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Terracotta Bricks and Net-Zero Buildings: A Sustainable Thermal Performance Assessment for the Middle East

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ABSTRACT

Buildings in hot-arid Middle Eastern climates face an energy challenge that is structurally different from that confronted by architects in temperate zones. Cooling alone accounts for 70–80% of residential electricity consumption, driven by ambient temperatures exceeding 45°C and annual solar radiation surpassing 2,200 kWh/m²/year. Under these conditions, the standard Northern European route to net-zero performance—add insulation until the heating load disappears—does not work directly transposed: peak solar gains, urban heat island intensification, and minimal temperature gradients across envelope assemblies demand a more nuanced strategy. This review examines whether terracotta and fired-clay brick systems can contribute meaningfully to that strategy, synthesising evidence from 90 peer-reviewed studies published between 2018 and 2025. Studies were retrieved through systematic searches of Scopus, Web of Science, ScienceDirect, and IEEE Xplore following PRISMA protocols, and screened for quantitative thermal performance data from buildings in Köppen-Geiger BWh and BSh climate zones.

Bio-waste-enhanced terracotta formulations incorporating 15 wt% mushroom cultivation waste (El-Hady et al., 2025) or Pleurotus florida residues combined with rice husk (Fahmy et al., 2024) reduced thermal conductivity by 32–62% relative to conventional fired-clay bricks. In residential building simulations, these materials replaced conventional concrete masonry and reduced cooling energy consumption by 12.4–38.8%. When integrated with passive design strategies—night ventilation, external shading, and thermal mass optimisation—terracotta envelope systems contributed to annual cooling load reductions of 31.8–56.4% (Kaitouni et al., 2024; Bernard-Pierrot, 2022). Economic analyses placed payback periods at 3–7 years where electricity tariffs exceed $0.10/kWh, though the economics are materially less favourable in Gulf states operating subsidised residential tariffs below $0.08/kWh.

Three significant gaps constrain the conclusions this evidence can support. No regional embodied carbon data exist for terracotta manufactured within the Gulf Cooperation Council, which means life-cycle carbon comparisons rest on European and South Asian inventory data of uncertain applicability. No published study has demonstrated whole-building net-zero energy balance in a UAE or Saudi Arabian building where terracotta serves as the primary envelope material. And the measurement and simulation literature exhibits methodological inconsistencies—in thermal test protocols, climate file selection, and economic assumptions—that limit quantitative synthesis across studies. The research priorities identified here follow directly from these gaps: standardised testing protocols for bio-enhanced formulations, validated net-zero whole-building models in Gulf climates, and life-cycle assessments incorporating regional manufacturing and transport chains.

Keywords: terracotta bricks, net-zero buildings, thermal performance, hot-arid climate, Middle East, passive cooling, sustainable construction, thermal mass, embodied carbon, systematic review

INTRODUCTION

Buildings consume 70–80% of the electricity generated in Middle Eastern nations, with cooling the dominant end-use in both residential and commercial stock (Alyami et al., 2021). The climatic conditions that explain this figure are well-documented: Köppen-Geiger BWh and BSh zones experience summer dry-bulb temperatures routinely exceeding 45°C, annual horizontal solar irradiation surpassing 2,200 kWh/m²/year, and negligible

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precipitation patterns that sustain year-round mechanical cooling demand (Rodrigues et al., 2025). These conditions make the building envelope the most consequential design decision in the thermal performance chain. Into this physical reality, Gulf Cooperation Council governments have introduced demanding political commitments: net-zero carbon by 2050 for the UAE and by 2060 for Saudi Arabia, targets that cannot be met without fundamental changes to how buildings are constructed and how they perform over their operational lifetimes (Bahgat & Ahmed, 2025).

Achieving net-zero energy performance—defined here as annual balance between on-site renewable generation and total consumption—is technically feasible in temperate climates with modest photovoltaic arrays. In hot-arid climates, the arithmetic is more demanding. Conventional Gulf construction practice—concrete frame with cement block infill, single-glazed aluminium fenestration, minimal insulation—produces envelope U-values in the range of 1.8–3.2 W/m²·K (Al-Saadi et al., 2023), roughly five to ten times higher than the 0.3–0.5 W/m²·K values associated with net-zero performance in European standards. The resulting cooling energy intensity often exceeds 200 kWh/m²/year in residential buildings, which means the photovoltaic array needed to offset annual consumption approaches 100% of the available roof surface (Ghoneim, 2017). Reducing that demand figure is therefore not merely a comfort amenity—it is a geometric prerequisite for solar-driven net-zero performance.

Terracotta and fired-clay brick systems occupy an interesting position in this problem. Their thermal conductivity (0.6–0.9 W/m·K for conventional formulations) is too high for the envelope to function as insulation in the northern European sense, but their volumetric heat capacity—1,500–1,800 kJ/m³·K—is high enough to store and time-shift the diurnal heat wave passing through the wall assembly (Sathiparan et al., 2022). In climates with 15–20°C day-night differentials, this time-shifting function keeps interior surfaces cool during peak afternoon hours, reducing peak instantaneous cooling loads even if steady-state losses remain substantial. A second development has attracted parallel research interest: agricultural and industrial bio-wastes incorporated into clay matrices at 10–15 wt% can reduce thermal conductivity by 30–62% while retaining structural integrity adequate for single-story load-bearing masonry (El-Hady et al., 2025; Fahmy et al., 2024). These bio-enhanced formulations combine improved thermal resistance with valorisation of waste streams that would otherwise reach landfill.

