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ADVANCES IN KAOLIN BENEFICIATION FOR CERAMIC APPLICATIONS: PROCESSING STRATEGIES, PROPERTY ENHANCEMENT, AND INDUSTRIAL IMPLICATIONS

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Abstract

Natural kaolin rarely meets the chemical, optical, particle-size and firing requirements of high-value ceramics without upgrading. This structured narrative review evaluates physical, chemical, biological, thermal and hybrid beneficiation routes, with particular attention to African deposits and the transfer of laboratory findings to ceramic production. The evidence audit covered publications from 2010 to September 2026, nine earlier foundational sources and relevant ceramic standards. It assembled 100 candidate records, screened 85 unique records and retained 57 documents. Results varied strongly by deposit. For Ethiopian kaolin, sequential beneficiation and oxalic-acid leaching lowered Fe_2O_3 from 2.40 to 0.36 wt%, an 85% reduction, and raised ISO whiteness from 72.0 to 81.4. The increase was 9.4 absolute ISO points or 13.1% relative to the starting value, while the treated sample remained below the commercial comparator value of 88.14. A separate route combining pre-agitation, high-pressure washing and oxalic-acid leaching reduced iron from 9.75 wt% to below 1 wt%, although it rejected up to 20% of the feed. Confidence in cross-deposit transfer was generally moderate because many experiments omitted replicate uncertainty, complete mass balances or ceramic-product validation. The evidence supports staged processing in which physical rejection of liberated impurities precedes selective leaching of accessible residual iron. Water and reagents should be recovered, and calcination should be reserved for products that require phase modification. Research priorities are standardized property reporting, dispersion control after leaching, pilot-scale mass and energy balances, residue utilization and deposit-specific predictive models. Proposed pilot targets are at least 90% wash-water reuse, 80% reagent recovery and a 30% reduction in thermal energy relative to the measured local baseline.

Keywords
kaolin; beneficiation; ceramics; iron removal; whiteness; acid leaching; calcination; scale-up

1. INTRODUCTION

Kaolin beneficiation must be assessed against the requirements of the intended ceramic product. Mineral purity, particle size, rheology and firing behaviour interact, and their response to treatment changes with the deposit. These relationships provide the basis for evaluating available beneficiation routes.

Kaolin is a kaolinite-rich industrial mineral whose layered aluminosilicate structure, plasticity, refractoriness and firing response make it central to whiteware, porcelain, tiles, electrical ceramics and porous ceramic membranes. Industrial value depends on the complete feed specification, including mineral assemblage, Fe_2O_3 and TiO_2 content, particle-size distribution, soluble salts, loss on ignition, colour, rheology and phase evolution during firing [1]–[2]. A treatment that improves brightness can still be unsuitable for ceramics if it damages plasticity, destabilizes slip casting, increases drying shrinkage or changes the vitrification window. Product acceptance depends on the intended ceramic body and the relevant performance standard, rather than

on one laboratory purity value [3]. Impurity identity and mode of occurrence vary among deposits. Quartz and feldspar may occur as liberated coarse grains, while iron may be present as discrete hematite or goethite, ultrafine surface coatings, Fe-bearing mica or illite, or structural Fe within the kaolinite lattice. Each form responds differently to classification, magnetic separation, flotation, reducing agents and heat. A flowsheet transferred without deposit characterization may consume unnecessary reagent, discard recoverable kaolinite or fail to improve fired colour. Each unit operation should address a measured impurity and should be evaluated using ceramic-relevant properties.

African deposits illustrate both the opportunity and the variability. Integrated beneficiation of Ethiopian kaolin has been evaluated for ceramic-membrane feed, while other Ethiopian studies report strong changes in chemistry and physical properties after wet processing and thermal treatment [4]–[5]. Characterization studies from Egypt, Nigeria, Algeria and Ghana show that deposits described generically as 'kaolin' differ markedly in accessory minerals, iron content, particle morphology and firing behaviour [6]–[11]. The region has substantial resources, but deposit-specific mineralogical findings are rarely converted into stable industrial specifications, pilot-scale mass balances and costed process routes. The form of iron is especially important. Spectroscopic and microscopic studies distinguish coarse iron oxides, superparamagnetic surface-associated particles and structural Fe, each of which influences colour differently and has a different removal ceiling [12]–[14]. Earlier mineralogical work similarly showed that impurity type, not total Fe alone, controls the response of raw and heat-treated kaolin [15]–[16]. Even a high total Fe value may be treatable when iron is liberated, while a lower value may resist beneficiation when iron is bound within the crystal lattice.

This review covers beneficiation evidence published principally from 2010 to September 2026, with older sources retained only when foundational to processing mechanisms or ceramic acceptance. The focus is kaolin intended for ceramic bodies, membranes, porcelain, whiteware, tiles and related fired products; studies directed solely to unrelated adsorption or catalytic applications were excluded unless they provided transferable beneficiation evidence. The review answers four questions:

- Which feed characteristics determine whether physical, chemical, biological, thermal or hybrid beneficiation is technically justified?
- What efficacy ranges are reported across deposits, and why do apparently similar treatments produce conflicting outcomes?
- How do purity, whiteness, particle size and surface modification translate into rheology, forming, sintering and fired performance?
- Which scientific, processing, environmental and industrial gaps must be closed for reproducible scale-up?

This review provides a characterization-led framework for selecting a treatment route, separates absolute property changes from relative changes in the quantitative evidence, and links process decisions to end-use specifications through a gated industrial flowsheet. It also proposes indicative technology-readiness levels (TRLs) and measurable research targets. The cited studies did not report these TRLs or targets; they are derived from the evidence assessed in this review.

