

Review

Thermal Performance of Ceramic Building Materials: The Influence of Clay Matrix and Organic and Inorganic Waste—A Review

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Abstract

This review evaluates how clay mineralogy, waste composition, and processing conditions govern the thermal, physical, and mechanical performance of fired clay ceramics containing organic and inorganic residues. Following PRISMA 2020, 125 original studies published between 2000 and 2025 were selected from Scopus and Web of Science. Key-word co-occurrence analysis and relative-change matrices were used to examine research trends and variations in apparent porosity, water absorption, bulk density, compressive strength, and thermal conductivity. Organic residues generally promoted pore formation, reduced density, and lowered thermal conductivity, but these changes were often accompanied by proportionally greater losses in compressive strength. Inorganic residues showed more heterogeneous responses because they may act as pore-forming, fluxing, filler, or phase-forming components, depending on their chemical composition, interaction with the clay matrix, and firing conditions. The results confirm that total porosity or residue content alone cannot predict thermal performance, since pore geometry, connectivity, phase development, and solid-matrix continuity also govern heat transfer and mechanical behavior. Relative-change matrices summarized net property trajectories within each experimental configuration, and intermediate incorporation levels were considered when they altered the apparent thermal–mechanical balance. Technically suitable formulations must balance thermal insulation, mechanical integrity, moisture stability, processing reproducibility, durability, and environmental safety.

Keywords: ceramics; organic waste; inorganic waste; thermal conductivity; porosity

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1. Introduction

Regulatory frameworks, such as the recent [1] EU Construction Products Regulation (2024), require the construction sector to adopt a robust approach to reducing its environmental impact. Ceramics have long been among the most important building materials worldwide [2]. Despite its tradition [3], in recent decades, the industry has achieved a high degree of technification in the selection and production processes [4]. However, the industry continues to generate a notable environmental impact [5], associated with the consumption of natural resources [6] and fuel [7,8], as well as carbon dioxide emissions,

with estimates exceeding 400 million tonnes across all types of building products [8]. Based on this premise, different areas of research have emerged globally that cover the manufacturing process, ranging from reducing firing temperatures [9] and modifying production techniques [10] to reducing reliance on traditional raw materials by incorporating waste from other economic sectors [9].

In this context, the use of organic waste (agricultural, agro-industrial, forestry, and domestic) and inorganic waste (minerals, ashes, sludges, and glass) in the formulation of ceramic pastes has emerged as a line of research based on the principles of the circular economy [10]. This line is based on three approaches: environmental, aimed at reducing waste and emissions [11–13]; economic, focused on reducing costs, taking advantage of the energy contribution of waste during firing [2]; and the optimization of the physical-mechanical and thermal properties of ceramic materials [14,15]. For this reason, the incorporation of waste is a viable alternative by taking advantage of the energy contained in it (released during firing) or the presence of fluxing elements (such as glass residue [16] or plant biomass [2]) reduces energy consumption in the burning phase, thus recovering waste and reducing greenhouse gas emissions.

The addition of organic or inorganic residues in the ceramic paste plays a significant role in the porosity of traditional ceramics (made between 900 °C and 1100 °C). Higher porosity may be advantageous for applications requiring a lightweight product [15,17,18], thermal insulation, or sound absorption, but it often reduces mechanical strength [16]. Depending on their chemical composition and granulometry, they can act as flux agent [15,19,20], pore generators, and/or stabilizers in the ceramic microstructure [20].

Particle size and chemical composition influence packing, reaction kinetics, gas release, liquid-phase formation, and pore connectivity; however, the final corpus does not support universal elemental thresholds applicable to all clay–residue systems. Muñoz et al. [21] and Nigay et al. [22] demonstrated that additive particle size modifies pore architecture and the resulting thermal and mechanical response. Glass-rich residues promoted softening, vitrification, and reinforcement of interparticle contacts under suitable firing conditions [16,23], whereas dolomite powder generated CO₂ through decarbonation and subsequently supplied Ca- and Mg-bearing components capable of participating in the fired matrix [24]. Soapstone processing waste followed a phase-forming pathway involving Mg–Ca silicates whose development depended on the clay matrix and firing regime [20]. Composition and granulometry must therefore be interpreted together with mineralogical state, dosage, and processing conditions rather than through fixed concentration thresholds.

The review articles on the use of waste materials for manufacturing traditional ceramics already available in the literature are characterized by analyses that focus only on organic waste [25], while others focus on inorganic materials [11]. However, they all share the common theme of the importance of utilizing waste with a focus on sustainability [9]. This involves classifying the waste by origin, the characterization techniques employed, the major chemical elements present, and correlations between waste content and macroscopic properties such as mechanical strength, water absorption percentage, and density. Although some studies present thermal conductivity data, they emphasize that the potential for waste to reduce this macroscopic property increases with higher waste content. However, a more in-depth analysis of the influence of variables such as the type of clay used as a matrix, the shaping method, the particle size distribution of the waste, its chemical composition, or the changes caused by increased temperature on this property has been little discussed. These are the aspects that this review aims to address.

Therefore, the aim of this literature review is to evaluate the influence of the clay matrix, the addition of organic and inorganic wastes, and the manufacturing process on

the macroscopic performance of ceramic products, with emphasis on thermal conductivity, bulk density, and their relationship to mechanical strength.

2. Methods

2.1. Literature Search and Study Selection

This review was conducted and reported following the PRISMA 2020 statement, which was used to structure the identification, deduplication, screening, eligibility assessment, and final inclusion of studies [26]. Scopus and Web of Science were selected as complementary multidisciplinary databases because they provide curated coverage of the peer-reviewed scientific literature but differ in journal indexing, disciplinary representation, and document coverage. Their combined use therefore broadened the retrieval scope and reduced the dependence of the evidence base on the indexing characteristics of a single source [27,28].

The search equation was structured into four conceptual blocks connected through the Boolean operator AND, while synonyms and singular or plural variants within each block were connected through OR. In Scopus, the search was applied to the title, abstract, and keyword fields using TITLE-ABS-KEY. The material block comprised the terms “clay ceramic,” “clay ceramics,” “clay-based ceramic,” “clay-based ceramics,” “clay brick,” “clay bricks,” “ceramic brick,” “ceramic bricks,” “fired clay brick,” “fired clay bricks,” “clay block,” “clay blocks,” “ceramic block,” “ceramic blocks,” “porous clay ceramic,” and “porous clay ceramics.” The waste-incorporation block included waste, wastes, residue, residues, “pore-forming agent,” “pore-forming agents,” “pore forming agent,” and “pore forming agents.” The thermal-performance block contained “thermal conductivity,” “thermal diffusivity,” and “thermal insulation,” whereas the complementary property block included porosity, porous, “water absorption,” “bulk density,” “compressive strength,” and “mechanical strength.” Accordingly, the strategy required each retrieved record to refer simultaneously to a clay-based ceramic system, waste or pore-forming-agent incorporation, a thermal-performance variable, and at least one physical or mechanical property. The same terms and Boolean structure were adapted to the Topic field in Web of Science to search titles, abstracts, author keywords, and Keywords Plus.

The search covered publications from 1 January 2000 to 31 December 2025, corresponding to the Scopus filters PUBYEAR > 1999 and PUBYEAR < 2026. The corpus was restricted to original research articles through DOCTYPE (ar). Equivalent publication-year and document-type filters were applied in Web of Science. Reviews, conference papers, book chapters, books, editorials, notes, and other non-article document types were not included in the primary search corpus. Variables such as clay mineralogy, waste chemical composition, incorporation percentage, particle size, forming method, firing temperature, heating conditions, and methodological traceability were not incorporated into the equation because they are not consistently reported in titles, abstracts, or keywords. These variables were examined during a detailed eligibility assessment to prevent the premature exclusion of studies whose relevance could only be established from the complete article. The resulting selection process is summarized in Figure 1.

The searches retrieved 495 records, comprising 223 from Scopus and 272 from Web of Science. After integrating both datasets, 179 duplicates were identified using normalized DOI and title matching, with supporting comparisons of authorship, publication year, and source, leaving 316 unique records. Title and abstract screening excluded 96 records associated with cementitious or gypsum-based materials, unfired products, geopolymer or alkali-activated systems, non-clay formulations, advanced or refractory ceramics, filtration applications, and other material systems not comparable to fired-clay construction ceramics. Consequently, 220 reports advanced to detailed eligibility assessment.

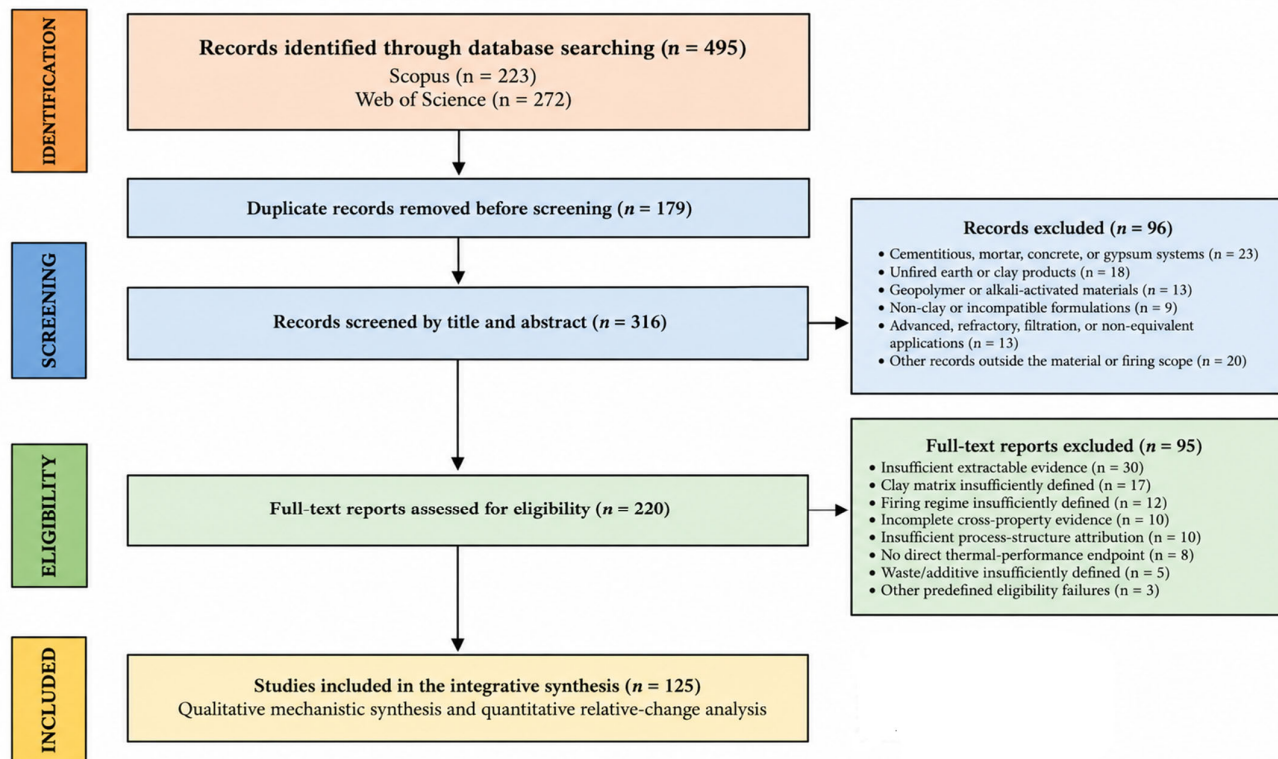


Figure 1. Summary of the selection and purification process using the PRISMA methodology.