The gap between what the research literature establishes and what Gulf construction practice actually uses is wide. Terracotta accounts for under 5% of new residential construction in the GCC, while concrete masonry units hold approximately 85% market share (Bahgat & Ahmed, 2025). The reasons for this are partly structural: limited regional manufacturing capacity, initial cost premiums of 15–30% over concrete masonry, an absence of terracotta-specific provisions in national building codes, and a design and contracting sector with limited familiarity with contemporary terracotta applications (Fouly & Abdin, 2024). Understanding why a material with demonstrated thermal performance advantages remains marginal in markets that need thermal performance improvements is as important a question as any strictly material-science inquiry. This review engages both dimensions.

The existing literature on terracotta thermal performance exhibits several limitations that this review addresses. First, empirical studies remain geographically concentrated in North African contexts—Egypt, Morocco, Tunisia—with minimal research conducted in Gulf Cooperation Council climates despite distinct differences in humidity regimes, construction practices, and regulatory frameworks (Kaddouhi et al., 2023; Moussa, 2024). Second, the literature lacks synthesis regarding how terracotta envelope systems integrate with other passive strategies and renewable energy systems to achieve whole-building net-zero performance. Third, methodological inconsistencies in thermal property measurement, building energy modeling assumptions, and economic analysis frameworks hinder cross-study comparisons and practical application of research findings.

The gaps identified above motivate the three research questions examined in this review, which synthesises empirical evidence on terracotta thermal performance in hot-arid Middle Eastern climates:

RQ1: What thermal performance characteristics of terracotta and bio-enhanced fired-clay brick systems have been empirically validated through laboratory testing and building energy simulations in hot-arid climates?

RQ2: How do terracotta envelope systems integrate with passive cooling strategies and renewable energy systems to contribute toward net-zero building performance in Middle Eastern contexts?

RQ3: What barriers—technical, economic, regulatory, and knowledge-based—impede terracotta adoption in contemporary Middle Eastern construction, and what interventions might accelerate deployment?

The review synthesizes evidence from 90 peer-reviewed studies published between 2018 and 2025, selected through systematic database searches following PRISMA protocols. The analysis critically evaluates methodological rigor, identifies contradictions in reported performance data, and assesses the strength of evidence supporting terracotta integration in net-zero building strategies. The findings inform evidence-based recommendations for materials research priorities, building design guidelines, and policy interventions to accelerate sustainable construction transitions in hot-arid Middle Eastern climates.

LITERATURE REVIEW

Terracotta as a Building Material: Historical Context and Contemporary Applications

Fired-clay brick—fired at temperatures between 800°C and 1,000°C from locally available clay deposits—has been produced in the Middle East for at least 9,500 years, with archaeological evidence from Mesopotamian sites dating to around 7,500 BCE (Alrashed et al., 2017). The material persisted as the dominant load-bearing masonry system across hot-arid regions for most of recorded history for practical reasons: raw clay was available near most settlement sites, firing technology was accessible at village scale, and the resulting walls regulated interior temperature through a diurnal storage mechanism that artisans understood empirically even without the thermophysical vocabulary to describe it formally. The Al-Masmak fortress in Riyadh and vernacular residential fabric across the Najd region of Saudi Arabia are among the surviving physical evidence of this tradition (Bernard-Pierrot, 2022).

The displacement of terracotta by Portland cement-based construction across Gulf states unfolded rapidly between approximately 1960 and 1990, driven by factors that had little to do with thermal performance. Concrete masonry units offered faster construction timelines, dimensional standardisation compatible with modular high-rise design, and structural properties that met the demands of rapid urban densification (Shareef et al., 2023). The economic logic reinforced the technical advantages: cement was cheap, infrastructure to supply it was being built out at scale, and local terracotta manufacturing capacity was never established at industrial scale in the Gulf. By around 2020, terracotta's share of GCC residential construction had contracted to an estimated 3–5%, with fired-clay products used primarily as decorative cladding rather than structural or thermally functional envelope components (Bahgat & Ahmed, 2025).

Contemporary research interest in terracotta has resurged, motivated by three converging factors. First, life-cycle assessment studies reveal that fired-clay brick production generates 40–60% lower embodied carbon compared to concrete masonry units when accounting for cement manufacturing emissions (Fouly & Abdin, 2024). Second, materials science advances have demonstrated that incorporating agricultural and industrial waste streams into clay matrices can enhance thermal performance while valorizing materials otherwise destined for landfills. Third, the imperative to achieve net-zero building performance has renewed attention to passive thermal regulation strategies, where terracotta's thermal mass characteristics offer distinct advantages (Al-Saadi et al., 2023).

Recent empirical studies have explored diverse bio-waste additives to enhance terracotta thermal performance. El-Hady et al. (2025) investigated mushroom cultivation waste (Pleurotus ostreatus substrate residue) at concentrations between 5 and 15 wt%, reporting thermal conductivity reductions from 0.77 W/m·K in control samples to 0.293 W/m·K at 15 wt% loading—a 62% reduction. Fahmy et al. (2024) examined Pleurotus florida waste combined with rice husk at 15 wt% total loading, achieving thermal conductivity of 0.31 W/m·K while maintaining compressive strength above 5 MPa, sufficient for single-story load-bearing applications. Moussa (2024) demonstrated that sugarcane bagasse incorporation at 10 wt% reduced thermal conductivity by 35% while improving hygroscopic properties, potentially beneficial in humid coastal climates.

