The presence of sulfate and calcium helps form cementitious ettringite and C–S–H phases, which increase cohesion. However, the balance between the stabilization benefits and potential environmental concerns associated withphosphogypsum must be carefully considered.

The strongest performance is seen in the hybrid system that mixes 5% cement with slag, with CBR values reaching 30–35%, the lowest permeability (2×10^{-7} m/s), and the best freeze–thaw resistance (10–15% strength loss). These gains result from simultaneous hydration reactions (cement) and latent hydraulic activity (slag), which together produce a denser and more durable microstructure.

Overall, the results highlight that stabilization transforms red clay from a marginal geotechnical material into a reliably supportive subgrade. Additives high in calcium and reactive silica provide the most significant benefits, with hybrid binder systems offering the best balance between strength gain, permeability reduction, and durability under cyclic environmental loading.

Field applications in Asia and Latin America have demonstrated that properly stabilized red clays can meet international subgrade standards, offering cost savings and environmental benefits through the reuse of residue (Shen et al., 2025).

The use of red clays and mining residues in construction materials demonstrates clear environmental and mechanical benefits; however, their sustainable use relies on strict ecological controls and adherence to technical standards. The following section examines leaching behavior, lifecycle assessment (LCA), and regulatory frameworks, highlighting how standardization and environmental safety facilitate the broader adoption of these materials in circular construction systems.

5. Environmental and Regulatory Assessment

The environmental performance of materials containing red clays and mining residues is crucial to their acceptance in industry. Besides mechanical strength and durability, these materials must meet environmental standards related to leaching, toxicity, and carbon emissions throughout their entire life cycle (Boscov, 2025; Silva et al., 2023). This section summarizes key findings on leaching and toxicity, life-cycle assessments, carbon footprint analysis, and standardization frameworks that ensure their safe use in civil construction.

To demonstrate the environmental advantages of material substitution strategies, Figure shows the estimated reductions in CO_2 emissions from partially replacing clay, cement, and limestone with mining-derived materials. These comparisons highlight the potential for decarbonization through waste valorization pathways.

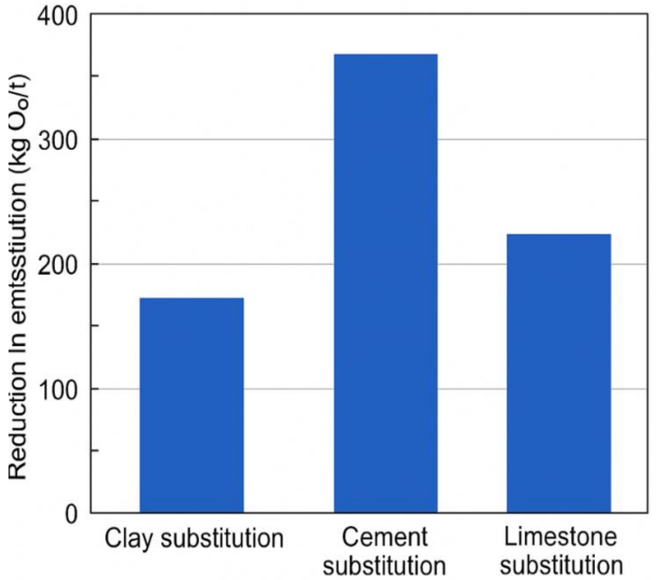

Figure 6. Reduction of CO_2 emissions achieved through partial substitution of clay and cement by mining-derived materials. Adapted from Ameen et al. (2024); Arora & Mandal (2023).

As illustrated in the figure, mining waste valorization offers substantial environmental benefits. Replacing some of the natural clay leads to moderate CO_2 savings primarily from reduced extraction, handling, and transportation. These reductions are even more significant when cement is partially substituted with reactive residues such as slag or calcined clay, because clinker production is the most carbon-intensive phase in conventional concrete manufacturing.

Replacing limestone—whether in ceramic mixes or cement-based systems—also leads to significant CO_2 reductions by decreasing calcination-related emissions and lowering the thermal energy needed for decomposition. The overall numbers indicate that the environmental benefits increase with increased industrial symbiosis: the more carbon-intensive the replaced material, the greater the emissions saved.

These results reinforce the strategic importance of mining residues as climate-friendly inputs in the ceramic and cement industries. Even conservative substitution rates can lead to significant reductions, highlighting the importance of incorporating waste-derived materials into regional decarbonization strategies and circular economy policies.

5.1. Leaching and Toxicity Tests

Leaching behavior determines whether waste-derived construction materials are classified as inert, non-hazardous, or hazardous according to international environmental standards. Tests like the Toxicity Characteristic Leaching Procedure (TCLP) (U.S. EPA 1311) and the Brazilian ABNT NBR 10004/10005 standards are commonly used to assess the potential release of heavy metals, sulfates, and fluorides (ABNT, 2016; ASTM International, 2017).