A recent review in this journal surveyed global and Nigerian beneficiation methods and highlighted green processing and industrial diversification [17]. The present review addresses a narrower analytical need. It documents record selection, compares quantitative results across deposits, appraises the strength and transfer limits of benchmark evidence, and links each processing decision to a ceramic release test. The contribution is therefore a decision framework for determining which treatment is justified, when treatment should stop and what must be measured before scale-up.

2. REVIEW METHODOLOGY

The review method was designed to show how records were identified, screened and compared. It also records the limits imposed by differences in deposit mineralogy, treatment conditions and reported outcomes.

2.1 Review Design and Reporting Approach

A structured narrative review was used because the studies examined different deposits, treatment sequences, analytical methods and outcome definitions. These differences did not support a defensible pooled effect size. Reporting was informed by PRISMA 2020 and PRISMA-S, and the findings were synthesized without meta-analysis in accordance with SWiM principles [18]–[20]. The review was not prospectively registered as a systematic review. It reconstructs the evidence set used for the revision and states the limits of cross-study comparison.

2.2 Search Sources, Period and Terms

The audit began with the manuscript's 27-item bibliography. Supplementary records were identified through targeted Google Scholar and Crossref searches, publisher platforms (including ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis, Cambridge Core and IOPscience), and backward and forward citation chaining from high-relevance studies. Searches covered January 2010 to September 2026. Nine pre-

2010 works were retained for foundational mechanisms, established ceramic processing relationships or historically important separation evidence. Search strings combined 'kaolin' or 'kaolinite' with 'beneficiation', 'ceramic', 'iron removal', 'whiteness', 'magnetic separation', 'flotation', 'selective flocculation', 'oxalic acid', 'bioleaching', 'calcination', 'rheology', 'sintering', 'membrane', 'energy', 'water recycling' and geographic terms including 'Africa', 'Nigeria', 'Ethiopia', 'Ghana', 'Algeria' and 'Egypt'. The final search was updated on 21 September 2026.

2.3 Selection and Eligibility

One hundred candidate records were assembled: 27 from the original bibliography and 73 from supplementary searches and citation chaining. After removal of 15 bibliographic duplicates, 85 unique records were screened. Twenty-eight were excluded because they were not kaolin-specific, did not evaluate beneficiation or ceramic-relevant outcomes, lacked sufficient methods or quantitative characterization, duplicated a dataset without adding evidence, or were non-scholarly promotional sources. Fifty-seven documents were retained: primary experimental studies, focused reviews, reporting guidance, industrial guidance and ceramic standards. Figure 1 summarizes the evidence audit. Counts refer to the reconstructed revision audit rather than an archived export from subscription databases; this distinction prevents the narrative review from being misrepresented as a fully reproducible systematic review.

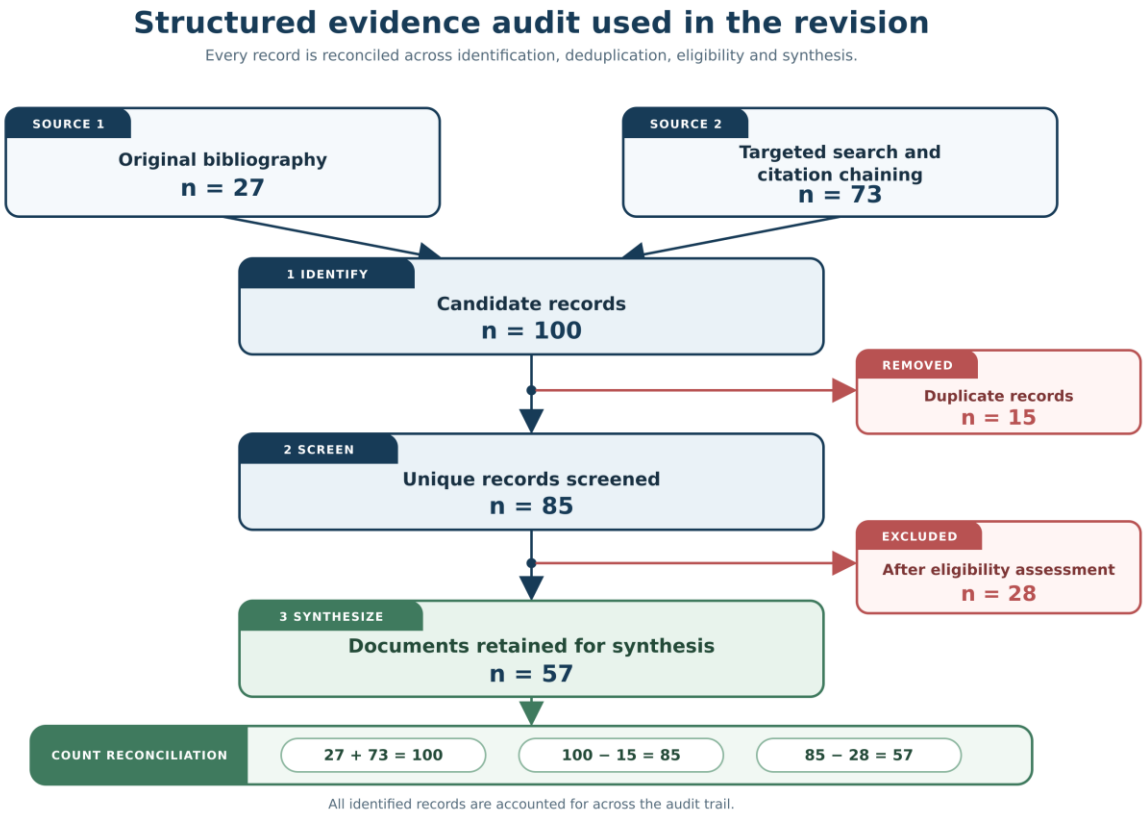


Figure 1. Evidence identification and selection used for the revised structured narrative review.

Table 1. Eligibility, quality assessment and data-extraction framework.