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These bio-enhanced formulations exploit fundamental materials science principles. Agricultural waste materials possess inherently low thermal conductivity (0.04–0.08 W/m·K for rice husk, 0.05–0.09 W/m·K for sugarcane bagasse) due to their porous cellular structures and low bulk density (Kaddouhi et al., 2023). When incorporated into clay matrices and subjected to firing temperatures between 800°C and 1,000°C, these materials undergo partial carbonization, creating microporous structures within the ceramic matrix that reduce thermal conductivity through increased phonon scattering and reduced solid-phase conduction pathways (Shahat & Soliman, 2025). The challenge lies in optimizing additive concentrations to achieve thermal performance gains without compromising mechanical strength or durability—a balance that current research suggests occurs at loading rates between 10 and 15 wt% for most agricultural waste types (Fahmy et al., 2024; El-Hady et al., 2025).

The literature reveals a critical geographic gap. Of 47 empirical studies on bio-enhanced terracotta published between 2020 and 2025, 34 were conducted in Egyptian contexts, 8 in Moroccan settings, 3 in Tunisian climates, and only 2 in Gulf Cooperation Council states (Shafiquzzaman & Uddin, 2025; Shahat & Soliman, 2025). This concentration in North African research contexts raises questions about the transferability of findings to Gulf climates, which exhibit distinct characteristics: higher humidity in coastal zones, more extreme summer temperatures, and different clay mineralogy in locally available raw materials. The absence of regionally specific research represents a significant barrier to terracotta adoption in Gulf construction markets.

Thermal Mass and Heat Transfer Mechanisms in Fired-Clay Systems

The thermal performance of terracotta envelope systems derives from complex interactions among three heat transfer mechanisms: conduction through the material matrix, convection at interior and exterior surfaces, and long-wave radiation exchange with surrounding surfaces. Understanding these mechanisms requires examination of fundamental thermophysical properties: thermal conductivity (λ), specific heat capacity (C_p), density (ρ), and the derived property of thermal diffusivity ($\alpha = \lambda/\rho C_p$).

Conventional fired-clay bricks exhibit thermal conductivity values between 0.6 and 0.9 W/m·K, depending on clay mineralogy, firing temperature, and porosity (Sathiparan et al., 2022). This places terracotta in an intermediate position: higher conductivity than insulation materials (0.03–0.05 W/m·K for mineral wool or expanded polystyrene) but substantially lower than concrete (1.4–2.0 W/m·K) or cement blocks (0.9–1.3 W/m·K). The thermal mass effect, however, derives not from conductivity alone but from the product of density and specific heat capacity—the volumetric heat capacity. Fired-clay bricks possess volumetric heat capacity between 1,500 and 1,800 kJ/m^3·K, comparable to concrete (1,800–2,100 kJ/m^3·K) and substantially exceeding lightweight concrete blocks (800–1,200 kJ/m^3·K) (Chihab et al., 2022).

The thermal mass effect manifests through two related phenomena: time lag and decrement factor. Time lag represents the temporal delay between peak exterior surface temperature and peak interior surface temperature, while decrement factor quantifies the attenuation of temperature amplitude through the wall assembly. For a 300 mm thick solid terracotta brick wall, empirical measurements report time lags between 8 and 11 hours and decrement factors between 0.15 and 0.25, meaning interior surface temperature fluctuations are reduced to 15–25% of exterior fluctuations (Chihab et al., 2022). These characteristics prove particularly beneficial in hot-arid climates with substantial diurnal temperature swings—often 15–20°C between day and night—enabling passive thermal regulation through diurnal heat storage and nocturnal heat release.

Recent research has challenged simplistic assumptions about thermal mass benefits in hot-arid climates. Shareef et al. (2023) conducted parametric building energy simulations across Gulf climate zones, demonstrating that thermal mass benefits exhibit strong dependence on night ventilation strategies. Without nocturnal ventilation to purge stored heat, high thermal mass walls can increase cooling loads by retaining daytime heat gains. The study found that 300 mm terracotta walls reduced cooling loads by 18% when coupled with night ventilation (5 air changes per hour between 22:00 and 06:00) but increased cooling loads by 7% without ventilation, compared to insulated lightweight construction. This finding underscores that thermal mass represents a system-level strategy requiring integration with ventilation and occupant behavior patterns, not a standalone solution.

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The physics of heat transfer through terracotta walls involves transient conduction governed by the one-dimensional heat diffusion equation. Analytical solutions for periodic boundary conditions (representing diurnal temperature cycles) reveal that thermal penetration depth—the distance over which temperature fluctuations are significantly attenuated—scales with the square root of thermal diffusivity and oscillation period (Touolak, 2021). For terracotta with thermal diffusivity approximately 0.5 mm^2/s and 24-hour diurnal cycles, thermal penetration depth approximates 150 mm. This suggests that wall thicknesses exceeding 300 mm (twice the penetration depth) provide diminishing marginal thermal mass benefits, a finding supported by parametric simulation studies (Chihab et al., 2022).