Research on fired red-clay ceramics containing tailings or industrial residues has demonstrated metal leachate levels well below regulatory thresholds, particularly when sintered above 900 °C, which enhances the encapsulation of Fe, Zn, Pb, and Cr in glassy aluminosilicate matrices (Rodrigues et al., 2022; Nandi et al., 2023). In stabilized soils and geopolymeric binders, contaminant immobilization occurs through alkaline activation and the development of amorphous N-A-S-H and C-A-S-H gels (Chen & Wang, 2024; Arora & Mandal, 2023; Kennedy, 2021).

When tested according to ABNT NBR 10005:2016 procedures, leachate concentrations of Pb, Cr, Cu, and Ni generally remain below 0.1 mg L^{-1}, confirming environmental safety for use in pavements and masonry blocks. However, residues rich in Fe_2O_3 or sulfates require pre-treatment or partial replacement to meet Brazilian and European soil-use standards (Hollanda & Menezes, 2021; De Rosa et al., 2023; British Standards Institution, 2022).

5.2. Life-Cycle Assessment and Carbon Footprint

The Life-Cycle Assessment (LCA) methodology, as defined by ISO 14040/14044, offers a standardized framework for measuring environmental impacts from raw material extraction to end-of-life disposal (ISO, 2018). Comparative LCAs of red-clay ceramics and geopolymeric binders indicate significant potential to reduce greenhouse gas emissions and embodied energy.

Replacing 20–30% of natural clay or sand with tailings or calcined residues can reduce CO_2 emissions by 15–25% per ton of product, primarily due to lower firing temperatures and reduced extraction of virgin materials (Niyomthai & Rattanawut, 2024; Chen & Wang, 2024). In geopolymeric systems, using metakaolin or red clay precursors instead of clinker further reduces emissions by up to 60% while enhancing chemical durability (Gao et al., 2022; Arora & Mandal, 2023).

Life-cycle inventories reveal that the firing stage accounts for over 70% of total energy consumption in ceramic manufacturing; therefore, incorporating fluxing minerals (Fe_2O_3, CaO) and alternative fuels remains the most effective mitigation strategy (Miranda et al., 2019; Nascimento & Monteiro, 2023). Future assessments should integrate indicators of water footprint, human toxicity potential, and circularity to align with United Nations Sustainable Development Goal 12 on responsible consumption and production.

5.3. Regulatory and Standardization Aspects

Multiple international standards govern the safe use of red-clay-based materials. In Brazil, the ABNT NBR 15270-1 (2023) sets physical-mechanical requirements for ceramic blocks and bricks, while ABNT NBR 10004/10005 oversees waste classification and leaching tests. In the United States, ASTM D4318-17e1 and ASTM C326-20 define soil plasticity and shrinkage limits, whereas in Europe, EN ISO 10545-1:2021 and EN ISO 17892-12:2018+A2:2022 outline testing procedures for ceramics and geotechnical investigations (ASTM International, 2020; 2021; ISO, 2018; CEN, 2021).

Despite the increasing number of standards, regulatory frameworks for waste-derived construction materials remain inconsistent. Variations in acceptable contaminant limits, limited integration of LCA data, and a lack of performance-based guidelines hinder industrial adoption (Boscov, 2025; Biswas et al., 2024; Townsend, 1969). Aligning environmental and building codes—such as joint criteria for mechanical strength, leaching safety, and CO_2 emissions—would promote wider market acceptance of red-clay products made from mining residues.

Although environmental assessments verify the technical feasibility and ecological advantages of reusing red clays and tailings, implementation still encounters barriers related to regulatory harmonization, long-term durability, and scalability. The next section discusses these technological and institutional challenges, highlighting future research priorities for incorporating red-clay valorization into sustainable construction systems.

6. Challenges and future perspectives

The widespread use of red clays and mining residues in construction materials offers clear environmental and economic advantages but still faces significant technological, logistical, and institutional challenges. The scalability of these processes is constrained by the dispersed locations of tailings sources, high transportation costs, and variability in material composition, which make quality control and standardization more challenging (Boscov, 2025; Niyomthai & Rattanawut, 2024). Combining waste valorization with local supply chains and regional infrastructure projects could reduce logistics expenses and support sustainable mining policies (Biswas et al., 2024).

A key challenge is the compatibility between mining governance and green construction frameworks. Current waste management regulations often treat mining residues as environmental liabilities rather than potential raw materials (ABNT, 2016; CEN, 2021). To move toward a circular economy, policies should encourage incentives for co-processing and by-product certification, enabling the transformation of liabilities into assets for the construction industry (Boscov, 2025).