Component	Applied criterion	Reason for use
Population/material	Natural kaolin, kaolinitic clay or kaolin waste with stated provenance	Preserves deposit context and limits inappropriate transfer
Intervention	Physical, chemical, biological, thermal or hybrid beneficiation	Directly addresses the review scope
Required evidence	At least one recognized characterization or ceramic-performance measure	Supports traceable comparison
Preferred outcomes	Fe_2O_3/TiO_2, whiteness/brightness, yield, PSD, surface area, rheology, shrinkage, absorption or strength	Connects treatment to product requirements
Exclusions	Unrelated end uses, conference abstract only, promotional source, missing process description,	Reduces non-verifiable evidence

Component	Applied criterion	Reason for use
	duplicate dataset	
Quality domains	Feed characterization; parameter reporting; analytical adequacy; quantitative outcome; scale/reproducibility	Guides confidence without converting heterogeneous studies into a false pooled score
Higher-confidence use	Clear feed provenance; complete process conditions; recognized analyses; quantitative outcomes; yield, replication or ceramic validation	Supports route conclusions within a defined material and product boundary
Moderate-confidence use	Core feed, treatment and before/after results reported, but mass balance, replication or end-use validation incomplete	Supports deposit-specific comparison, not a universal benchmark
Lower-confidence use	Important feed, process or outcome details missing	Used only to identify a possible mechanism or research gap
Extraction fields	Deposit, impurity mode, unit operations, temperature/time/reagent, mass yield, properties, uncertainty and scale	Enables structured cross-study synthesis

2.4 Quality Appraisal and Synthesis

Each experimental study was examined against five domains: representative feed characterization, completeness of process parameters, adequacy of analytical methods, quantitative reporting of before and after outcomes, and evidence of repeatability or scale. Table 1 shows how these domains controlled the use of evidence. Higher-confidence evidence supported conclusions within a stated feed and product boundary. Moderate-confidence evidence supported deposit-specific comparison. Lower-confidence evidence was used only to identify mechanisms or gaps. No study was excluded solely because it lacked one domain.

Reported values were normalized only when the basis was explicit. Absolute changes in ISO whiteness points were kept separate from relative percentage changes, and composition values were not compared across dry, ignited and unspecified bases. Meta-analysis was not attempted because deposits, process conditions and endpoints were too heterogeneous. Among the quantitative benchmarks in Table 4, only the Spanish study combined several feeds with ceramic-body validation. The remaining cases were treated as moderate-confidence laboratory evidence because at least one of replication, full mass balance, uncertainty or end-use validation was incomplete.

3. FEED CHARACTERIZATION AND ROUTE-SELECTION LOGIC

The minimum characterization train should combine X-ray diffraction (XRD) for mineral phases, X-ray fluorescence (XRF) for bulk chemistry, particle-size analysis, colour measurement using a declared standard, loss on ignition, and thermal analysis. Scanning electron microscopy with energy-dispersive spectroscopy helps distinguish liberated grains from coatings or intergrowths; magnetic susceptibility, electron paramagnetic resonance or X-ray photoelectron spectroscopy is valuable when the iron mode is ambiguous. Representative compositing and moisture-basis control are as important as instrument choice because a technically precise analysis of a non-representative grab sample leads to the wrong flowsheet.

Figure 2 converts characterization into an initial route decision. The branches are not mutually exclusive; they define the least-intensive first intervention. Coarse liberated quartz or feldspar supports classification, discrete magnetic Fe/Ti phases support magnetic separation, fine surface-associated impurities support surface separation or leaching, and structural Fe or firing-related limitations require blending, controlled thermal treatment or acceptance of a lower-value product. The process should escalate only when a measured gap remains.

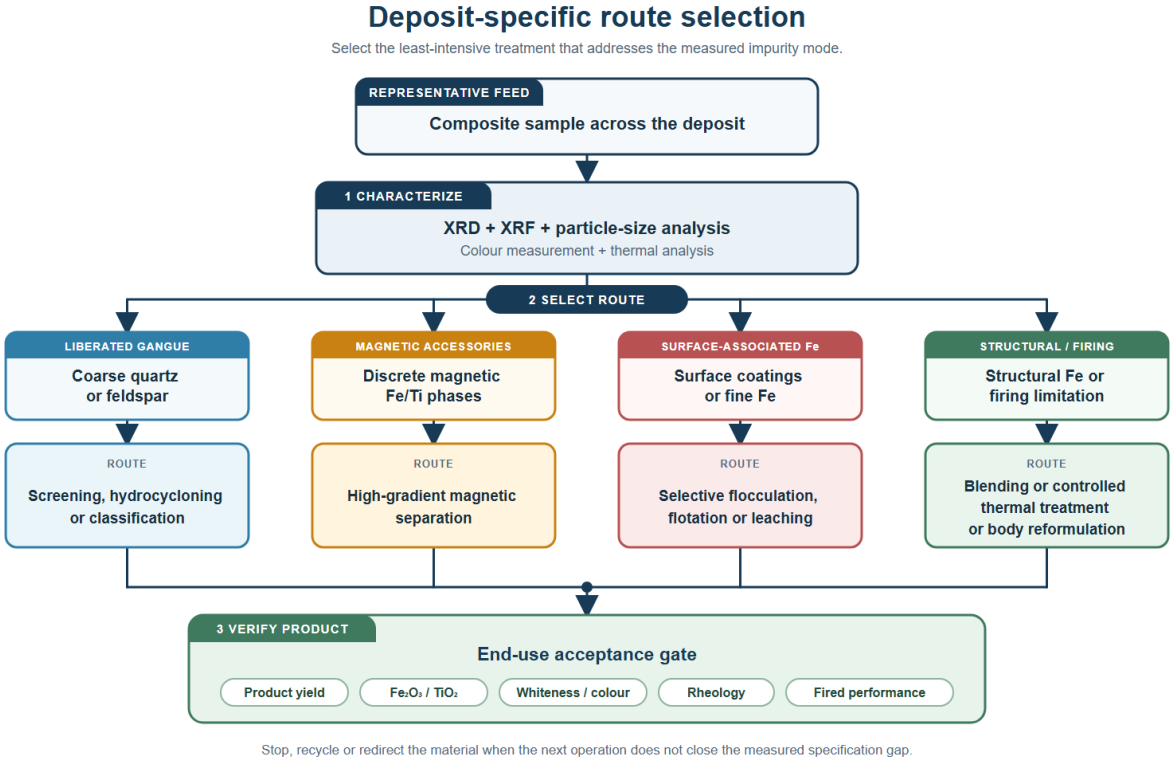


Figure 2. Characterization-led selection of the least-intensive technically plausible beneficiation route.