The eligibility assessment examined the definition of the clay matrix, waste identity and incorporation level, firing or sintering conditions, direct thermal relevance, complementary physical and mechanical evidence, process–structure attribution, methodological traceability, and data extractability. Ninety-five reports were excluded because these elements were insufficient to establish a technically reproducible relationship among formulation, processing, pore or phase evolution, and material performance, resulting in a final corpus of 125 studies. Missing variables were recorded as methodological limitations when the remaining evidence supported consistent interpretation; however, exclusion was applied when the omissions prevented identification of the material system, attribution of the response to defined experimental conditions, or reproducible extraction of results. Quantitative relative-change matrices were restricted to configurations reporting paired numerical values under equivalent clay matrix, firing temperature, forming conditions, and testing procedures.

2.2. Keyword Normalization and Co-Occurrence Analysis

Records retrieved from Scopus and Web of Science were exported and consolidated into a single bibliographic database. During the selection process documented through the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, duplicate records were identified and removed, after which the eligibility criteria were applied to obtain the final corpus used for analysis. Record merging and cleaning followed the methodology established by [29] for integrating bibliometric information from Scopus and Web of Science.

Keywords were cleaned using a VOSviewer 1.6.20 thesaurus file structured as labels, and the keywords were mapped to columns. The preprocessing procedure developed by [30] was applied to correct spelling differences, word separation, hyphenation, and variants derived from British and American English. The terms included in the thesaurus were replaced before constructing the network; consequently, only the standardized term was

represented as a node (see Table 1). The co-occurrence network was constructed in VOSviewer using full counting and a minimum threshold of seven occurrences per keyword. Using the same network, the software generated a temporal visualization based on the average publication year for each term. The thematic structure and its temporal evolution represent two visualization modes of the same analysis, following the bibliometric and systematic integration framework proposed by Marzi et al. [31].

Table 1. Harmonized spelling variants using the keyword thesaurus.

Label	Replace by
brick making, brick-making, brickmaking	brickmaking
pore forming agents, pore-forming agents	pore-forming agents
micro filtration, micro-filtration, microfiltration	microfiltration
cost-effectiveness, cost effectiveness	cost effectiveness
particle-size analysis, particle size analysis	particle size analysis
aluminum oxide, aluminum oxide	aluminum oxide
clay-brick, clay brick	clay brick
water-absorption, water absorption	water absorption

2.3. Quantitative Synthesis and Heat Map Visualization

Separate relative-change matrices were constructed for organic and inorganic residues using numerical data extracted from the primary studies. The selected properties were apparent porosity, water absorption, bulk density, compressive strength, and thermal conductivity. Each configuration was defined by the primary study, residue type, clay matrix, firing temperature, experimental conditions, and incorporation range. Configurations from the same study were retained separately when the firing temperature or clay matrix differed and were linked through a common study identifier.

Before calculating the relative changes, the numerical dataset was screened to establish within-configuration comparability. Eligible records were required to report waste incorporation on a mass basis (wt.%) and numerical property values obtained for the same residue, clay matrix, firing temperature, forming conditions, and testing procedure. Configurations involving different firing temperatures or clay matrices within the same study were treated separately, whereas incomplete endpoint pairs, modeled values, internally inconsistent results, and data that could not be standardized through direct and traceable unit conversions were excluded. When a 0 wt.% reference formulation was available, it was assigned as a_{min} ; otherwise, the lowest positive incorporation level was retained as the baseline. For each configuration, a_{max} corresponded to the highest incorporation level evaluated under the same experimental conditions, and the same a_{min} – a_{max} pair was applied to all properties. Properties not numerically reported at both levels were recorded as n.r., and no missing values were imputed. Under these criteria, the relative change represents the net property variation across the reported incorporation interval and enables comparison of response direction and magnitude within each configuration. Intermediate levels were considered in the narrative analysis when they materially modified the technological interpretation of that variation. The relative change was determined using Equation (1):

$$\Delta X_{c,p}(\%) = \frac{X_{c,p}(a_{max}) - X_{c,p}(a_{min})}{X_{c,p}(a_{min})} \times 100 \quad (1)$$

where (c) denotes the configuration and (p) the evaluated property. Positive values represented increases, negative values represented reductions, and 0% indicated equal values at both incorporation levels; missing values were not imputed, and calculations were not performed when the baseline value was zero. Data availability was calculated relative to the total number of configurations, whereas the frequencies of increase, reduction, and

stability were calculated only among configurations with complete endpoint pairs. Comparisons between two properties included only configurations reporting both variables. The matrices were represented as heat maps using a common divergent color scheme, numerical annotations within the cells, and diagonal hatching for n.r. values, following the multidimensional heat-map visualization approach described by [32].

2.4. Methodological Traceability and Uncertainty Treatment

Because the reviewed studies differed in experimental design, processing conditions, and reporting completeness, a conventional risk-of-bias score was not applied. Instead, methodological traceability was evaluated for each property and experimental configuration. (Table 2) Interpretation assessed whether studies reported clay mineralogy, waste chemical composition, particle-size distribution, forming method, heating rate, dwell time, firing atmosphere, specimen geometry, test method, number of replicates, and uncertainty measures. Missing methodological information was treated as a limitation for reproducibility and comparability, but not as automatic evidence of poor experimental execution. No missing values were imputed, and mechanistic interpretations were moderated when mineralogical, microstructural, or uncertainty information was incomplete.

Table 2. Methodological traceability criteria considered for interpreting the reviewed evidence.

Criterion	Relevance for Interpretation	Treatment in This Review
Clay mineralogical characterization	Determines firing transformations, phase formation, sintering behavior, and pore evolution.	Used to support mechanistic interpretation when reported; missing information was treated as a limitation for matrix-level inference.
Waste chemical composition	Defines whether the residue may behave as a pore-forming, fluxing, filler, or phase-forming component.	Used to classify the thermochemical function of residues when compositional data were available.
Particle size/granulometry	Affects packing, reactivity, gas release, pore size, pore connectivity, and densification.	Considered when available; not imputed when absent and used to moderate comparisons among studies.
Forming method	Influences compaction, anisotropy, pore distribution, particle orientation, and mechanical response.	Used to contextualize property differences between pressed, extruded, or hand-molded specimens.
Heating rate and dwell time	Affect combustion, decarbonation, sintering, phase formation, and pore closure.	Not imputed when absent; interpretations involving thermal evolution were moderated when these data were not reported.
Specimen geometry and test direction	Affects comparability of compressive strength and thermal conductivity, particularly in anisotropic ceramic products.	Used to qualify cross-study comparisons when geometry or measurement direction differed or was not reported.
Replicates and uncertainty	Determine the reliability of reported values and the extent to which variability can be assessed.	Missing standard deviations, error bars, or replicate numbers were treated as uncertainty and not as zero variability.
Test standard or method	Influences comparability of measured properties across studies and laboratories.	Considered when interpreting property trajectories; differences in methods were treated as comparability limitations.

3. Research Landscape

Research on fired clay bricks incorporating residues is organized around the convergence of four thematic nuclei that connect material diversification, functional valorization, manufacturing control, and ceramic-matrix transformation. In Figure 2a, node size represents keyword occurrence, link thickness indicates co-occurrence strength, spatial proximity reflects the frequency with which concepts are examined jointly, and color

distinguishes the thematic structure generated by the association algorithm. The most connected region is formed around fired clay bricks, thermal conductivity, compressive strength, firing temperature, bulk density, and waste valorization. This configuration shows that the literature is structured around a common technological decision rather than around isolated residue categories. Secondary raw materials acquire practical relevance when their incorporation generates a functional advantage while preserving the properties required for manufacturing and use. The network consequently provides a conceptual overview of the field, whereas the thermochemical mechanisms, processing variables, and quantitative property trajectories are developed in the subsequent sections to avoid duplicating their detailed analysis.

The red cluster represents the diversification of secondary raw materials and their technological validation. Its thematic structure brings together agricultural by-products, industrial residues, ashes, sludges, glass-derived fractions, and construction wastes through a shared set of physical and mechanical assessment criteria. This organization reflects the historical tendency to introduce new residue streams into established ceramic formulations and determine whether the resulting products remain compatible with conventional construction requirements. However, the proximity of these materials within the network should not be interpreted as evidence of equivalent behavior. Biomass ashes, mineral residues, glass-rich wastes, and sludges may be evaluated through similar response variables while contributing different chemical components and following distinct thermal trajectories. Rice husk ash and wood ash, for example, generated differentiated property changes according to their composition, replacement level, and firing temperature, demonstrating that the classification of both materials as ashes is insufficient to anticipate their ceramic response [33]. Ground concrete waste produced a more moderate modification of the fired body, with changes in porosity, water absorption, strength, and thermal conductivity that remained dependent on incorporation level and processing conditions [34]. The cluster therefore reveals both the breadth of the residue portfolio and the persistence of a product-acceptance approach in which feasibility is established mainly through conventional ceramic properties.

The green cluster constitutes the functional-valorization nucleus of the network. Its internal relationships connect residue incorporation with thermal functionality, lightweighting, energy efficiency, environmental performance, and formulation optimization. This arrangement indicates that waste recovery has progressively moved beyond partial clay replacement and has become a strategy for modifying the functional behavior of ceramic units. Organic and lignocellulosic residues occupy a relevant position within this nucleus because they have been widely investigated as additives for reducing density and heat transfer. Nevertheless, their incorporation does not produce an unrestricted improvement. Waste microcellulose generated a pronounced reduction in thermal conductivity, accompanied by a substantial loss of compressive strength, showing that the formulation with the highest insulating response did not provide the most balanced technological performance [15]. Sawdust-containing bricks followed a comparable trajectory, with lower heat transfer occurring together with reductions in density and mechanical resistance [35]. The bibliometric proximity of thermal, mechanical, environmental, and optimization-related concepts consequently reflects an increasing recognition that residue valorization must be assessed as a multicriteria problem rather than through the isolated maximization of incorporation percentage or porosity.