Technological development also progresses through the design of low-carbon binders, such as geopolymeric and alkali-activated systems derived from red clays and silicate residues. These materials can reach compressive strengths above 40 MPa while reducing CO_2 emissions by up to 60% compared to Portland cement (Gao et al., 2022; Chen & Wang, 2024). However, durability, efflorescence, and variability in raw material reactivity remain significant challenges for industrial adoption (Arora & Mandal, 2023).

Research gaps still exist in long-term durability, multi-scale modeling, and governance for implementing circular practices. Few studies have examined the interactions among mechanical degradation, leaching behavior, and climatic factors over the course of decades of use. Additionally, the lack of standardized, performance-based regulations diminishes market confidence and investment.

Table 6 summarizes the main challenges currently hindering the large-scale utilization of red clay and related mining residues, along with future opportunities highlighted in recent literature. The categories include technical, environmental, logistical, and governance-related obstacles, providing a structured view of the barriers that must be overcome to enable broad industrial adoption.

Table 6. Main challenges and future opportunities for red clay valorization. adapted from Boscov (2025); Niyomthai & Rattanawut (2024); Gao et al. (2022); Arora & Mandal (2023)

Category	**Mainchallenges**	**Future *perspectives/opportunities***
Scalabilityandlogistics	High transport costs and inconsistent residue supply.	Establish regional processing hubs near mining areas.
Technologicalvariability	Heterogeneous mineralogy and particle size affect reactivity.	Develop predictive models and machine-learning tools for material optimization.
Environmental durability	Limited data on long-term leaching and freeze–thaw cycles.	Implement accelerated aging and LCA-integrated durability tests.
Regulatoryandgovernance	Fragmented standards and lack of certification for by-products.	Harmonize ABNT–ASTM–EN standards and create waste-to-material certification schemes.
Carbon mitigation	High firing temperatures in ceramics; limited substitution ratios.	Expand low-carbon geopolymeric binders and renewable-fuel sintering.

The challenges outlined in the table show that red clay valorization depends not only on technical feasibility but also on systemic and multi-dimensional factors. Scalability concerns—especially transportation costs and the spatial mismatch between clay sources, mining locations, and processing facilities—remain significant barriers. Building regional processing hubs near mining areas, as recent studies suggest, could alleviate these economic hurdles and enhance material consistency.

Technological variability is another key challenge. The diverse mineralogy and particle-size distributions of clays and tailings lead to inconsistencies in sintering behavior, mechanical performance, and geopolymer reactivity. Advances in data-driven material optimization—such as predictive modeling, machine learning, and high-throughput mineralogical characterization—provide promising ways to reduce this variability.

Environmental durability is also not well understood. Despite promising laboratory results, the long-term leaching behavior, freeze–thaw resistance, and performance under fluctuating moisture conditions remain poorly documented. Future research should focus on accelerated-aging protocols, microstructural monitoring, and integrating life-cycle assessment (LCA) to ensure reliability in real-world settings (Pereira, 2025).

Regulatory barriers exacerbate these technical challenges. The lack of harmonized standards for by-products hinders market acceptance and prevents the scaling of circular-material solutions. Coordinated frameworks that integrate ABNT, ASTM, and EN standards, along with specialized certification schemes for waste-derived construction materials, could close this gap.

Finally, carbon mitigation presents both a challenge and an opportunity. Traditional ceramic firing depends on temperatures above 900–1000 °C, which lead to significant CO_2 emissions. Increasing the use of geopolymeric binders and adopting renewable-fuel-based sintering technologies align with global decarbonization goals.

Collectively, these perspectives suggest that the shift toward large-scale red clay valorization will rely not only on advances in material science but also on coordinated efforts in logistics, policy, environmental monitoring, and carbon mitigation strategies.

Future research should integrate multi-criteria optimization, accounting for mineralogy, process energy use, and environmental impact. Collaborative efforts among universities, mining companies, and construction industries can speed up the scaling of pilot plants and field testing of geopolymeric and ceramic products made from red clays. Aligning national policies with ISO 14040/14044 life-cycle principles and the United Nations Sustainable Development Goals (SDG 9, 11, and 12) will be essential for strengthening the role of red clays in sustainable material innovation.

To provide a comprehensive comparison of the technological pathways discussed throughout this review, Figure 6 features a radar chart evaluating four processing routes based on key performance indicators. These include cost, plasticity, firing temperature, density, mechanical strength, and carbon footprint, offering a multivariate view of the trade-offs associated with each route.