Table 2. Impurity diagnosis, likely response and verification measurement.

Observed condition	Likely impurity mode	First route	Verification gate
Coarse silica/feldspar; broad PSD	Liberated gangue	Screening, attrition, hydrocyclone or sedimentation	Yield, XRD and D10/D50/D90
Magnetic response; Fe-rich discrete grains	Hematite/goethite or Fe–Ti accessory minerals	High-gradient magnetic separation	Fe_2O_3/TiO_2 and mass recovery
Fine calcite or surface-selective gangue	Surface-chemistry contrast	Flotation or selective flocculation	Grade–recovery curve and reagent residual
Colouring film removable by reductant/acid	Surface coating or accessible Fe oxide	Selective chemical leaching	Iron extraction, whiteness and Al/Si loss
Low magnetic response; persistent colour	Ultrafine or structural Fe	Blend, reject, or targeted hybrid treatment	Spectroscopy and fired colour
Poor firing response despite acceptable chemistry	Dehydroxylation/vitrification constraint	Controlled calcination or body reformulation	TGA/DSC, shrinkage, absorption and strength

4. CRITICAL SYNTHESIS OF BENEFICIATION ROUTES

The beneficiation routes are compared by the impurities they can remove, the reported extent of improvement, product recovery and the resources required. Deposit mineralogy and impurity liberation are used to explain differences among studies.

4.1 Physical Beneficiation

Physical treatment is generally suitable as the first stage because it can reject liberated impurities without dissolving the kaolinite framework. Screening, sedimentation and hydrocycloning narrow the particle-size distribution. Attrition exposes coated surfaces, magnetic separation targets susceptible Fe/Ti phases, and flotation or selective flocculation uses differences in surface chemistry. Liberation controls the outcome. Magnetic separation produced only a small brightness change in three Brazilian samples because the iron oxides and hydroxides were not magnetically recoverable, whereas 30 min of chemical bleaching produced a substantial improvement [21]. Wet sieving, hydrocycloning and electromagnetic filtering substantially

reduced iron-bearing and organic impurities in selected Spanish clays. The purified clays produced porcelain-stoneware formulations comparable with the imported-clay reference [22]. The different results reflect differences in impurity occurrence and magnetic response.

Flotation studies likewise show that mineralogy and reagent regime dominate recovery. Coal-series kaolin required mineralogical control of pyrite and carbonaceous matter, while hydrocyclone–flotation comparisons demonstrated that calcite reduction depends on the separation objective and particle-size window [23]–[24]. Selective flocculation and conventional flotation can upgrade fine kaolin but require narrow control of pH, dispersant/collector dose, shear history and water chemistry [25]–[26]. Grade–recovery curves are needed because an increase in brightness may be uneconomic when it is accompanied by excessive kaolinite loss.

4.2 Chemical Beneficiation

Chemical leaching is most valuable after low-cost removal of liberated gangue. Oxalic acid combines reductive dissolution and complexation of ferric iron, but the necessary dose and contact time depend on iron accessibility. A 2023 study used pre-agitation and high-pressure washing to discard up to 20% of the raw feed, remove more than 54% of total iron, and lower iron from 9.75 wt% to below 6 wt% before leaching; 0.3 M oxalic acid at 97 °C for 1 h then reduced product iron below 1 wt%. Without pretreatment, at least 0.5 M acid and 2 h were required [27]. Pretreatment reduced acid concentration and residence time, but the rejected mass and heated slurry remain material and energy penalties in the plant balance.

Sulfuric-acid factorial experiments reported a highest single-step iron extraction of 26.3% and a two-step maximum of 37.0%, reducing Fe_2O_3 from 2.40 to 1.51 wt% under the best tested sequence [28]. Oxalic-acid kinetic and optimization studies confirm sensitivity to particle size, temperature, acid concentration, pulp density and mixing [29]–[31]. Citrate–thiosulfate provides a different reductant and complexant mechanism. Nigerian and Jordanian studies also show that regional ores can respond to oxalic acid or sodium dithionite, although the treatment conditions must be established for each deposit [32]–[34]. The available evidence does not identify one reagent as the best choice for every deposit.

Mechanical activation and ultrasound can accelerate access to iron-bearing phases. Thiourea-dioxide studies used ball grinding or mechanical activation to increase removal, and ultrasonic assistance shortened mass-transfer paths [35]–[37]. These routes may reduce residence time, but they add electricity demand, wear, fines generation and reagent-handling requirements. Their industrial advantage must be demonstrated as net cost and environmental benefit per tonne of accepted product, not as iron extraction alone.

4.3 Biological and Lower-Impact Routes

Iron-reducing bacteria and microbial metabolites can mobilize accessible Fe under milder chemical conditions. Laboratory studies have examined carbon/nitrogen sources, organic acids, complexing agents and two-stage contact modes [38]–[41]. Scale-up remains difficult because residence times are commonly measured in days, culture control is demanding and iron removal depends strongly on the deposit. In kaolin-waste trials, optimized chemical leaching removed 32% of iron, whereas 14-day *Bacillus* leaching removed less than 1% [42]. Reviews and earlier microbial-refinement studies support bioleaching as a selective treatment or pretreatment for suitable deposits [43]–[44].