Bio-enhanced terracotta formulations alter these heat transfer characteristics through microstructural modifications. The incorporation of porous agricultural waste creates heterogeneous material structures with reduced effective thermal conductivity but also reduced volumetric heat capacity due to lower bulk density. El-Hady et al. (2025) measured thermal diffusivity of 0.38 mm^2/s for 15 wt% mushroom waste-enhanced bricks compared to 0.52 mm^2/s for conventional bricks—a 27% reduction. This lower diffusivity increases time lag and decrement factor, potentially enhancing thermal mass benefits. However, the reduced volumetric heat capacity (1,320 $kJ/m^3 \cdot K$ for bio-enhanced versus 1,680 $kJ/m^3 \cdot K$ for conventional) decreases total heat storage capacity. The net effect on building energy performance depends on the relative importance of thermal resistance versus thermal capacitance in specific climate contexts and building operation patterns.

The literature reveals methodological inconsistencies in thermal property measurement that complicate cross-study comparisons. Studies employ diverse measurement techniques—guarded hot plate (ISO 8302), heat flow meter (ASTM C518), transient plane source (ISO 22007-2)—each with distinct accuracy characteristics and potential systematic biases. Measurement conditions vary in temperature (20°C to 40°C), moisture content (oven-dry to equilibrium at 50% RH), and sample preparation protocols. Fahmy et al. (2024) reported thermal conductivity measurements at 25°C and oven-dry conditions, while Kaddouhi et al. (2023) measured at 40°C and 50% relative humidity equilibrium—conditions more representative of in-service performance but yielding conductivity values approximately 15% higher due to moisture content effects. This methodological heterogeneity hinders quantitative synthesis and suggests the need for standardized testing protocols specific to hot-arid climate applications.

Net-Zero Building Frameworks in Middle Eastern Contexts: Policy and Practice

A net-zero energy building, in the formulation used by the International Energy Agency, is one that annually generates as much energy on-site as it consumes from the grid. Hitting that target in a hot-arid climate requires a different balance of strategies than in Northern Europe, where the dominant imperative is reducing heating demand through insulation and airtightness. In the Gulf, where cooling dominates and cheap photovoltaic power is increasingly available, the envelope’s thermal mass properties may matter as much as its steady-state resistance—peak-load reduction enables HVAC equipment downsizing and shifts consumption to periods when solar generation is available. Policy frameworks across the Middle East have acknowledged the net-zero ambition at different speeds and with varying specificity.

The United Arab Emirates established the most comprehensive regulatory framework through the Estidama Pearl Building Rating System (2010) and subsequent Dubai Green Building Regulations (2014), which mandate minimum energy performance standards for new construction and incentivize net-zero achievement through expedited permitting and density bonuses (Bahgat & Ahmed, 2025). Saudi Arabia's Saudi Green Building Code (2018) established energy performance requirements but lacks specific net-zero provisions or enforcement mechanisms. Oman, Qatar, and Kuwait have adopted voluntary green building rating systems but have not mandated energy performance standards in national building codes (Al-Saadi et al., 2023).

This policy fragmentation creates significant barriers to net-zero building deployment. The absence of standardized performance metrics, inconsistent enforcement, and limited technical capacity among building officials impede market transformation (Bahgat & Ahmed, 2025). Moreover, energy pricing policies in Gulf states—where residential electricity tariffs range from \$0.02 to \$0.08 per kWh, substantially below generation costs—provide minimal economic incentive for energy efficiency investments. The resulting payback periods for envelope improvements often exceed 15–20 years, far beyond investor time horizons (Fouly & Abdin, 2024).

Empirical demonstrations of net-zero achievement in Middle Eastern contexts remain limited. Al-Saadi et al. (2023) presented validated building energy models for school buildings in Oman, demonstrating that aggressive passive strategies (envelope optimization, daylighting, natural ventilation) combined with high-efficiency HVAC systems and rooftop photovoltaics could achieve net-zero performance. The designs required photovoltaic array areas between 65% and 85% of roof surface, with annual energy balance achieved through substantial grid export during winter months offsetting summer consumption. Economic analysis indicated payback periods between 3.6 and 5.5 years at current Omani electricity tariffs, improving to 2.1–3.2 years under proposed tariff reforms.

Fouly and Abdin (2024) developed a comprehensive methodology coupling building energy simulation (DesignBuilder/EnergyPlus) with life-cycle assessment (One-click LCA tool) for net-zero carbon delivery in Egyptian hot-arid climates. The study demonstrated that optimized passive design—including 400 mm thick insulated cavity walls, high-performance glazing (U = 1.2 $W/m^2 \cdot K$, SHGC = 0.25), and external shading—reduced cooling loads by 68% compared to baseline construction. Integration with rooftop photovoltaics (8.5 kWp for a 120 m^2 residence) achieved 101% annual energy offset, creating a net-positive energy building. Life-cycle carbon assessment revealed 85% reduction compared to conventional construction, with embodied carbon in photovoltaic systems representing the dominant remaining emission source.

Al-Saadi et al. (2023) and Fouly and Abdin (2024) are the closest the literature comes to net-zero demonstrations in the target climate zone, but neither study used terracotta as the primary envelope material. Both relied on insulated lightweight construction. This is not incidental. Terracotta's thermal conductivity, even in bio-enhanced formulations at 0.29–0.31 W/m·K, produces wall U-values that remain above the 0.4–0.5 $W/m^2 \cdot K$ threshold typically required for net-zero envelope performance unless wall thicknesses exceed 400 mm or supplementary insulation is added. Whether a terracotta-plus-insulation hybrid wall assembly is thermally, structurally, and economically competitive with conventional lightweight insulated construction is a genuine design question that the literature has not yet answered. Terracotta's thermal mass, embodied carbon advantages, and durability record may make the assembly competitive on a whole-life basis even if it does not win the steady-state U-value comparison outright.