The same cluster shows that the performance of agricultural residues is not transferable solely from their biological origin. Differences in particle morphology, distribution, and interaction with the ceramic body can redirect the balance between insulation and mechanical preservation. Wheat straw, for instance, produced a stronger reduction in thermal conductivity than olive-stone flour, but also caused a greater mechanical penalty,

indicating that the physical configuration of the additive contributes to the resulting technological response [36]. The presence of environmental-assessment concepts within this nucleus further broadens the meaning of valorization. Bio-based pore-forming agents have been associated with reductions in thermal conductivity and several life-cycle impact categories [10]. Even so, the lower connectivity of environmental assessment compared with thermal and mechanical properties indicates that system-level verification remains secondary to laboratory characterization. The cluster thus reflects a field in which environmental justification has gained conceptual relevance but has not yet been incorporated with the same consistency as product-performance testing.

The blue cluster represents the methodological consolidation of the research area around processing control, microstructural characterization, and specific technological responses. Its central position between residue selection and functional performance indicates that manufacturing conditions provide the operational link through which compositional changes are translated into measurable ceramic properties. Firing temperature occupies a particularly prominent position, since it is routinely examined together with shrinkage, density, water absorption, porosity, strength, and microstructure. The study of coconut-shell-containing bricks illustrates this integrated approach by combining residue dosage and thermal treatment with physical, mechanical, and thermal characterization [18]. Likewise, bricks containing recycled ceramics and paper pulp were evaluated through complementary thermophysical, mechanical, mineralogical, and microstructural methods [37]. The structure of this cluster therefore indicates a transition from reporting isolated variations in final properties toward examining coordinated relationships among formulation, processing, internal structure, and performance.

The association of advanced characterization techniques with processing variables also reflects the need to explain responses that cannot be interpreted through residue content, density, or total porosity alone. Micromechanical analysis has shown that the geometry and spatial arrangement of pores affect both thermal transport and mechanical behavior, making the internal architecture of the material a more informative descriptor than a single porosity value [38]. This methodological expansion includes micro-computed-tomography analysis to distinguish spatially differentiated pore populations [39], durability assessment of fired bricks containing quarry residues [40], and phase and environmental-safety evaluation of bricks incorporating complex industrial residues [41]. This broader analytical scope indicates that technological feasibility is increasingly being linked to structural stability and environmental safety, although these dimensions remain less frequent than strength, absorption, density, and thermal conductivity.

The yellow cluster forms a smaller but strategically positioned mineralogical and sintering nucleus. Its proximity to the processing cluster and its connections with lightweight ceramic development indicate that matrix transformation is recognized as an essential bridge between residue incorporation and final performance. The comparatively reduced size of this nucleus suggests that detailed mineralogical interpretation has been less frequent than conventional technological testing, even though it provides the basis for distinguishing among pore generation, densification, phase formation, and defect development. Formulations combining corn cob and waste glass illustrate the value of this perspective. The two residues contributed complementary functions that enabled the development of lightweight bricks while maintaining the reported technological requirements at a reduced firing temperature [8]. The cluster therefore positions mineralogy and sintering as explanatory dimensions that articulate raw-material composition with manufacturing response, rather than as independent lines disconnected from product design.

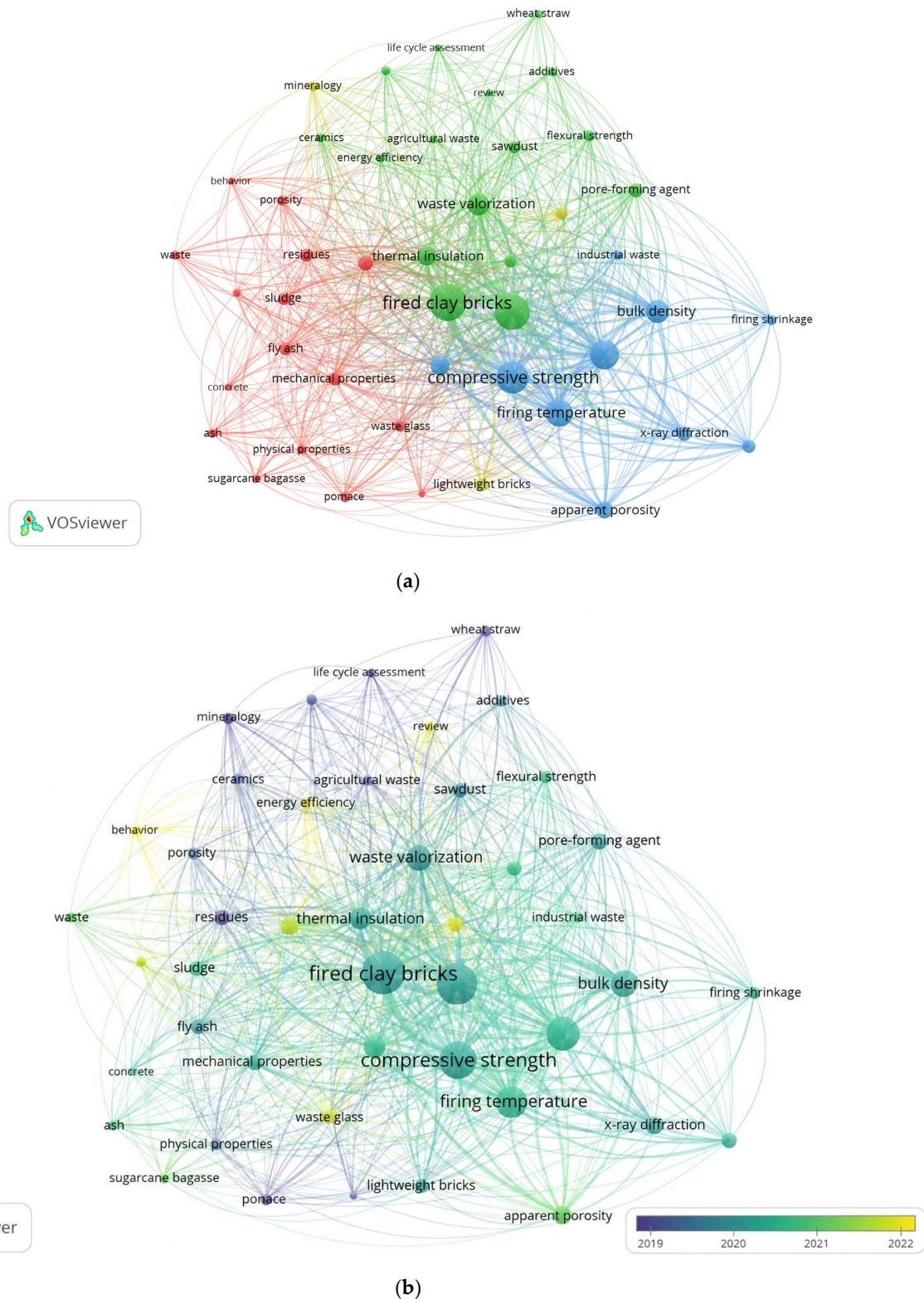


Figure 2b complements the thematic network by showing the relative temporal position of the research agenda according to the average publication year associated with each concept. Violet and blue tones represent themes with earlier average years, green tones occupy an intermediate position, and yellow tones correspond to topics emphasized

more strongly in recent publications. This distribution does not represent a strict chronological succession or the disappearance of previous research lines. The persistence of central nodes across the color scale indicates cumulative development, in which conventional technological assessment remains active while newer studies expand the analytical scope toward circularity, energy performance, optimization, and application-level validation.

The earlier temporal region is associated with the demonstration of technical feasibility, the exploration of specific agricultural and industrial residues, and the development of lightweight ceramic products. This orientation coincided with increasing concern over waste accumulation, continued extraction of clay resources, and the search for valorization routes compatible with existing brick-manufacturing infrastructure. Fired ceramics provided an attractive pathway because the sector consumes large quantities of raw material and operates at temperatures capable of transforming or immobilizing several waste components. In regions with extensive masonry construction and limited waste-processing capacity, the incorporation of locally available residues also offered the possibility of connecting waste management with the production of lower-density building materials. Research during this period consequently concentrated on whether residues could be incorporated without preventing shaping, firing, and compliance with basic product requirements. Environmental assessment was already present, but its comparatively limited occurrence indicates that it had not yet become a standard component of formulation development [10].

The intermediate temporal region reflects the consolidation of residue incorporation as a materials-engineering problem rather than only as a disposal alternative. The growing diversity of residues and experimental outcomes exposed the limitations of transferring an incorporation percentage or firing condition from one material system to another. Research consequently moved toward more controlled examination of particle characteristics, dosage, thermal treatment, and analytical methods. The study of grapevine-shoot particle size exemplifies this transition, since the residue was evaluated not merely as a clay replacement but as a component whose physical configuration influenced the resulting ceramic behavior [21]. The increasing association of microstructural and mineralogical techniques with conventional property measurements also reflects the need to interpret apparently contradictory results, such as similar density reductions accompanied by different mechanical or thermal responses. This stage strengthened the experimental foundations required to distinguish the contribution of residue characteristics from the influence of the ceramic matrix and processing route.

The movement toward more recent temporal positions is connected with global pressure to improve resource efficiency and reduce the environmental burden of both waste disposal and building operation. The construction sector faces simultaneous demands to incorporate secondary materials, reduce dependence on virgin resources, limit production impacts, and improve the thermal performance of building envelopes. These pressures have redirected attention from the mere possibility of manufacturing a residue-containing brick toward the functional value delivered during its use. Energy-oriented studies increasingly evaluate whether lower thermal conductivity can translate into improved wall performance and reduced cooling or heating demand, particularly in climates where operational energy consumption represents a major component of building impacts. The recent prominence of energy efficiency and thermal functionality therefore reflects the convergence of circular-economy objectives with climate-responsive construction.

This transition has also promoted the use of multivariable experimental designs and optimization techniques. Earlier investigations commonly examined one residue at several incorporation percentages and selected a formulation according to individual property thresholds. More recent approaches attempt to identify operating regions that reconcile thermal, mechanical, moisture-related, and processing requirements simultaneously.