4.4 Thermal and Hybrid Processing

Thermal treatment alters the mineral structure as well as its impurity content. Dehydroxylation produces metakaolin; higher-temperature firing promotes spinel-type intermediates, mullite and glassy phases depending on composition and schedule. Acid leaching followed by calcination can improve iron removal and reactivity, but structural Fe and accessory minerals modify the transformation pathway [45]–[46]. Temperature and dwell time affect surface area, amorphization and reactivity, so they must be selected for the intended product [47]–[48].

Premature calcination may destroy the plasticity needed for extrusion or slip preparation. Properly selected calcined kaolin can control shrinkage, serve as grog or chamotte, or support mullite development. Reaction-sintered Algerian kaolin, mullite-based hollow-fibre bodies, porous catalytic substrates, additively manufactured clay bodies and kaolin microfiltration membranes each require a different combination of phases and particle sizes [49]–[53]. The forming and firing requirements of the specified product should determine the calcination conditions.

Table 3. Cross-study comparison of route capability, evidence range and principal limitation.

Route	Reported response across studies	Main strength	Principal limitation	Best-supported role
Classification / hydrocyclone	PSD narrowing; removal of liberated quartz, feldspar or calcite; outcome depends on cut size [24]	Low chemical burden	Kaolinite loss in fine or coarse rejects	First-stage size and gangue control
Magnetic separation	Small brightness change when Fe is non-magnetic; stronger response for	Dry/wet physical option	Cannot remove structural or weakly	Preconcentration after Fe-mode diagnosis

Route	Reported response across studies	Main strength	Principal limitation	Best-supported role
	discrete susceptible phases [21]–[22]		magnetic Fe	
Flotation / selective flocculation	Selective removal of pyrite, calcite or fine gangue; strongly reagent- and water-dependent [23], [25]	Useful for fine particles	Sensitive to pH, ions and slimes	Targeted surface separation
Acid/reductive leaching	Iron extraction from about 26–37% in one sulfuric-acid study to >90% in an optimized physical–oxalic hybrid [27]–[28]	High optical/purity potential	Acid use, heat, washing and effluent	Residual accessible iron after physical upgrading
Bioleaching	From <1% in a 14-day waste-kaolin test to useful removal in selected culture systems [40], [42]	Mild conditions	Slow kinetics and biological control	Niche pretreatment or low-throughput application
Calcination / hybrid	Phase and surface-area modification; ceramic benefit depends on temperature, Fe and body formulation [45], [48]	Tailors firing/reactivity	Energy use and loss of plasticity	End-use-specific final modification

5. EFFECTS ON CERAMIC-RELEVANT PROPERTIES

A beneficiation route has practical value only when the treated kaolin performs satisfactorily during forming, drying and firing. Chemical purity must be considered together with particle behaviour, optical properties and fired performance.

5.1 Particle Size, Aggregation and Dispersion

Beneficiation can reduce D90, remove coarse abrasives and increase specific surface area, although a finer particle-size distribution does not necessarily improve dispersion. In the Ethiopian sequence, D90 decreased from 45.0 to 30.7 μm, a reduction of 31.8%, while specific surface area increased from 11.6 to 30.5 m^2/g [4]. These changes may improve packing or membrane formation, but they can also increase water and dispersant demand. Removal of cementing Fe coatings may release platelets and improve dispersion. Residual acid, dissolved multivalent ions, high ionic strength or inadequate washing can instead compress the electrical double layer and promote flocculation. Zeta potential, viscosity as a function of shear rate, soluble-ion analysis and tests at a standardized solids content are required to demonstrate improved rheology.

5.2 Chemical Purity and Optical Performance

Whiteness and brightness should be reported with the measurement system and the basis used to calculate change. In the Ethiopian study, ISO whiteness increased from 72.0 to 81.4 after beneficiation and acid leaching. This represents 9.4 absolute ISO-whiteness points and a 13.1% increase relative to the starting value. The commercial comparator had a value of 88.14; it was not the measured whiteness of the treated sample [4].

A single percentage cannot describe performance across deposits. Thirty minutes of chemical bleaching increased brightness from 78.2 to 90.2 in one Brazilian sample, 91.3 to 95.7 in another and 86.9 to 90.4 in a third, while magnetic separation produced little improvement [21]. A Spanish study showed substantial physical purification and then validated the treated clays in porcelain-stoneware bodies [22]. The pretreated oxalic-acid route reduced iron from 9.75 wt% to below 1 wt%, but it required heated leaching and rejected part of the feed [27]. These results apply to the tested deposits, methods and colour metrics and should not be treated as a universal efficacy range.

5.3 Forming, Firing and Mechanical Response

The suitability of beneficiated powder must be verified during forming, drying and firing. Lower coarse-quartz content can reduce abrasion and stress concentration, but excessive fines can increase drying shrinkage. Removing flux-bearing impurities may improve colour control while shifting the vitrification temperature. Iron can alter mullite formation and liquid-phase development, so the lowest Fe content is not automatically the optimum for every non-white body [46]. Physical purification of Spanish clays was validated in porcelain-stoneware compositions using sintering, morphology, colour, flexural strength and dilatometry. This provides stronger end-use evidence than chemistry alone [22].

For membranes and porous ceramics, pore-former content, particle packing, burnout and firing schedule control permeability and strength. For tiles and dense whiteware, water absorption, modulus of rupture, dimensional stability and fired colour should be evaluated using declared standards [54]. Laboratory claims

should also report replicate variability. Most included papers provide single mean values or no uncertainty; this prevents statistical pooling and should be corrected in future experimental designs.

Table 4. Quantitative evidence from multiple deposits and the appropriate interpretation.