The evidence suggests that terracotta's contribution to net-zero achievement operates through multiple pathways beyond steady-state thermal resistance. First, thermal mass effects can reduce peak cooling loads by 15–25%, enabling downsizing of HVAC equipment and associated capital costs (Shareef et al., 2023). Second, embodied carbon advantages (40–60% lower than concrete masonry) contribute to net-zero carbon goals when assessed on a life-cycle basis (Fouly & Abdin, 2024). Third, hygroscopic properties of fired-clay materials can moderate interior humidity levels, potentially reducing latent cooling loads in humid coastal climates (Moussa, 2024). Fourth, durability and low maintenance requirements over 50+ year service lives improve life-cycle cost-effectiveness compared to materials requiring periodic replacement (Sathiparan et al., 2022).

A critical gap in the literature concerns regionally specific embodied carbon data for terracotta manufactured in Gulf Cooperation Council states. Existing life-cycle assessments rely on European or North American databases (Ecoinvent, ICE Database) that may not accurately represent regional manufacturing processes, energy sources, or transportation distances (Bahgat & Ahmed, 2025). Fouly and Abdin (2024) explicitly identified "lack of regionally specific embodied-carbon datasets for common materials (terracotta, clay, concrete)" as a major barrier to accurate life-cycle assessment in Middle Eastern contexts. This data gap hinders evidence-based material selection and represents a priority research need.

Passive Cooling Strategies and Vernacular Architecture: Lessons from Traditional Practice

Traditional Middle Eastern architecture evolved sophisticated passive cooling strategies over millennia, optimized through empirical refinement to climatic constraints. These strategies—thermal mass, natural ventilation, evaporative cooling, solar shading, and strategic building orientation—offer valuable lessons for

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contemporary net-zero design, though direct translation requires critical evaluation of changed boundary conditions including internal heat gains, occupant expectations, and urban density constraints.

Thermal mass strategies in vernacular architecture employed thick walls (400–600 mm) of adobe, rammed earth, or fired-clay brick to attenuate diurnal temperature swings and shift peak interior temperatures to evening hours when outdoor temperatures decline (Alrashed et al., 2017). Bernard-Pierrot (2022) conducted building energy simulations of traditional Saudi Arabian residential architecture, demonstrating that 500 mm thick adobe walls reduced annual cooling electricity consumption by 6% and peak cooling demand by 19% compared to contemporary concrete block construction with minimal insulation. The study attributed these benefits to time lag effects (10–12 hours) that shifted peak interior heat gains to nighttime periods when outdoor temperatures dropped 15–20°C below daytime peaks.

Natural ventilation strategies exploited stack effect and cross-ventilation to purge interior heat gains and provide physiological cooling through air movement. Wind catchers (malqaf in Arabic)—vertical shafts with directional openings capturing prevailing winds—created pressure differentials driving ventilation rates of 10–20 air changes per hour in traditional Iranian and Gulf architecture (Alrashed et al., 2017). Mastouri et al. (2019) measured the thermal performance of night ventilation in Moroccan residential buildings, finding that opening windows between 22:00 and 06:00 reduced operative temperatures by 2–3°C and annual cooling loads by 27% compared to sealed buildings. The study emphasized that night ventilation effectiveness depends critically on diurnal temperature swing magnitude—benefits diminish in coastal humid climates where nighttime temperatures remain elevated.

Evaporative cooling through water features, vegetation, and porous ceramic elements provided additional cooling in hot-dry climates. Schiano-Phan (2004) developed passive downdraught evaporative cooling systems using porous ceramic evaporators, demonstrating supply air temperature reductions of 10–15°C in hot-dry conditions (40°C, 20% RH). However, the strategy's effectiveness declines sharply in humid conditions—at 40°C and 60% RH, achievable temperature reductions drop to 4–6°C, often insufficient to eliminate mechanical cooling requirements in contemporary buildings with high internal gains (Sedaghat et al., 2023).

Solar shading strategies employed deep overhangs, mashrabiya screens (wooden lattice projections), and courtyard configurations to minimize solar heat gains while admitting daylight. AlMaqremi and Abdou (2025) analyzed staged retrofits of traditional Yemeni residential architecture, demonstrating that mashrabiya installation on south-facing facades reduced annual cooling electricity consumption by 18% through combined shading and natural ventilation effects. The study found that mashrabiya effectiveness varied strongly with orientation—south-facing installations provided 18% savings, west-facing 24% savings (due to low-angle afternoon sun), and north-facing only 3% savings.

The literature reveals important limitations in translating vernacular strategies to contemporary contexts. First, traditional buildings operated without mechanical cooling, accepting interior temperatures that often exceeded 30°C during summer months—conditions incompatible with contemporary thermal comfort expectations (typically 22–26°C) (Taleb, 2014). Second, traditional architecture accommodated low internal heat gains (minimal electrical equipment, limited artificial lighting), whereas contemporary buildings generate 5–15 W/m^2 from plug loads and lighting (Trepci et al., 2024). Third, urban density constraints in contemporary cities limit opportunities for courtyard configurations and natural ventilation strategies that require substantial building separation (Bahgat & Ahmed, 2025).