A Box–Behnken design applied to wheat-straw-containing bricks integrated residue proportion, firing temperature, and mixture conditions into predictive models for thermal and mechanical performance [42]. This methodological shift responds to the need for reproducible design criteria and to the recognition that maximum waste incorporation, minimum density, or minimum thermal conductivity do not necessarily define the most technically suitable product. Optimization therefore becomes a bridge between experimental knowledge and the formulation decisions required for industrial implementation. The most recent temporal trajectory further extends material characterization toward building-scale and economic performance. Mushroom-waste-enhanced bricks were evaluated through laboratory testing, energy simulation, sensitivity analysis, and economic projection under hot-arid conditions, showing that practical benefits depend jointly on material composition, wall thickness, cooling settings, and the period required to recover the investment [13]. This analytical expansion reflects a broader change in the research question. The field is moving from determining whether a residue can be incorporated toward establishing the geographical, climatic, technological, and economic conditions under which the resulting material creates measurable value. It also responds to the need to convert laboratory property improvements into evidence relevant to manufacturers, designers, regulators, and building users.

The temporal structure therefore reveals successive levels of integration. Initial studies established incorporation feasibility and basic technological compliance; the intermediate period strengthened processing control and microstructural interpretation; and more recent research increasingly connects material development with circularity, energy performance, predictive optimization, and practical application. Conventional indicators such as strength, water absorption, density, and thermal conductivity remain the experimental foundation of the field, but their role is changing from isolated acceptance criteria toward components of application-specific performance assessment. The comparatively lower visibility of long-term durability, emissions during firing, contaminant mobility, production-scale variability, regulatory compliance, and full economic evaluation indicates that the transition from experimental formulations to widely implemented circular construction products remains incomplete.

4. Thermochemical Framework

The thematic relationships identified through the co-occurrence analysis become functionally meaningful when linked to the transformations the material undergoes during manufacturing. Figure 3 illustrates this articulation through a sequence that connects input variables, processing conditions, microstructural configuration, and macroscopic properties. Within this structure, the performance of residue-containing ceramics is interpreted as the outcome of a coupled system in which the mineralogy of the clay matrix, residue composition, particle-size distribution, incorporation level, and thermal reactivity govern the transformations occurring during firing. This perspective makes it possible to recognize that residues from the same source may elicit different responses when their composition or interactions with the clay change, whereas materials of different origin may converge toward similar mechanisms by acting as pore-forming agents, fluxing agents, or precursors of new phases [15,18]. In this regard, [20] demonstrated that the response of lightweight bricks depends significantly on the nature of the clay used, confirming that the function of the residue is conditioned by the mineralogical and chemical system into which it is incorporated. The classification of residues as organic or inorganic retains descriptive value; however, composition and thermochemical function provide a more precise explanation of their influence on structure and performance.

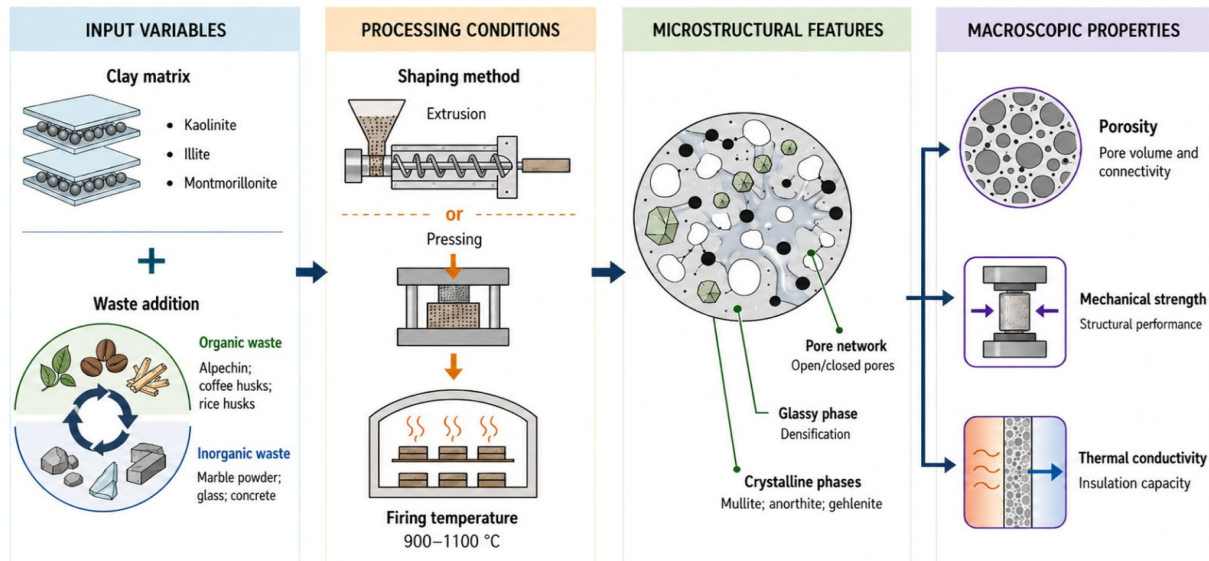


Figure 3. Conceptual framework linking clay matrix, residue characteristics, processing, microstructure, and ceramic performance.

Processing governs how these initial variables are translated into microstructural characteristics. Extrusion induces particle orientation and modifies the spatial distribution of pores, whereas pressing promotes initial compaction, the uniformity of which depends on particle-size distribution, moisture content, and applied pressure. Refs. [43,44] showed that the orientation induced during shaping can generate anisotropy in ceramic materials, producing differences between measurement directions even before the effects of firing are considered. Subsequently, temperature controls the dehydroxylation of clay minerals, the combustion of the organic fraction, the decomposition of compounds, the formation of liquid phases, and the crystallization of new phases. The interaction among these processes allows three response pathways to be distinguished: a pore-forming pathway associated with gas release and void generation, a densification pathway promoted by fluxing components, and a mixed pathway in which both mechanisms compete during firing. The latter is particularly relevant because increasing temperature may initially favor the removal of volatile compounds and subsequently induce partial vitrification and pore closure. The coexistence of the two phenomena explains why a higher level of residue incorporation does not produce a linear evolution of properties. The findings of [8] support this dependence between formulation and temperature by showing that the development of porous bricks requires the incorporation level and firing regime to be adjusted jointly to control density, porosity, and strength.

Microstructure occupies a mediating position within this sequence because it translates thermal and chemical transformations into measurable macroscopic responses. The pore network comprises the void volume, its size distribution, morphology, connectivity, and relationship with the solid phase. In turn, the glassy phase may fill discontinuities, reinforce particle contacts, and reduce pore connectivity, whereas the formation of crystalline phases modifies the stiffness, thermal stability, and consolidation of the matrix. Ref. [20] related mineralogical composition and microstructural development to simultaneous changes in the physical and mechanical properties of ceramic materials, whereas [23] showed that residue incorporation can promote reactions and phases capable of modifying densification during firing. These relationships reveal that similar total porosity may result in different performance when pore connectivity or geometry changes. A structure

with fine, poorly interconnected pores may reduce heat transfer while preserving a continuous load-bearing matrix fraction, whereas an open network facilitates water ingress and increases local stress concentrations. For this reason, water absorption and bulk density serve as complementary indicators for interpreting pore connectivity and the degree of consolidation, although their explanatory power increases when assessed together with the microstructure and the phases formed.

The relationship among porosity, mechanical strength, and thermal conductivity ultimately constitutes a multivariable optimization problem. Increasing porosity may promote lightweighting and reduce heat transfer; however, the spatial distribution of voids, the continuity of the solid phase, and interfacial quality determine the magnitude of the mechanical response. Refs. [15,18,38,45] showed that controlling porous structure makes it possible to adjust thermal insulation and load-bearing capacity simultaneously, whereas [42] demonstrated that residue dosage and temperature generate distinct combinations of density, thermal conductivity, and strength. Accordingly, the selection of formulation and thermal treatment depends on the intended function of the product. An element designed for insulation may tolerate reduced mechanical performance within limits compatible with its use, whereas a unit with a structural function requires preservation of matrix continuity and limitation of critical defects. Figure 3 organizes these relationships into a multiscale framework that links formulation and processing decisions to the microstructural mechanisms responsible for performance, enabling the identification of combinations that balance thermal, moisture-related, and mechanical properties to meet the requirements of the intended application.

4.1. Thermal Evolution of Clay Matrices

The mineralogy of the matrix defines the transformation pathway of the ceramic body during firing because it governs dehydroxylation, liquid-phase development, phase crystallization, and sintering. This influence is compounded by quartz and carbonate contents, fluxing oxides, particle-size distribution, and heating conditions. Experimental evidence in the final corpus confirms that clay matrices follow differentiated firing pathways. Ref. [46] compared kaolinitic, smectitic, and illitic–chloritic matrices processed under an equivalent firing condition, whereas [47] followed the mineralogical, microstructural, physical, mechanical, and thermal evolution of an illite–chlorite–calcitic clay between 900 and 1200 °C.

Experimental evidence within the final corpus shows that clay mineralogy redirects the physical, mechanical, and thermal response under equivalent firing conditions. Ref. [46] compared kaolinitic, smectitic, and illitic–chloritic matrices processed at 900 °C and obtained different phase assemblages and trajectories in density, porosity, water absorption, compressive strength, and thermal conductivity. The kaolinite-rich system developed abundant mullite with residual quartz and hematite, whereas the illitic–chloritic matrix contained quartz and wollastonite with minor enstatite and periclase; the smectitic system developed quartz, augite, anorthite, and minor akermanite. These differences show that the nominal clay classification does not by itself predict consolidation or heat transfer.

Temperature further modifies this matrix-specific response. Ref. [47] followed an illite–chlorite–calcitic clay between 900 and 1200 °C and related progressive vitrification and interparticle-neck development to lower water absorption and open porosity, higher mechanical strength, and a moderate increase in thermal conductivity. Ref. [48] compared two phyllosilicate-based ceramic matrices containing *Musa paradisica* waste and identified different trajectories in open porosity, shrinkage, compressive strength, thermal conductivity, and microstructural development between 900 and 1200 °C. Ref. [20] similarly demonstrated that soapstone waste developed different phase assemblages and

thermomechanical responses in Vendian- and Cambrian-clay formulations. The response to firing therefore depends on the complete mineral assemblage, residue–matrix interaction, and thermal cycle rather than on an isolated clay designation.

The function of the residue is therefore determined by the thermal state the clay attains. An organic component may act primarily as a pore-forming agent when its combustion alters the pore architecture without substantially changing the mineral assemblage, as observed in bricks containing coconut shell [18]. Conversely, an inorganic residue that provides alkalis, alkaline-earth elements, or amorphous silica may participate directly in vitrification and in the crystallization of new phases. This dependence explains why compositions with similar residue contents and equivalent maximum temperatures may reach different states of densification, pore connectivity, and dimensional stability.