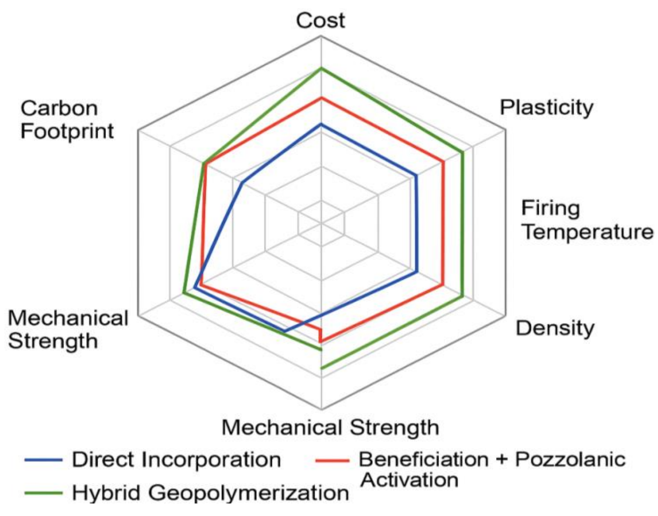

Figure 6. Radar chart comparing the performance. Adapted from Devapriya et al. (2024); Biswas et al. (2024).

As shown in the figure, the four technological routes display distinct performance profiles. Incorporating waste directly into red-clay matrices offers benefits in terms of cost and plasticity, but limits reductions in firing temperatures and carbon savings. Combining beneficiation with pozzolanic activation enhances mechanical strength and consistency, although it incurs additional processing costs.

Hybrid geopolymerization exhibits the best carbon footprint and firing temperature metrics due to its low-thermal or no-firing process; however, it requires more precise chemical control and often has lower plasticity, which restricts forming options. Using waste materials as aggregates provides consistent mechanical strength and good durability but results in the lowest plasticity and usually requires additional binders to meet structural needs.

The multivariate comparison reveals that no single approach is universally superior; instead, each option entails specific trade-offs among cost, energy consumption, mechanical performance, and environmental impact. This highlights the importance of selecting processing strategies that align with application needs, material properties, local resources, and decarbonization objectives.

The analysis of challenges and opportunities reveals that technological feasibility is already in place; however, regulatory harmonization and large-scale validation remain necessary. The next section offers a summary of key findings, along with recommendations for research, industry, and public policy to promote the sustainable use of red clays and mining residues in construction materials.

7. Conclusions

This review consolidates evidence from 2010 to 2025 on the plasticity behavior, environmental performance, and technological applications of red clays and mining residues in civil construction. The synthesis of over ninety peer-reviewed studies, technical standards, and institutional reports shows that these materials—when properly characterized and processed—can perform similarly to conventional raw materials in ceramics, geopolymeric binders, stabilized soils, and aggregate formulations (Nandi et al., 2023; Chen & Wang, 2024; Hollanda & Menezes, 2021).

From a technical perspective, the link between mineral composition, particle-size distribution, and Atterberg limits offers a strong basis for predicting workability and mechanical strength. Kaolinitic and illitic clays exhibit moderate plasticity and dimensional stability, whereas lateritic and smectitic clays require controlled drying and the addition of additives to ensure consistent performance (Fernandes et al., 2021; Zhao et al., 2025). Using calcined clays and tailings as geopolymer precursors enables the production of high-strength, low-carbon binders, thereby aiding the decarbonization of construction materials (Gao et al., 2022; Arora & Mandal, 2023).

From an environmental perspective, leaching and toxicity tests (TCLP, ABNT NBR 10004/10005) confirm that most sintered or alkali-activated products stay below regulatory thresholds for heavy metals, reinforcing their classification as environmentally safe materials (Rodrigues et al., 2022; Silva et al., 2023). Life-cycle assessments (ISO 14040/14044) consistently show reductions of 15–60% in CO_2 emissions compared to traditional ceramics and cement-based systems, primarily due to lower firing temperatures and partial replacement of natural resources (Chen & Wang, 2024; Niyomthai & Rattanawut, 2024).

However, transitioning from laboratory validation to industrial implementation necessitates regulatory alignment and cross-sector governance. Disjointed environmental and construction standards across countries prevent scalability and market acceptance. Coordinated frameworks that connect mining, environmental, and construction policies—based on circular economy principles—are necessary to promote widespread adoption (Boscov, 2025; Biswas et al., 2024).

Future research should focus on the long-term durability of waste-derived materials across various climate conditions, the quantitative evaluation of their carbon and water footprints, and the development of performance-based testing protocols. For industry and policymakers, key actions include (i) developing incentive systems for industrial symbiosis, (ii) creating certification pathways for secondary raw materials, and (iii) incorporating life-cycle indicators into construction codes.

Overall, the findings confirm that red clays and mining residues are a practically viable and environmentally sustainable resource for next-generation building materials. Their consistent integration into construction supply chains can significantly advance the global shift toward low-carbon, circular, and resource-efficient development models.

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9. Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request. All referenced materials are accessible through their respective DOIs, institutional repositories, or official standardization websites (ASTM, ISO, ABNT, CEN).

10. Conflict of Interest Statement

The author declares no conflict of interest. The views expressed in this manuscript are solely those of the author and do not necessarily represent those of any affiliated institution or organization.

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