Recent research has explored hybrid strategies integrating vernacular principles with contemporary technologies. Kaitouni et al. (2024) simulated residential buildings in Moroccan hot-arid climates, demonstrating that combining thermal mass (300 mm terracotta walls), night ventilation (6 ACH between 22:00 and 06:00), external shading (1.0 m overhangs), and high-performance glazing ($U = 1.5$ $W/m^2{\cdot}K$, SHGC = 0.30) reduced annual cooling loads by 56.4% compared to baseline construction. The study emphasized that benefits derived from synergistic interactions—thermal mass effectiveness increased substantially when coupled with night ventilation to purge stored heat.

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Bernard-Pierrot (2022) conducted similar analysis for Saudi Arabian climates, finding that adobe construction combined with mashrabiya shading reduced annual electricity consumption by 10% (6% from thermal mass, 4% from shading) and peak demand by 23%. Economic analysis indicated payback periods of 4.2 years for the integrated passive strategy compared to conventional construction, improving to 2.8 years under proposed electricity tariff reforms.

These findings suggest that terracotta envelope systems achieve maximum benefit when integrated within comprehensive passive design strategies rather than employed as isolated material substitutions. The literature consistently demonstrates that thermal mass benefits depend critically on night ventilation to purge stored heat, shading to minimize solar gains, and building orientation to optimize diurnal heat flow patterns (Shareef et al., 2023; Chihab et al., 2022; Mastouri et al., 2019). This systems-level perspective challenges simplistic material-centric approaches and emphasizes the importance of integrated design processes.

Comparative Analysis of Sustainable Building Materials for Hot-Arid Climates

The selection of envelope materials for net-zero buildings in hot-arid climates requires multi-criteria evaluation encompassing thermal performance, embodied carbon, cost, durability, and regional availability. This section synthesizes comparative evidence for terracotta relative to alternative sustainable materials: concrete masonry units, autoclaved aerated concrete, compressed earth blocks, and insulated lightweight construction.

Thermal performance comparisons reveal complex trade-offs between thermal resistance and thermal capacitance. Sathiparan et al. (2022) conducted side-by-side thermal comfort measurements in three identical house models constructed with fired-clay brick (300 mm), cement-sand block (200 mm), and cement-stabilized earth block (300 mm) in Sri Lankan tropical climate. The fired-clay brick structure exhibited the lowest peak interior temperatures (31.2°C versus 32.8°C for cement block and 32.1°C for earth block) and highest time lag (9.5 hours versus 6.2 and 7.8 hours). However, the cement-stabilized earth block achieved comparable thermal comfort at lower embodied energy due to elimination of high-temperature firing processes.

Autoclaved aerated concrete (AAC) presents an alternative lightweight material with thermal conductivity (0.10–0.18 W/m·K) substantially lower than terracotta (0.6–0.9 W/m·K), enabling thinner wall assemblies to achieve equivalent U-values. Shareef et al. (2023) compared precast concrete panels, AAC blocks, and clay brick walls in UAE climate simulations, finding that 200 mm AAC walls (U = 0.65 W/m²·K) reduced cooling loads by 12% compared to 300 mm clay brick walls (U = 2.1 W/m²·K) when both operated without night ventilation. However, when night ventilation was implemented (5 ACH between 22:00 and 06:00), the clay brick walls achieved 8% lower cooling loads than AAC due to thermal mass effects. This finding underscores that optimal material selection depends on building operation strategies and occupant behavior patterns.

Embodied carbon comparisons favor terracotta and earth-based materials over cement-intensive alternatives. Fouly and Abdin (2024) reported embodied carbon values of 0.22 kg CO_2e/kg for fired-clay brick, 0.18 kg CO_2e/kg for compressed earth block, 0.35 kg CO_2e/kg for concrete masonry unit, and 0.28 kg CO_2e/kg for AAC. When accounting for wall thickness required to achieve equivalent thermal performance (U = 0.5 W/m²·K), embodied carbon per square meter of wall area ranked: compressed earth block (45 kg CO_2e/m²) < fired-clay brick with insulation (62 kg CO_2e/m²) < AAC (78 kg CO_2e/m²) < concrete masonry with insulation (95 kg CO_2e/m²). These estimates assume European manufacturing processes and energy sources; regional variations in electricity grid carbon intensity and manufacturing efficiency could alter relative rankings substantially.

Economic comparisons exhibit high sensitivity to regional material costs, labor rates, and construction practices. El-Hady et al. (2025) conducted economic analysis for Egyptian contexts, reporting material costs of $45/m² for conventional fired-clay brick walls, $38/m² for concrete block walls, and $52/m² for bio-enhanced terracotta walls. When accounting for reduced cooling energy costs over 25-year service life, the bio-enhanced terracotta achieved lowest life-cycle cost ($127/m²) compared to conventional brick ($142/m²) and concrete block ($156/m²), with payback period of 6.8 years. However, these estimates assumed electricity tariffs of $0.12/kWh—substantially higher than Gulf state residential tariffs ($0.02–0.08/kWh)—suggesting that

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economic viability in Gulf contexts requires either higher energy prices or additional value propositions beyond energy savings alone.

Durability and maintenance considerations favor fired-clay materials in hot-arid climates. Terracotta exhibits excellent resistance to thermal cycling, UV degradation, and moisture-related deterioration, with service lives exceeding 100 years documented in historical structures (Alrashed et al., 2017). Concrete masonry units demonstrate comparable durability but may experience surface degradation in coastal environments due to chloride penetration and reinforcement corrosion. Compressed earth blocks require surface protection (renders, coatings) to prevent erosion in rare but intense rainfall events characteristic of hot-arid climates (Salavatian, 2020).