The overlap among dehydroxylation, the transformation of quartz (present as an accessory phase), the formation of spinel-type phases, and the development of a silicate liquid phase means that the same maximum temperature may correspond to different reaction states depending on the matrix. Table 3 organizes these thermal windows to identify the dominant mechanism and its continuity toward the subsequent stage, thereby facilitating the interpretation of differences observed among apparently comparable firing cycles. The intervals must be related to the overall composition, heating rate, dwell time, and firing atmosphere, as these variables can shift the transitions and modify their manifestation in the ceramic body.

Table 3. Thermal transformations of clay matrices.

Matrix	T (°C)	Transformation	Phases	Ceramic Effect	References
Kaolinite-type clay (KT), untreated or previously used for oily wastewater decontamination	900	Dehydroxylation and phase reorganization of the kaolinite-rich matrix. In previously used clays, combustion of retained oils increases mass loss without substantially changing the fired crystalline assemblage.	Abundant mullite, with residual quartz and hematite.	Produces a comparatively low-conductivity fired matrix. Retained organic matter increases pore generation and reduces bulk density, compressive strength, and thermal conductivity relative to the untreated clay.	[46]
Illitic–chloritic clay (CS), untreated or previously used for oily wastewater decontamination	900	Dehydroxylation of the clay minerals, carbonate-related reactions, and combustion of retained organic compounds.	Quartz and wollastonite as major phases, with minor enstatite and periclase.	The quartz-rich assemblage limits firing shrinkage but supports comparatively greater heat transfer. Retained oils increase porosity and reduce density, strength, and thermal conductivity.	[46]
Smectite-type clay (CT), untreated or previously used for oily wastewater decontamination	900	Collapse and reorganization of the smectitic structure, accompanied by sintering and formation of Ca–Mg aluminosilicate phases.	Quartz, augite, and anorthite, with minor akermanite.	Develops greater consolidation and compressive strength than the kaolinite- and illite–chlorite-based matrices. Organic compounds retained during wastewater treatment increase porosity and partially reduce this mechanical advantage.	[46]
Illite–chlorite–calcitic clay	900–1000	Decomposition of organic matter and calcite, dehydroxylation of illite and chlorite, and initial development of interparticle contacts.	Dehydroxylated illite–chlorite remnants, residual quartz, and an incompletely vitrified porous matrix.	Maintains relatively high water absorption and open porosity, limited linear shrinkage, and moderate mechanical consolidation.	[47]

Illite–chlorite– calcitic clay	1100	Increased interparticle contact and transition toward a more continuous vitrified structure.	Quartz relicts, dehydroxylated clay–mineral remnants, and a developing glassy phase.	Water absorption and open porosity decrease, mechanical strength increases, and thermal conductivity begins to rise slightly as solid-phase continuity develops.	[47].
Illite–chlorite– calcitic clay	1150– 1200	Advanced vitrification, neck formation, and development of vitrified bridges between particles.	Anorthite and hematite, with quartz relicts and fine crystalline precipitates embedded in a vitrified structure.	Produces the greatest matrix consolidation and mechanical strength, together with lower water absorption and open porosity. Thermal conductivity increases moderately because densification strengthens the solid heat-transfer network.	[47]
Two kaolinitic–illitic clay matrices (NZ1 and KO) containing 1–10 mass% Musa paradisiaca waste	900– 1000	Combustion of the plant fraction and initial matrix sintering. The resulting response depends on the original clay and the amount of organic additive.	Kaolinitic–illitic assemblages with quartz and iron oxides as accessory phases. The complete fired-phase sequence was not reported with sufficient detail for further subdivision.	Plant-waste combustion maintains a porous structure; at 1000 °C, open porosity remains approximately within 30–40% as the incorporation level increases. The two matrices exhibit different shrinkage and property trajectories.	[48]
Two kaolinitic–illitic clay matrices (NZ1 and KO) containing Musa paradisiaca waste	1100– 1200	Progressive sintering and matrix-dependent densification. Optimized waste contents modify the temperature at which functional consolidation is achieved.	The source reports microstructural evolution but does not provide a complete quantitative phase assemblage for each matrix–temperature combination.	Open porosity decreases with temperature. At 1200 °C, optimized additions of 3 and 5 mass% improve the combined mechanical and thermal response relative to the corresponding waste-free clay specimens.	[48]
Vendian and Cambrian hydromica clays containing 40 wt.% soapstone processing waste	950– 1100	Progressive decomposition, recrystallization, and interaction of talc-, chlorite-, carbonate-, and clay-derived components. At the upper temperature, the matrix becomes enriched in crystalline Mg–Ca silicates and a glassy fraction.	At 1100 °C: enstatite, diopside–augite, albite, quartz, hematite, and an amorphous or glassy phase.	Increasing temperature raises density and flexural strength, slightly lowers water absorption, improves thermal-shock resistance, and reduces thermal conductivity. The magnitude of the response differs between the Vendian- and Cambrian-clay formulations.	[20]

4.2. Thermochemical Role of Residues Within Clay Matrices

The incorporation of residues simultaneously modifies mass loss, gas generation, and the reactive composition of the ceramic body. Organic fractions may generate pores through pyrolysis and oxidation, whereas the retained mineral fraction may act as a filler, reactant, flux, or phase precursor. Coconut-shell powder followed a predominantly pore-forming pathway [18]. In contrast, ash and glass residues exhibited distinct inorganic mechanisms: Sütçü et al. reported dosage- and temperature-dependent changes in fired bricks containing bottom and fly ashes, whereas [23] showed that waste-contaminated glass dust modified vitrification, pore structure, and matrix consolidation. The effective function of a residue therefore depends on its physicochemical state and compatibility with the clay matrix rather than on its industrial or biological origin.

Among organic residues, a continuum can be recognized between materials dominated by combustible components and those that have been previously mineralized. Spent coffee grounds, sawdust, wheat straw, argan nutshell, and palm-kernel shell contain combustible fractions that promote mass loss and gas release during firing [19,35,49,50]. This condition offers lightweighting potential; however, the resulting porosity depends on particle geometry and distribution, the rate of volatile release, and the degree of consolidation achieved during combustion. In sawdust-containing ceramics, modification of the pore network was associated with simultaneous changes in density, water absorption, strength, and thermal behavior [35,51,52]. LOI therefore expresses the potential magnitude of mass loss, whereas thermal kinetics and particle-size distribution control the conversion of the released volume into open, closed, or interconnected pores.

Rice husk ash and wood ash exhibit differentiated chemical and mineralogical compositions, loss-on-ignition values, and thermal reactivities, which condition their participation in the fired clay matrix [33], whereas coffee grounds contain comparatively high proportions of MgO, CaO, P₂O₅, and K₂O [19]. This heterogeneity implies that, after combustion, ashes may remain as refractory inclusions, react with the aluminosilicates of the matrix, or modify the viscosity of the silicate liquid phase. In materials with a high organic fraction and poorly reactive ash, retention of the generated porosity is favored, whereas ash enriched in alkali and alkaline-earth components may promote particle bonding and partially close pores formed during earlier stages. The final response depends on the temporal offset between the disappearance of the combustible fraction and the onset of sintering, which explains why residues with similar mass-loss values may produce different pore architectures.

Carbonate-rich residues follow a biphasic pathway. Decarbonation releases CO₂ and generates pores, whereas the residual Ca and Mg oxides may subsequently react with the available silica and alumina. The incorporation of dolomite powder increased porosity and reduced the thermal conductivity of fired bricks, although it also decreased strength with increasing dosage [24]. In eggshell-containing systems, decarbonation of the calcium precursor and subsequent phase evolution depended on temperature and the degree of incorporation [53]. The ceramic effect of calcium results from a balance between porosity due to gas release and consolidation promoted by subsequent reactions. Complete gas release before the closure of the pore network facilitates gas escape, whereas gas release coinciding with a partially vitrified matrix may produce closed pores, expansion, or internal defects.

The SiO₂ and Al₂O₃ contents become predictive when considered in relation to the residue's mineralogical state. Silicon may occur as quartz, glass, amorphous silica, or as part of aluminosilicates, and these forms differ in reactivity and contribution to sintering. In glassy residues, the combination of an amorphous structure with Na₂O, K₂O, or CaO promotes softening and liquid-phase development at temperatures lower than those required for crystalline siliceous particles. Waste glass acted as a fluxing component whose softening during firing strengthened interparticle contacts and partially compensated for the porosity generated by the organic addition [8]. Trachyte quarry waste introduced feldspar-rich silicate phases with fluxing potential, while its effects on porosity, water absorption, density, mechanical response, and thermal conductivity depended on residue content and firing temperature [40]. The combination of chemical composition, X-ray diffraction, and thermal behavior enables differentiation among refractory contribution, reactive participation, and fluxing activity.

These responses can be organized according to two interacting thermochemical potentials. The first governs gas generation and is controlled primarily by the combustible fraction, bound moisture, and carbonate decomposition, whereas the second represents the capacity to form a liquid phase through amorphous, alkali, alkaline-earth, Si-, and Al-

bearing components. A residue with high gas-generating potential and limited fluxing capacity tends to retain a porous microstructure, as observed for coconut-shell powder [18]. When gas generation and fluxing capacity coexist, pore formation competes with liquid-phase-assisted bonding, as demonstrated in formulations combining corn cob with waste glass [8] and rice husk with glass and marble sludges [54].

Thermal conductivity, strength, and water absorption arise from the consolidated microstructure rather than from the isolated concentration of a given oxide. Heat transfer depends on total porosity, pore size and connectivity, the continuity of the solid phase, and the nature of the amorphous and crystalline phases [38]. A reduction in density may decrease thermal conductivity by increasing the volume of immobilized air, but it may also reduce the load-bearing cross-sectional area and promote water absorption if open pores predominate. The combined incorporation of sanitary ware waste and corn-stalk digestate showed correlations among porosity, water absorption, and thermal conductivity, with strength decreasing as the porous fraction increased [55]. Composition (detailed in Table 4) enables anticipation of available transformations, whereas the spatial distribution of phases and pores determines their macroscopic manifestation.

Residue selection requires integrating loss on ignition with the balance among network-forming oxides, fluxing components, and gas-releasing compounds. High SiO₂ or Al₂O₃ contents become relevant when their mineralogical or amorphous state permits reaction within the firing interval, whereas Ca-, Mg-, and alkali-bearing components modify phase evolution, gas release, and liquid-phase viscosity. This interpretation links silicoaluminous quarry residues to mineral replacement and sintering [40], glass-rich residues to liquid-phase-assisted consolidation [23], and carbonate-rich residues to competition between decarbonation-induced pore formation and calcium- or magnesium-mediated reactions [24,53].