Study / deposit	Route	Reported change	Correct interpretation	Evidence strength and transfer limit
Ethiopia [4]	Physical + oxalic leach	Fe_2O_3 2.40→0.36 wt%; whiteness 72.0→81.4; D90 45.0→30.7 μm	85% Fe_2O_3 reduction; +9.4 ISO points (+13.1% relative)	Moderate: full chemistry and membrane validation; single-deposit laboratory study; commercial comparator was 88.14
Brazil, 3 samples [21]	Classification + bleaching	78.2→90.2; 91.3→95.7; 86.9→90.4 brightness	Response varies with initial mineralogy; magnetic step added little	Moderate: three samples and defined brightness route; no plant mass balance
Spain, 3 clays [22]	Wet sieve, hydrocyclone, electromagnetic filter	Substantial physical purification followed by ceramic-body testing	Purified clays performed comparably with the imported-clay reference	Higher: three clays and ceramic-body validation; site-specific physical route
High-Fe kaolin [27]	Pre-agitation/washing + oxalic leach	9.75→<6 wt% Fe before leach; <1 wt% after leach	>54% Fe removed physically; >89.7% overall relative to feed	Moderate: explicit feed rejection and leach conditions; no ceramic-product validation
Turkey [28]	H_2SO_4, one/two step	26.3% single-step; 37.0% two-step extraction; 2.40→1.51 wt% Fe_2O_3	Moderate response despite severe conditions	Moderate: factorial design and before/after chemistry; no ceramic-product validation
Kaolin waste [42]	Oxalic/citric vs. *Bacillus*	32% chemical Fe removal; <1% biological removal in 14 d	Mild biological route was ineffective for this waste	Moderate: comparative chemical/biological design; waste feed limits transfer

The review questions lead to a practical decision rule. Impurity occurrence determines the candidate route, and the ceramic specification determines whether treatment has succeeded. Physical methods have the broadest role at the first stage. Leaching is justified only for accessible residual iron after product yield and washing demand are known. Bioleaching remains deposit-sensitive and slow. Calcination is a product-design operation, not a routine cleaning step. The available studies do not support a universal efficacy range because most omit at least one of product recovery, uncertainty, rheology or fired validation.

6. INTEGRATED INDUSTRIAL IMPLEMENTATION

Industrial adoption requires more than a laboratory improvement in purity or colour. The process must tolerate feed variation, recover an acceptable product yield, control water and energy use, and release a kaolin that meets the intended ceramic specification.

6.1 Gated process sequence

Figure 3 presents an integrated flowsheet in which each stage has a stop/go gate. Feed characterization defines a provisional route. Degritting and classification are followed by a mineralogy/PSD gate; magnetic or surface separation is followed by an Fe-mode/colour gate; leaching is followed by chemistry, soluble-salt and rheology checks; washing is coupled to water and reagent recovery; and thermal treatment is used only if the

release specification requires it. This sequence avoids the common error of applying every available unit operation and then reporting purity without product yield.

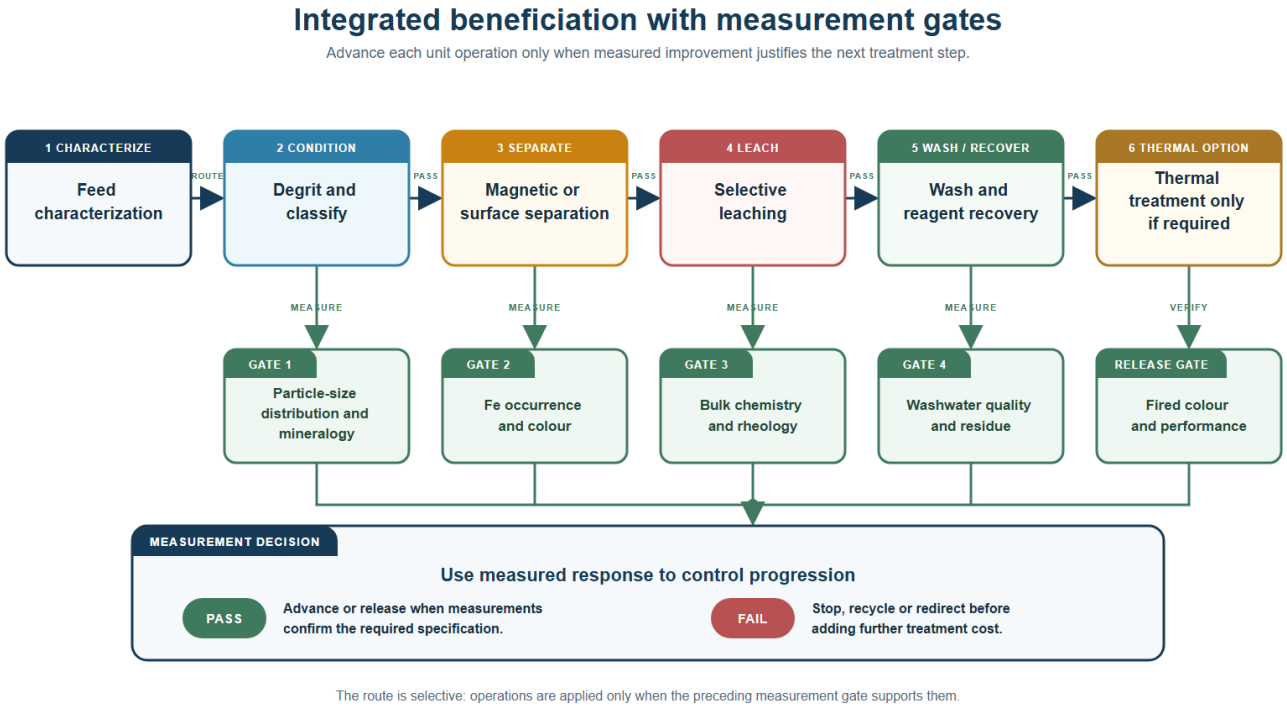


Figure 3. Integrated beneficiation sequence with measurement gates and recycle decisions.