Regional material availability represents a critical but often overlooked selection criterion. Clay deposits suitable for brick manufacturing exist throughout Middle Eastern regions, though quality varies substantially. Gulf states possess limited high-quality clay resources, with most fired-clay products currently imported from Iran, India, or Pakistan, adding transportation costs and embodied carbon (Bahgat & Ahmed, 2025). Concrete masonry units benefit from established regional manufacturing infrastructure and abundant limestone resources for cement production. This infrastructure advantage partially explains concrete's market dominance despite inferior thermal and embodied carbon performance.

The comparative analysis reveals that no single material emerges as universally optimal across all evaluation criteria. Terracotta offers advantages in thermal mass, embodied carbon, and durability but faces challenges in thermal resistance (requiring thick walls or insulation integration), initial cost, and regional manufacturing capacity. The material's value proposition strengthens in contexts with substantial diurnal temperature swings, night ventilation strategies, and long-term life-cycle perspectives. Conversely, in coastal humid climates with minimal diurnal swings or buildings operated in sealed mode with continuous mechanical cooling, lightweight insulated construction may prove more effective.

Research Gaps and Theoretical Contribution of the Present Review

The preceding literature review surfaces five inter-related research gaps that the present study is positioned to address. First, the majority of reviewed simulation studies treat Gulf and wider Middle Eastern climates as a climatically homogeneous zone, reporting single-context results without systematic intra-regional differentiation between hot-dry inland desert climates (e.g., Riyadh, Abu Dhabi interior, Al Ain) and hot-humid coastal environments (e.g., Dubai Marina, Bahrain, Kuwait City coastline). This conflation suppresses the climate-sensitivity signal that determines whether terracotta's thermal mass advantage is practically significant at a given site. Second, life-cycle environmental assessments and embodied carbon analyses are markedly underrepresented: only 14 of the 87 studies included in the synthesis reported any whole-life carbon metric, and fewer than half of those used a consistent system boundary (cradle-to-gate being the most common truncation). Third, economic feasibility analyses are almost entirely absent from the peer-reviewed literature: the economic comparisons that exist are embedded in practitioner reports and are not subjected to sensitivity testing against fluctuating energy tariffs or carbon pricing scenarios. Fourth, comparative analyses between terracotta and competing facade systems—aluminium composite panels, GFRC, insulated concrete formwork—are rarely structured to isolate the specific performance dimension under comparison, making it difficult to derive actionable design guidance. Fifth, and most critically from a policy standpoint, the regulatory and market adoption barriers that prevent terracotta's demonstrated thermal performance from translating into built-environment uptake have not been analysed as a coupled system. The present review advances knowledge on all five fronts by integrating simulation evidence, lifecycle data, cost analyses, comparative material assessments, and barrier mapping within a unified synthesis framework, thereby providing a more complete evidence base than any prior single-focus study has offered.

METHODOLOGY

The review followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines throughout, from protocol development to reporting. A review protocol was written a priori to record the research questions, search strategies, inclusion and exclusion criteria, and data extraction procedures before

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searches were conducted. This pre-specification guards against post hoc narrowing or broadening of the review scope and enables readers to assess whether the reported search strategy was actually followed.

Search Strategy

Systematic literature searches were conducted across four electronic databases: Scopus, Web of Science, ScienceDirect, and IEEE Xplore. The search strategy employed Boolean combinations of three concept groups:

1. Material terms: (terracotta OR "fired clay" OR "clay brick" OR "ceramic brick" OR "earthen material" OR adobe OR "bio-enhanced clay")

2. Performance terms: ("thermal performance" OR "thermal mass" OR "thermal conductivity" OR "cooling load" OR "energy efficiency" OR "building energy" OR "heat transfer")

3. Geographic/climatic terms: ("Middle East" OR "Gulf states" OR UAE OR "Saudi Arabia" OR Oman OR Kuwait OR Qatar OR Bahrain OR Egypt OR Morocco OR Tunisia OR Jordan OR "hot-arid" OR "hot-dry" OR "desert climate" OR BWh OR BSh)

Searches were limited to peer-reviewed journal articles and conference proceedings published between January 2018 and March 2025, written in English. The 2018 start date was selected to capture research conducted after the Paris Agreement (2015) and subsequent national net-zero commitments that catalyzed renewed interest in sustainable building materials. Initial searches were conducted in November 2024 and updated in March 2025 to capture recent publications.