Table 4. Reported chemical composition of residues incorporated into construction ceramics.

Classification	Residue	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	P ₂ O ₅	K ₂ O	Loss-On-Ignition (LOI)	References
Organic	Rice husk	15.56	0.2	0.06	0.09	0.09	0.15	0.28	83.5	[33]
	Palm kernel shell	47.1	15.19	12.2	0.93	7.59	0.68	0.25	9.23	[50]
	Sawdust	0.35	0.39	0.19	0.41	1.68	0.02	0.34	95.28	[51]
	Wheat straw	7.84	0.29	0.73	0.21	4.36	0.25	1.84	82.97	[36]
	Argan nut shell	NR	NR	0.01	NR	0.08	NR	0.05	99.52	[49]
	Coffee grounds	1.09	0.79	1.26	22.93	13.73	23.66	23.87	NR	[14]
Inorganic	Marble dust	3.72	0.87	NR	0.76	52.9	NR	0.27	41.3	[56]
	Sanitary ware ceramic waste	67.6	24.44	1.47	0.16	0.86	NR	3.86	NR	[55]
	Fly ash	35.67	18.52	14.17	NR	11.64	NR	NR	0.74	[57]
	Crushed glass	72.26	1.47	0.47	3.16	9.32	NR	0.54	NR	[16]
	Ornamental stone waste	56	19.9	5.8	1.6	3.6	0.48	4.3	0.74	[40]
	Wood ash	49	3.43	3.29	2.66	17.3	0.47	1.98	19.64	[58]

NR: not reported.

Composition delimits the available thermochemical pathways, but processing determines which pathway dominates and the extent to which it is expressed. Grinding modifies the reactive surface area and combustion rate; dosage controls the continuity of residue-rich regions; shaping establishes the initial density and gas-escape pathways; and the thermal cycle governs the overlap among decomposition, liquid-phase formation, and pore closure. The response of sawdust varied with the pore architecture developed during firing [51], whereas the combined action of corn cob and waste glass depended on the balance between gas-induced pore formation and liquid-phase-assisted bonding at a

reduced firing temperature [8]. In carbonate systems, dosage and temperature modified the balance among decarbonation, porosity, and consolidation [24]. This dependence establishes the shaping method, particle-size distribution, and firing schedule as necessary variables for interpreting the resulting variations in density, water absorption, strength, and thermal conductivity.

5. Processing and Macroscopic Response

The macroscopic response of waste-containing clay ceramics is governed not only by the composition of the clay–waste system but also by the physical state established during manufacturing. Moisture content, compaction pressure, particle-size distribution, and shaping route determine the green bulk density, particle arrangement, and initial pore geometry. These characteristics subsequently influence firing shrinkage, bulk density, water-accessible porosity, mechanical strength, and heat transfer. Experimental and modeling evidence shows that thermal conductivity cannot be represented as a single-valued function of total porosity because pore shape, orientation, spatial distribution, and connectivity modify the effective heat-transfer path [38]. The relationship between thermal conductivity and physical characteristics also varies with raw-material composition and processing conditions. Refs. [59,60] demonstrated the influence of mineralogical composition on the thermal response of traditional ceramics, whereas Sutcu et al. showed that molding pressure and firing temperature jointly modified density, porosity, compressive strength, and thermal conductivity in waste-tuff bricks. Bulk density and total porosity are therefore necessary descriptors, but neither is sufficient to explain thermal response independently.

Processing also introduces directional and measurement-dependent effects that are commonly omitted in inter-study comparisons. Extrusion and the morphology of incorporated particles can generate preferential orientations within the ceramic body. Ref. [43] demonstrated that particle shape and orientation modified the anisotropy and the resulting thermal and mechanical properties of clay ceramics, whereas [44] represented fired clay bricks through a transversely isotropic thermal-conductivity tensor associated with their multiscale internal organization. Consequently, conductivity values obtained in different measurement directions cannot be treated as equivalent. Moisture introduces an additional source of variation because water progressively replaces air in accessible pores, thereby increasing heat transfer. Consequently, absolute property values obtained under different shaping, conditioning, or measurement protocols cannot be treated as equivalent observations. Processing must therefore be examined as a source of experimental variability before comparing the relative changes in properties associated with waste incorporation.

5.1. Forming and Experimental Comparability

Compaction pressure controls interparticle contact and the pore volume retained in the green body, while the forming route introduces a directional component into the fired microstructure. However, anisotropy cannot be represented by a universal numerical ratio transferred among products. Ref. [43] demonstrated that the shape and orientation of organic additive particles modified the thermal and mechanical anisotropy of clay ceramics, whereas [44] represented fired clay bricks through a transversely isotropic thermal-conductivity tensor associated with their multiscale internal organization. Measurement direction must therefore be reported because conductivity values obtained along different material axes cannot be treated as equivalent.

Particle-size distribution acts at both the packing and pore-generation scales. Nigay et al. demonstrated that the particle-size distribution of organic additives modified pore morphology and the resulting thermal and mechanical properties of clay ceramics.

Complementarily, ref. [52] showed that sawdust granulometry altered directional pore distributions, heat transfer, and compressive strength. Waste content alone therefore does not define the resulting pore architecture because particle dimensions, morphology, and spatial distribution also govern the continuity of the fired matrix.

Thermal-conductivity measurements are affected by specimen conditioning and orientation. Water occupying accessible pores creates a more conductive pathway than air; consequently, values obtained under different moisture states cannot be treated as equivalent. Direction must also be reported because processing-induced organization may generate anisotropic thermal behavior [43]. Reliable comparison therefore requires documentation of forming pressure, particle-size distribution, specimen geometry, moisture condition, measurement direction, and thermal test method. Within-study contrasts that preserve composition and modify a single processing variable provide stronger evidence than comparisons assembled from unrelated experimental series. All this experimental evidence is showed in Table 5.

Table 5. Experimental evidence on processing and measurement variables affecting clay-ceramic properties.

Variable	Matrix and Configuration	Experimental Contrast	Implication	Reference
Compaction pressure	Waste-tuff brick specimens molded at different pressures and fired at 900–1100 °C	Molding pressure varied from 20 to 60 MPa under defined firing conditions	Pressure modified apparent porosity, density, thermal conductivity, and compressive strength; its effect depended on firing temperature	[61]
Forming route	Nine commercial Italian clay matrices; extrusion and uni-axial pressing	Clay fractions processed using both forming routes	No universal conductivity–density relationship was obtained across matrices and processing routes. A statistically valid model was achieved for the extruded subset, indicating process-dependent calibration.	[62]
Extrusion-induced orientation	Kaolinite–quartz–muscovite clay body; extrusion	Measurements parallel and perpendicular to the extrusion axis	Preferential platelet orientation produced a macroscopic thermal-anisotropy ratio of approximately two, demonstrating that scalar density cannot represent directional heat transfer.	[43,44]
Particle-size distribution	Kaolin–ball clay–sawdust and dry-pressed clay–sawdust systems	Independent changes in mineral and sawdust particle sizes; longitudinal and transverse characterization	Finer mineral particles increased thermal diffusivity, whereas larger sawdust particles reduced it. Pore-former size also modified directional porosity and mechanical continuity.	[22,52]
Moisture state	Handmade, extruded and pressed historic brick masonry	Thermal measurements from dry to moisture-containing conditions	Conductivity increased with moisture content and density, but the magnitude of the change depended on the manufacturing route and the relationship between open and closed porosity.	[63]
Measurement direction	Two red-fired bricks and one decalcium-silicate brick from commercial manufacturers	Thermal conductivity determined in three orthogonal directions	Directional conductivity differences reached 36%. Measurements in a single direction can bias comparisons between anisotropic products.	[43,44]

5.2. Relative Changes in Macroscopic Properties

Because the absolute property values reported in the literature are influenced by the processing and measurement variables discussed above, the cross-study synthesis was based on relative changes calculated within each experimental configuration. Each configuration was defined by a specific waste, firing temperature, and incorporation range, and the relative change was determined as the difference between the minimum and maximum incorporation levels evaluated under those conditions. This approach preserves the internal direction of each experimental series while reducing the influence of differences in units and baseline values. It does not render the studies experimentally equivalent because the magnitude of the variation remains dependent on the incorporation interval and the original property value. Firing shrinkage, bulk density, porosity, water absorption, mechanical strength, and thermal conductivity were therefore interpreted as a coupled property vector rather than as independent responses. The inorganic and organic datasets are therefore examined separately to identify the dominant and divergent trajectories within each family. Unreported properties were retained as unavailable data and were not treated as zero change.

5.2.1. Inorganic Waste

Across the ten residue–temperature configurations represented in Figure 4, the inorganic additions produced markedly heterogeneous physical, mechanical, and thermal responses. Apparent porosity increased in 100% of the available comparisons, although this property was reported for only 10% of the configurations. Water absorption was available for 70% of the configurations; among these, it increased in 85.7% and decreased in 14.3%. Bulk density was also available for 70% of the configurations, decreasing in 57.1% and increasing in 42.9% of the available comparisons. Compressive strength was reported for 70% of the configurations and decreased in 71.4% of the available comparisons, while increasing in the remaining 28.6%. Thermal conductivity was available for only 30% of the configurations; among these, it decreased in 66.7% and increased in 33.3%. Increased water absorption coincided with reduced compressive strength in coal bottom ash at 900 and 1000 °C and aluminum filter dust at 950 °C, but coal bottom ash at 1100 °C combined increased absorption with higher strength, whereas crushed waste beer-bottle glass simultaneously reduced absorption and increased strength. These divergent responses confirm that water absorption and bulk density cannot independently predict mechanical or thermal performance. Ref. [38] demonstrated that elastic and thermal behavior depends on pore geometry, aspect ratio, orientation, and spatial distribution rather than on total porosity or density alone.