The mass balance should report dry feed, each reject, soluble loss, recovered product and moisture. A plant should also calculate iron removal on a constant basis, kaolinite recovery, acid consumption per tonne of accepted product, wash-water intensity, energy per tonne and the value of downgraded co-products. Route selection should minimize life-cycle cost and environmental burden while meeting the required product specification.

6.2 Scale-up, energy and economics

Scale-up is constrained by slurry handling, filtration rate, corrosion-resistant materials, mixing, heat transfer, fine-particle losses and variability of mine feed. Laboratory studies commonly optimize concentration and temperature in small batches but omit filter area, washing demand, residence-time distribution and recycle accumulation. Pilot trials should use several feed lots and closed-water loops so that these effects can be measured under variable operating conditions.

Thermal treatment and ceramic firing account for much of the energy demand. At 1150 °C, the European ceramic BREF gives 1.90–4.80 GJ/t for once-fired roller kilns, 3.40–4.62 GJ/t for twice-fired roller kilns, 5.42–6.30 GJ/t for once-fired tunnel kilns and 5.92–7.30 GJ/t for twice-fired tunnel kilns. In representative Italian plants, firing used 1.9–4.8 GJ/t of natural gas plus 0.02–0.15 GJ/t of electricity, while spray drying used 1.1–2.2 and 0.01–0.07 GJ/t, respectively [55]. An Egyptian sector benchmark reported an international best-available-technology reference of 3.31 GJ per tonne of ceramic tiles, a weighted average of 6.76 GJ/t for participating plants and 5.66 GJ/t for the most efficient plant in that sample [56]. These values cover the manufacture of ceramic tiles as a whole. They do not represent stand-alone kaolin calcination and should not be assigned directly to a beneficiation kiln. Few of the reviewed kaolin studies measured calcination energy. Future studies should report fuel and electricity use in kWh or GJ per dry tonne, heat recovery, feed moisture and final yield. The proposed 30% reduction in Section 7 is measured against each pilot plant's own baseline.

6.3 Environmental, regulatory and circular-economy controls

Chemical beneficiation transfers impurities to a liquid or solid waste stream. Acidic washwater may contain Fe complexes, sulfate/oxalate, dissolved Al/Si and fine solids; neutralization creates additional sludge. Reagent substitution is not automatically greener if it raises temperature, residence time or toxicity. Oxalic-acid recovery by ultrasound-assisted conversion and cooling crystallization shows a technically relevant circular route, but recovery yield, impurity build-up and energy demand must be demonstrated in the actual kaolin liquor [57].

A practical environmental plan should prioritize counter-current washing, closed-loop water reuse, segregation of high- and low-strength liquors, reagent recovery, iron-rich by-product assessment, dust capture and lined residue storage. Compliance must cover water discharge, worker exposure to

acids/reductants and silica-bearing dust, chemical storage, and waste classification. The BREF provides a baseline for industrial permitting and best-available-technique discussions, but local discharge limits and mining regulations control final design [55].

Table 5. Industrial decision risks, evidence required and control action.

Decision risk	Evidence required before scale-up	Control or design response
Feed variability	Geostatistical/mineralogical domains and monthly composite testing	Blending plan; route set-points by ore domain
Low product yield	Complete dry mass balance and kaolinite recovery	Recover co-products; change cut size; stop unnecessary stages
Leach underperformance	Fe-mode analysis, kinetics and mixing/temperature profile	Pretreat only when liberation benefit exceeds reject loss
Rheology deterioration	Conductivity, ion profile, zeta potential and flow curve	Counter-current wash, pH conditioning and dispersant optimization
Energy escalation	Metered kWh/GJ per dry tonne and moisture balance	Heat recovery, dewatering and lowest effective temperature/time
Water/effluent burden	m^3 water per tonne; recycle quality; sludge chemistry	≥90% reuse target, liquor segregation and reagent recovery
Ceramic rejection	Fired colour, absorption, shrinkage, strength and dimensional stability	Release product only against end-use standard

6.4 Beneficiation Versus Body Reformulation

An ore should not be forced into whiteware when structural iron or poor recovery sets a practical beneficiation ceiling. The alternatives are blending with a cleaner clay, using washed or calcined commercial kaolin, selecting a ball-clay or alumina-bearing route, or redirecting the material to a coloured ceramic body. Physical purification of Spanish clay showed that local material can replace an imported reference only after body-level colour, sintering, strength and dimensional tests [22]. Membrane and porous-body studies likewise show that kaolin and ball-clay routes serve different phase and pore objectives [50], [53].

Beneficiation is justified when a limited treatment closes the specification gap at acceptable recovery. Reformulation or an alternative feed becomes preferable when structural Fe, excessive fines, acid or heat demand, or low yield makes further upgrading uneconomic. The comparison should use cost, energy, water, emissions and rejection risk per tonne of accepted ceramic product, not the composition of the feed alone.

7. RESEARCH GAPS AND FUTURE DIRECTIONS

The remaining research needs fall into scientific, processing, environmental and industrial categories. Separating them clarifies the evidence required at each stage, from mechanism studies to continuous demonstration.

7.1 Scientific Gaps

The main scientific gap is the weak connection between iron speciation and process response. Total Fe_2O_3 does not reveal whether iron is liberated, adsorbed, associated with interlayers or present in the crystal structure. Future studies should combine quantitative phase analysis, microscopy and at least one Fe-sensitive spectroscopic method, then relate impurity occurrence to extraction kinetics, colour and firing. Each deposit should be described by its mineralogy, particle-size distribution, Fe/Ti occurrence, organic carbon and soluble-ion content so that results can be compared across studies.