Waste marble powder and crushed waste beer-bottle glass define the two most clearly opposed pathways. Marble-powder incorporation reduced compressive strength by 81.7% at 950 °C and 80.1% at 1050 °C, while thermal conductivity decreased by 58.8% and 59.5%, respectively. The similarity between both firing temperatures indicates that the thermal benefit and mechanical penalty remained comparatively stable within this interval. The source study associated marble addition with lower bulk density, pore generation and a reduction in thermal conductivity from approximately 0.97 to 0.40 W m^{−1} K^{−1}, although the final compressive strength remained compatible with the requirements considered by the authors [56]. Crushed beer-bottle glass followed the opposite trajectory at 1050 °C: water absorption decreased by 93.9%, bulk density increased by 9.5%, compressive strength increased by 171.3%, and thermal conductivity increased by 71.4%. The 171.3% value is retained because strength increased from 42.0 to 113.93 MPa, meaning that the final value was approximately 2.71 times the reference value. The same study identified 113.93 MPa as the maximum compressive strength obtained with 10 wt.% glass at 1050 °C and related glass incorporation to vitrification, reduced water-accessible voids,

and improved consolidation [16]. The accompanying increase in thermal conductivity demonstrates that the denser and mechanically stronger structure also created a more continuous solid pathway for heat transfer; therefore, improved strength and moisture resistance did not translate into improved thermal insulation.

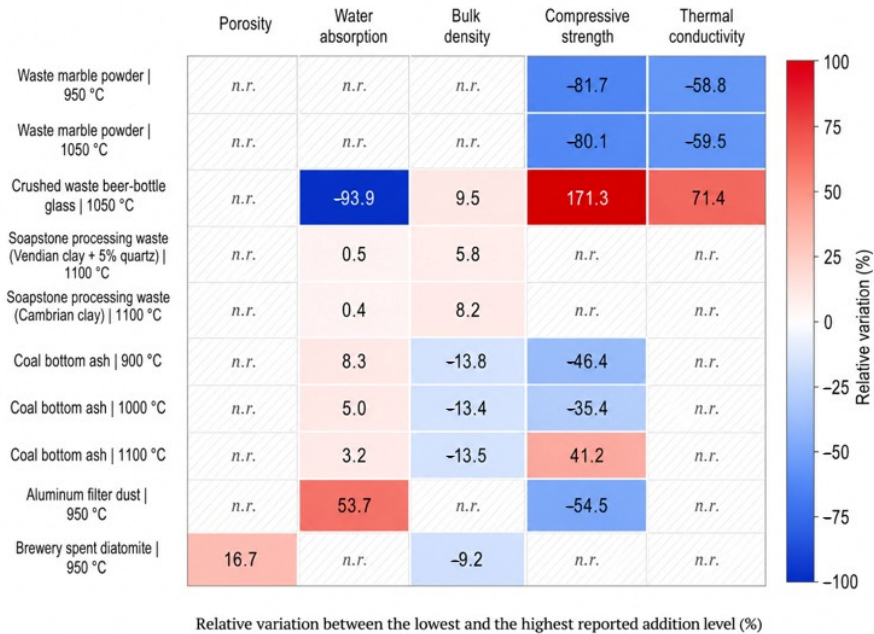


Figure 4. Heat map of relative property changes in clay ceramics containing inorganic waste. *n.r.*: not reported.

The soapstone and coal-bottom-ash configurations demonstrate how matrix composition and firing temperature redirect the response of mineral residues. Increasing soapstone processing waste produced only marginal changes in water absorption, reaching 0.5% in the Vendian-clay formulation and 0.4% in the Cambrian-clay formulation, whereas bulk density increased by 5.8% and 8.2%, respectively. The difference between the two systems should be attributed to the complete matrix composition rather than to clay designation alone, because the Vendian formulation also contained added quartz, and both clays differed in mineralogical and granulometric characteristics [20]. The same investigation related the improved mechanical and thermal stability of soapstone-containing ceramics to the formation of a glassy phase, enstatite, and diopside during firing [20]. Coal bottom ash maintained a nearly constant bulk-density reduction of 13.4–13.8% from 900 to 1100 °C, while the increase in water absorption progressively declined from 8.3 to 3.2%. More importantly, compressive strength shifted from reductions of 46.4% at 900 °C and 35.4% at 1000 °C to an increase of 41.2% at 1100 °C. The primary study similarly reported increasing strength and density with firing temperature in clay–bottom-ash ceramics [64]. This reversal is consistent with enhanced sintering and interparticle bonding at the highest temperature, although the property matrix alone cannot identify the responsible phase transformations. This reversal is consistent with temperature-dependent changes in sintering and interparticle bonding, although the coal-bottom-ash study did not directly resolve the responsible phase transformations. Martinez Martinez et al. [47]. demonstrated that increasing firing temperature modified mineralogical evolution, pore structure, density, mechanical strength, and thermal conductivity in illite–chlorite–calcitic clay ceramics, supporting a cautious interpretation of temperature-driven matrix restructuring.

Aluminum filter dust and brewery spent diatomite represent predominantly pore-related responses, but with different levels of documented property coverage. Aluminum filter dust increased water absorption by 53.7% and reduced compressive strength by 54.5% at 950 °C. The residue contains a high proportion of aluminum oxide together with calcium oxide, sodium chloride, and potassium chloride. This progression indicates a dosage-dependent transition in the predominant mechanism. Additions up to 20 wt.% maintained a comparatively balanced interaction between fluxing and pore-forming effects, whereas at 25 wt.% pore generation became dominant and produced a less favorable physical-mechanical response [65]. The heat-map value consequently represents the net transition across the complete incorporation interval, while the intermediate results delimit the range in which the two thermochemical contributions remained more effectively balanced. The figure therefore reflects the deterioration observed at the upper incorporation level rather than the more balanced response obtained at intermediate additions. Brewery spent diatomite increased apparent porosity by 16.7% and reduced bulk density by 9.2%, indicating a lightweighting response, although the unavailable strength and conductivity cells prevent quantification of its thermal-mechanical balance in Figure 4. The original investigation likewise reported that incorporating spent diatomite increased open porosity and reduced density, while the resulting technological performance depended on the residue content and firing conditions [17]. The contrast among marble, glass, soapstone, bottom ash, aluminum filter dust, and spent diatomite shows that inorganic residues cannot be classified through a single densification or pore-forming pathway; their responses arise from interactions among residue chemistry, matrix mineralogy, and firing-induced changes in pore and phase architecture.

5.2.2. Organic Waste

Across the seven residue-temperature configurations represented in Figure 5, bulk density and thermal conductivity were available for 57.1% of the configurations and decreased in every available comparison, whereas compressive strength was reported for 71.4% and decreased consistently. Apparent porosity was available for only 14.3% of the configurations and increased in that case, while no complete water-absorption comparison was available. The response magnitudes differed substantially, with bulk-density reductions of 13.1–25.7%, compressive-strength losses of 57.4–94.5%, and thermal-conductivity reductions of 31.7–70.1%. The common direction of these properties indicates that organic additions recurrently weakened the solid ceramic network while reducing heat transfer, but the mechanical penalty was systematically greater than the thermal benefit wherever both properties were available. The ratio between compressive-strength loss and thermal-conductivity reduction reached 1.35 for residual micro-cellulose fiber, 1.62 and 1.51 for waste millet husk at 900 and 1000 °C, respectively, and 2.28 for olive mill waste. The residues therefore did not produce an equivalent thermal return for a given mechanical deterioration, even though all available conductivity values decreased. The studies represented in the figure confirm that organic additions can act as pore-forming agents, but their technical performance depends on the balance among density reduction, thermal conductivity, and mechanical continuity rather than on the direction of change alone [15,59,66].

Waste millet husk provides the most internally complete temperature comparison because bulk density, compressive strength, and thermal conductivity were available at both 900 and 1000 °C. At 900 °C, these properties decreased by 15.1, 68.2, and 42.1%, respectively, while the corresponding reductions at 1000 °C were 13.1, 65.4, and 43.4%. The limited variation between temperatures shows that the higher firing condition only slightly moderated density and strength losses and did not improve the thermal response, which remained close to a 43% reduction. More importantly, strength decreased

approximately 4.5 times more than density at 900 °C and 5.0 times more at 1000 °C, demonstrating that bulk density did not adequately represent the deterioration of the load-bearing network. The primary investigation reported that the complete experimental series decreased bulk density from 2.06 to 1.58 g cm⁻³, reduced compressive strength by as much as 68%, and lowered thermal conductivity by 42% at 16 wt.% incorporation, whereas the best mechanical response was obtained at the lower content of 4 wt.% [66]. The separation between the dosage that maximized the insulating response and the level that better preserved mechanical capacity demonstrates that both properties were governed by different sensitivities to residue incorporation. A comparable dosage dependence was observed in grapevine-shoot-containing bricks, where replacement percentage modified both thermal and mechanical performance, while particle size exerted an increasingly pronounced influence on strength as additive content increased [21]. These responses indicate that residue content controls not only the volume of pores generated but also their capacity to interrupt mechanically effective sections of the ceramic body. Consequently, the formulation with the lowest thermal conductivity cannot be considered the most technically suitable without examining its absolute mechanical performance.

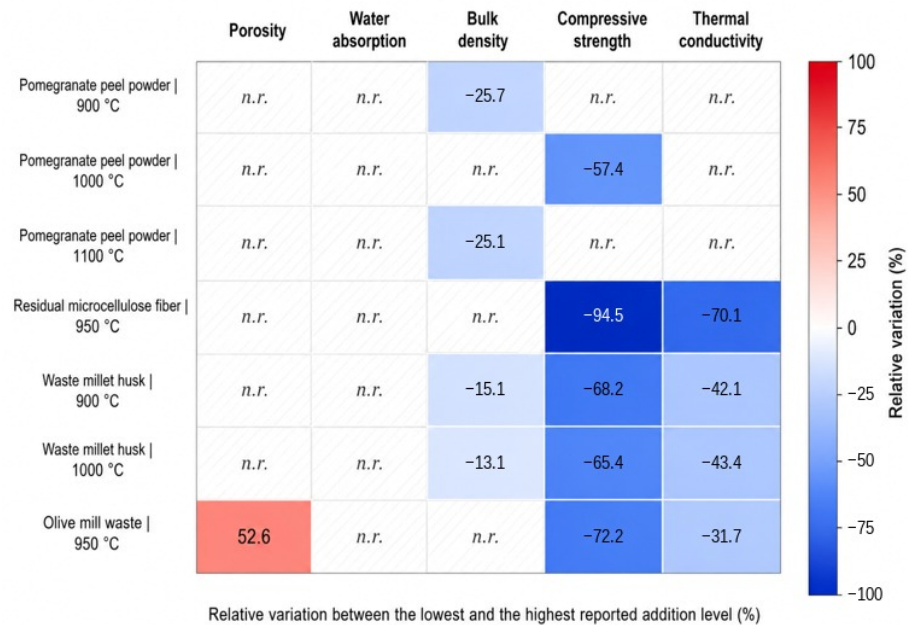


Figure 5. Heat map of relative property changes in clay ceramics containing organic waste. n.r.: not reported.