A second gap is inconsistent optical and colloidal reporting. Whiteness, brightness and colour coordinates are often used interchangeably; particle-size metrics omit dispersion state; and uncertainty is rarely reported. Studies should identify the instrument/standard, distinguish absolute points from relative percent change, provide D10/D50/D90 and report replicate mean, standard deviation and sample number. Mechanistic work should test the corrected hypothesis that leaching may either improve or impair dispersion depending on washing and ionic strength.

7.2 Processing Gaps

Most studies optimize one unit operation at a time. Future work should optimize the full sequence against product yield, reagent intensity, water use, energy demand and fired performance. Immediate priorities include closed-loop washing, continuous solid–liquid separation, measurement of impurity build-up during recycle and pilot runs with variable ore. Machine-learning models may become useful when standardized

datasets are available. Mineralogy and process conditions could then be related to Fe removal, whiteness, rheology and yield, while physics-informed constraints preserve mass and chemical balances. Models developed from small datasets should report uncertainty and should be tested on deposits that were not used for training.

7.3 Environmental Gaps

Environmental studies often report impurity removal without characterizing the resulting waste stream. Future work should quantify water use, toxicity, sludge volume, carbon intensity and reagent recovery per tonne of accepted product. Possible circular uses include recovery of oxalic acid, reuse of clarified washwater, recovery of iron-bearing solids and incorporation of suitable mineral rejects as grog, filler or construction feed after leachability testing. Comparative life-cycle assessments should use one tonne of kaolin meeting a stated ceramic specification as the common functional unit.

7.4 Industrial Gaps

Industrial evidence is limited by single-deposit laboratory batches, incomplete costs and scarce long-duration trials. Demonstration should progress from laboratory route screening (TRL 3–4), through continuous pilot operation with recycle (TRL 5–6), to a pre-commercial line with quality-control integration (TRL 7). Procurement specifications should include mineralogy and fired performance, not chemistry alone. Policymakers can support shared pilot facilities, accredited clay-characterization laboratories, mine-residue inventories and performance-linked finance for water and energy efficiency.

7.5 Prioritized Roadmap

Table 6 orders the proposed actions by time horizon and expected development stage. The targets are intended for pilot planning and should be verified against the feed, product specification and measured site baseline.

Table 6. Prioritized research roadmap TRLs and targets are review-derived proposals, not reported study results.

Horizon / priority	Research action	Measurable target	Indicative TRL transition
0–2 y / highest	Standardize feed, colour, PSD, uncertainty and mass-balance reporting	100% of pilot campaigns use common minimum dataset	TRL 3→4
0–3 y / highest	Closed-loop washing and liquor segregation	≥90% wash-water reuse without off-spec rheology	TRL 4→6
0–3 y / high	Reagent recovery and impurity control	≥80% recoverable reagent returned; stable quality for ≥10 cycles	TRL 4→6
1–4 y / high	Low-energy thermal/hybrid route	≥30% lower measured GJ/t than site baseline at equal product quality	TRL 4→6
2–5 y / high	Deposit-specific predictive model	External-deposit error and uncertainty reported; mass balance enforced	TRL 3→5
2–6 y / medium	Residue/by-product valorization	≥70% of solid rejects directed to verified safe use	TRL 4→7
3–7 y / high	Continuous demonstration line	≥1,000 h operation with variable feed and ≥95% on-spec output	TRL 6→7
Policy / enabling	Accredited testing, water-discharge and product-specification framework	Shared protocols adopted by producer–user consortium	System readiness

7.6 Limitations of the Review

The evidence audit was reconstructed for this revision rather than generated from archived Scopus or Web of Science exports or a prospectively registered protocol. Targeted Google Scholar, Crossref and publisher searches, combined with citation chaining, improved traceability but cannot guarantee exhaustive retrieval. English-language and publisher discoverability may also have favoured readily accessible studies. The record counts therefore describe this review's evidence set, not a complete census of kaolin-beneficiation research. Cross-study comparison is further limited by different deposits, sample preparation, composition bases, colour standards and ceramic tests. Most studies used laboratory batches, and few reported replicate uncertainty, closed-loop water performance, metered energy or a complete dry mass balance. The review therefore does not pool effects or present global efficacy averages. Quantitative values are treated as deposit-specific benchmarks, while the proposed TRLs and targets remain hypotheses for pilot testing.

8. CONCLUSIONS

The appropriate beneficiation route is determined by impurity occurrence and the specification of the intended ceramic product. Physical separation should first remove liberated impurities. Chemical leaching is appropriate for accessible residual iron when product yield, washing demand and effluent control remain acceptable. Biological treatment remains sensitive to the deposit and often requires long residence times. Thermal treatment should be used only when the resulting phase changes suit the forming and firing route.

The quantitative results show substantial variation among deposits. The Ethiopian integrated route reduced Fe_2O_3 from 2.40 to 0.36 wt% and increased whiteness from 72.0 to 81.4 ISO units. The treated material did not reach the commercial comparator value of 88.14. Other studies reported modest iron extraction with sulfuric acid and iron contents below 1 wt% after a combined physical and oxalic-acid process, although the latter required feed rejection and heated leaching. Deposit-specific testing is necessary before these results can be used for process design. Industrial development now requires consistent characterization, uncertainty reporting, closed water and reagent loops, metered energy use per dry tonne, and product validation through forming and firing tests. Pilot programmes should test targets of at least 90% wash-water reuse, 80% reagent recovery and a 30% reduction in thermal energy relative to the measured baseline while maintaining product yield and ceramic performance. These measurements will show whether a local deposit can supply ceramic production without transferring excessive cost or pollution to the waste streams. These conclusions are strongest for deposit-specific route selection and weakest for plant-wide cost, energy and circularity because those data were rarely reported. Pilot decisions should therefore use the evidence-confidence labels in Table 4 and verify all proposed targets against the local feed and product specification.

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