Pomegranate peel powder followed a different data pattern because bulk density was available at 900 and 1100 °C, whereas compressive strength was represented at 1000 °C. Bulk-density reductions were nearly identical, reaching 25.7% at 900 °C and 25.1% at 1100 °C, which indicates that the relative lightening effect was maintained across the evaluated temperature interval. At 1000 °C, compressive strength decreased by 57.4%, but this value cannot be interpreted as a coupled density–strength response because both properties were not simultaneously available at all three temperatures in the audited matrix. The original investigation nevertheless reported that increasing pomegranate-peel incorporation decreased density, thermal conductivity, and compressive strength while increasing total porosity and water absorption, with 12.5 wt.% producing 48% porosity, 38% water absorption, 5.5 MPa compressive strength, and approximately 0.20 W m⁻¹ K⁻¹ thermal conductivity at 1000 °C [67]. These complementary results support the pore-forming function of the residue but also reinforce the need to distinguish between lightweighting and

structural adequacy. A similar dosage-dependent balance was investigated in bricks containing spent coffee grounds, where the organic addition was used to reduce heat transfer and produce lightweight ceramic units, although the formulation had to reconcile insulation gains with the accompanying changes in physical and mechanical properties [19]. Both studies show that the largest residue content should not automatically be treated as the technically preferable formulation merely because it produces the lowest density or conductivity.

Residual microcellulose fiber represents the most severe coupled response in Figure 5. Compressive strength decreased by 94.5%, from 25.4 to 1.4 MPa, while thermal conductivity decreased by 70.1%, from 0.893 to 0.267 W m⁻¹K⁻¹ [15]. Although this was the largest thermal-conductivity reduction among the available configurations, it was accompanied by the greatest loss of compressive capacity, showing that extensive pore formation can exceed the range in which the ceramic skeleton remains mechanically functional. The source study reported that 15 wt.% microcellulose increased porosity by as much as 104%, confirming that the reduction in heat transfer occurred together with a substantial restructuring of the fired body [15]. Olive mill waste produced a lower thermal reduction but an even less favorable proportional balance: porosity increased by 52.6%, while compressive strength and thermal conductivity decreased by 72.2 and 31.7%, respectively [59]. The mechanical loss was therefore more than twice the conductivity reduction, indicating that the additional pore volume affected stress transfer more strongly than thermal conduction. This lack of proportionality agrees with the grapevine-shoot study, in which particle-size changes had a clearer effect on mechanical properties than on thermal behavior [21]. The response is consistent with strength being controlled by critical defects and local discontinuities, whereas conductivity reflects the combined contribution of the solid phase, gaseous pore volume, pore distribution, and connectivity.

The limited porosity coverage and absence of complete water-absorption comparisons in Figure 5 prevent total pore volume from being equated with moisture accessibility. External contrasts contained in the consolidated database confirm that these variables may evolve differently. Ground olive stones increased porosity while reducing apparent density, compressive strength, and thermal conductivity, yet the measured water-absorption coefficient decreased as residue content increased [68]. This result does not contradict pore formation because the reported coefficient characterizes capillary water uptake rather than the total volume of water-accessible voids, and it demonstrates that pore amount and liquid transport cannot be treated as interchangeable descriptors. Coconut-shell powder provides a complementary temperature contrast: increasing residue content reduced density and mechanical strength while increasing porosity and water absorption, whereas higher firing temperatures reversed part of these physical changes; at 1100 °C and 30 wt.% incorporation, the material reached a thermal conductivity of 0.37 W m⁻¹ K⁻¹ while retaining a tensile strength of 9.88 MPa [18]. Although tensile strength is not directly comparable with the compressive-strength values in Figure 5, this formulation shows that temperature can improve matrix continuity without completely eliminating the insulating effect of an organic pore former. The patterns identified across microcellulose, millet husk, pomegranate peel, olive mill waste, grapevine shoots, spent coffee grounds, ground olive stones, and coconut shell establish that residue content and firing temperature regulate different aspects of the pore network and solid phase; consequently, thermal conductivity must be assessed together with mechanical capacity and moisture-related behavior rather than inferred from density or porosity independently.

6. Future Perspectives: Toward Predictive and Scalable Design

The principal challenge is to establish the conditions under which residue incorporation can deliver reproducible, functional, and environmentally justifiable performance.

Residue origin is insufficient as a predictive variable because its behavior depends on matrix mineralogy, particle characteristics, incorporation level, and the manufacturing cycle. Differentiated matrix responses have been documented for mineralogically contrasting clays [46], for an illite–chlorite–calcitic clay fired between 900 and 1200 °C [47], and for soapstone processing waste incorporated into Vendian- and Cambrian-clay formulations [20]. Particle-size and dosage effects were demonstrated for grapevine shoots [21], while micromechanical evidence shows that thermal and elastic behavior also depends on pore geometry and spatial distribution [38]. Future analysis should therefore focus on matrix–residue–processing configurations and compatibility domains rather than on universal residue percentages.

On this basis, a scientific priority is the development of processing windows that relate residue transformation to the thermal state attained by the matrix. The temporal coincidence of gas release, shrinkage, liquid-phase formation, and pore closure determines whether incorporation yields a stable porous structure, partial densification, or gas-entrapment defects. Firing design should therefore consider the complete reaction sequence rather than only the maximum temperature. Future studies should combine thermal analysis, evolved-gas identification, dilatometry, and high-temperature diffraction to determine when each transformation occurs and how it is modified by the matrix. This approach would support the construction of thermochemical maps capable of anticipating whether the pores formed remain isolated, become interconnected, are sealed by a liquid phase, or evolve into critical discontinuities.

Developing predictive relationships first requires overcoming the limited comparability among studies. Direct transfer between formulations remains restricted because the response changes with clay matrix [20,46], particle-size distribution and incorporation level [21], molding pressure and firing temperature [61], and processing-induced orientation [43,44]. New experimental designs should therefore evaluate equivalent controls and report clay mineralogy, residue composition, incorporation level, particle-size distribution, moisture content, shaping conditions, thermal cycle, specimen orientation, number of replicates, and data dispersion. Standardization should encompass complete traceability from raw materials to the conditions under which the fired product is measured.

Experimental standardization should be accompanied by multiscale characterization capable of explaining the observed decoupling among properties. Total porosity and water absorption provide complementary information, but neither independently describes the size, shape, orientation, connectivity, or location of defects that govern heat transfer and fracture. Accordingly, pore structure should be analyzed by distinguishing among open, closed, and interconnected fractions, along with their spatial distribution and relationships with crystalline and glassy phases. Ref. [38] demonstrated that effective elastic properties and thermal conductivity depend on pore geometry, aspect ratio, orientation, and spatial distribution rather than on total porosity alone. On this basis, technological assessment should progress toward multicriteria performance envelopes that integrate the absolute values of thermal conductivity, strength, water absorption, shrinkage, and density, as well as the durability required for each application. The objective would not be to maximize incorporation or minimize thermal conductivity in isolation, but to identify configurations that maintain a verifiable balance among insulation, moisture-related stability, and mechanical capacity, as proposed in the recent assessment of organic additives by [25].

Finally, industrial transfer should incorporate environmental, production, and regulatory criteria from the initial selection of formulations. Residue valorization does not automatically imply environmental improvement, as its preparation, transport, and treatment may alter energy consumption, kiln emissions, and rejection rates. Life cycle assessments should therefore consider residue preparation, changes in firing, product

durability, and end-of-life management. Life-cycle assessment of porous fired-clay bricks containing bio-based additives has shown that environmental performance depends on the complete production system rather than on waste incorporation alone [10]. For complex industrial residues, environmental assessment should additionally include phase identification and leaching or immobilization tests [41], together with verification of potential gaseous emissions during firing [12]. In parallel, pilot-scale trials should determine the sensitivity of formulations to batch-to-batch variability and thermal gradients in industrial kilns. Industrial and application-scale validation remains comparatively limited within the final corpus. Ref. [69] evaluated thermally efficient waste-marble-sludge bricks under industrial-scale manufacturing conditions, whereas [13] extended material characterization toward building-energy and economic performance. The limited number of such studies indicates that broader validation is still required to quantify production variability, kiln-scale thermal gradients, durability, environmental safety, and application-specific compliance before widespread implementation. Only after establishing a comparable database integrating composition, mineralogy, processing, microstructure, properties, and their dispersion will it be scientifically justified to develop statistical or machine-learning models with external validation capability.

7. Conclusions

The thermal performance of residue-containing clay ceramics results from the coupled interaction among clay mineralogy, residue composition, incorporation level, processing conditions, and the microstructure developed during firing. Residue origin alone has limited predictive value because materials within the same organic or inorganic category may follow different thermochemical pathways, whereas residues from different sources may perform similar functions as pore-forming, fluxing, filler, or phase-forming components. The clay matrix actively controls these responses through dehydroxylation, liquid-phase formation, crystallization, sintering, and pore closure, determining whether the generated porosity remains stable, becomes interconnected, is partially sealed, or produces critical discontinuities.

Within the endpoint-comparable organic configurations, the relative-change analysis showed consistent reductions in bulk density, compressive strength, and thermal conductivity wherever complete property pairs were available. Bulk-density reductions ranged from 13.1 to 25.7%, thermal-conductivity reductions from 31.7 to 70.1%, and compressive-strength losses from 57.4 to 94.5%. The mechanical penalty was greater than the thermal benefit in the configurations reporting both properties, indicating that reduced heat transfer cannot be interpreted independently of the continuity of the load-bearing ceramic network. Inorganic residues exhibited more heterogeneous and temperature-dependent responses, ranging from pore generation and mechanical deterioration to vitrification, pore sealing, increased density, and strengthening. These contrasting trajectories confirm that porosity, water absorption, density, strength, and thermal conductivity do not necessarily evolve proportionally and that total pore volume is insufficient to predict performance without considering pore size, geometry, connectivity, orientation, phase composition, and solid-matrix continuity.

The relative-change matrices provide a consistent representation of net property trajectories within each experimental configuration, while the complete experimental series remains necessary for selecting an incorporation level. The intermediate responses identified in several studies showed that the formulation producing the greatest reduction in thermal conductivity did not necessarily preserve the most favorable mechanical performance. A residue-containing ceramic should therefore be considered technically suitable only when reduced heat transfer is achieved without disproportionate losses in mechanical capacity, moisture stability, durability, processing reproducibility, or environmental

safety. Formulation design must consequently be based on application-specific performance windows for the matrix–residue–process system rather than on the isolated maximization of residue content, porosity, or thermal-conductivity reduction.

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