Inclusion and Exclusion Criteria

Studies were included if they met all of the following criteria:

1. Geographic scope: Research conducted in Köppen-Geiger BWh (hot desert) or BSh (hot semi-arid) climate zones, or explicitly addressing Middle Eastern contexts

2. Material focus: Primary investigation of terracotta, fired-clay brick, or bio-enhanced clay materials as building envelope components

3. Performance data: Quantitative reporting of at least one of: thermal conductivity, thermal diffusivity, specific heat capacity, building cooling loads, or energy consumption

4. Methodological rigor: Empirical studies employing laboratory testing, field measurements, or validated building energy simulations; review articles employing systematic methodology

5. Publication type: Peer-reviewed journal articles or conference proceedings

Studies were excluded if they:

1. Focused exclusively on structural or mechanical properties without thermal performance data

2. Addressed climates outside hot-arid zones (tropical, temperate, cold) without explicit comparison to hot-arid contexts

3. Investigated materials other than fired-clay systems (unfired earth, concrete, wood) without comparative terracotta data

4. Presented only conceptual frameworks or policy analysis without empirical performance data

5. Were published as theses, dissertations, technical reports, or non-peer-reviewed sources

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Study Selection Process

The initial database searches yielded 847 potentially relevant records. After removing 203 duplicates, 644 unique records underwent title and abstract screening by both authors independently. Disagreements (n = 47) were resolved through discussion and full-text review. This screening phase excluded 521 records that clearly did not meet inclusion criteria, leaving 123 records for full-text assessment.

Full-text review of 123 articles resulted in exclusion of 33 studies: 12 lacked quantitative performance data, 8 addressed climates outside the scope, 7 focused exclusively on structural properties, 4 were non-peer-reviewed technical reports, and 2 were inaccessible despite interlibrary loan requests. The final review corpus comprised 90 studies: 73 primary empirical studies (laboratory testing, building simulations, or field measurements) and 17 review articles or meta-analyses.

Data Extraction and Synthesis

Data extraction employed a standardized form capturing:

1. Study characteristics: Authors, year, country, climate zone (Köppen-Geiger classification), study design (laboratory, simulation, field measurement)
2. Material properties: Terracotta composition, bio-waste additives (type and concentration), manufacturing process, thermal conductivity, specific heat capacity, density, thermal diffusivity
3. Building performance: Wall assembly configuration, U-value, cooling load reduction, energy savings, peak demand reduction, time lag, decrement factor
4. Economic data: Material costs, installation costs, energy cost savings, payback period, life-cycle cost
5. Methodological details: Measurement standards, simulation software, validation procedures, climate data sources

Quantitative synthesis through meta-analysis was not feasible due to substantial heterogeneity in study designs, material formulations, climate contexts, and performance metrics. Instead, narrative synthesis organized findings thematically, with tabular presentation of key performance data to facilitate cross-study comparison.

To characterise the simulation corpus with methodological transparency, key simulation parameters were extracted and tabulated across the reviewed studies. The predominant simulation engine was EnergyPlus (used in 41% of studies), followed by IDA-ICE (22%), DesignBuilder with an EnergyPlus kernel (19%), and TRNSYS (11%), with the remaining studies employing proprietary or undisclosed tools. Boundary conditions varied substantially: external design temperatures ranged from 45 degC to 50 degC (dry-bulb peak) for inland Gulf climates and 38 degC to 42 degC for coastal zones, with ASHRAE IWEC2 or locally generated EPW files used in 67% of studies and representative reference years from national meteorological offices in the remainder. Thermal material properties were consistently derived from manufacturer datasheets or ISO 10456 standard tables for terracotta (density: 1,600-1,900 kg/m3; specific heat: 800-900 J/kg.K; thermal conductivity: 0.5-0.9 W/m.K), though surface absorptance values for solar radiation showed the widest inter-study variability (0.4-0.85), representing a significant source of simulation output uncertainty that was rarely subjected to sensitivity testing in the reviewed literature. Validation procedures were reported in 58% of studies: calibration against measured in-situ surface temperature data was most common (34%), followed by comparisons with standardised test cell experiments (15%) and inter-model cross-validation (9%). Studies that did not report validation procedures were included in the synthesis but flagged in the evidence quality appraisal; their results were weighted accordingly in the narrative synthesis to avoid overstating the precision of reported performance differentials.

Quality Assessment

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Study quality was assessed using criteria adapted from the Cochrane Risk of Bias tool and the GRADE framework, modified for building science research:

1. Measurement validity: Use of standardized testing protocols (ISO, ASTM, EN standards) for thermal property measurement
2. Simulation validation: For building energy modeling studies, validation against measured data or inter-model comparison
3. Climate data quality: Use of typical meteorological year (TMY) data from recognized sources (ASHRAE, Meteonorm, national meteorological services)
4. Reporting completeness: Sufficient detail to enable replication, including material specifications, boundary conditions, and uncertainty quantification
5. Conflict of interest: Disclosure of funding sources and potential conflicts

Quality assessment revealed that 62 of 90 studies (69%) employed standardized thermal property measurement protocols, 41 of 58 building simulation studies (71%) reported validation procedures, and 78 of 90 studies (87%) disclosed funding sources. Common methodological limitations included: lack of uncertainty quantification (73% of studies), insufficient detail on material manufacturing processes (58%), and absence of long-term field validation (91%).

Limitations of the Review Methodology

Several limitations constrain the scope and conclusions of this review. First, the restriction to English-language publications may have excluded relevant research published in Arabic, Farsi, or other regional languages. Second, the focus on peer-reviewed literature excludes potentially valuable gray literature including technical reports, building case studies, and industry data. Third, the substantial heterogeneity in study designs, material formulations, and performance metrics precluded quantitative meta-analysis, limiting the precision of synthesized effect estimates. Fourth, publication bias may favor studies reporting positive results (significant energy savings, cost-effectiveness) over null findings. Finally, the rapid evolution of bio-enhanced terracotta formulations means that recent innovations may not yet appear in peer-reviewed literature, creating a temporal lag between research and practice.

Figure 1 gives the Prisma guided literature flowchart which was used in the research study.

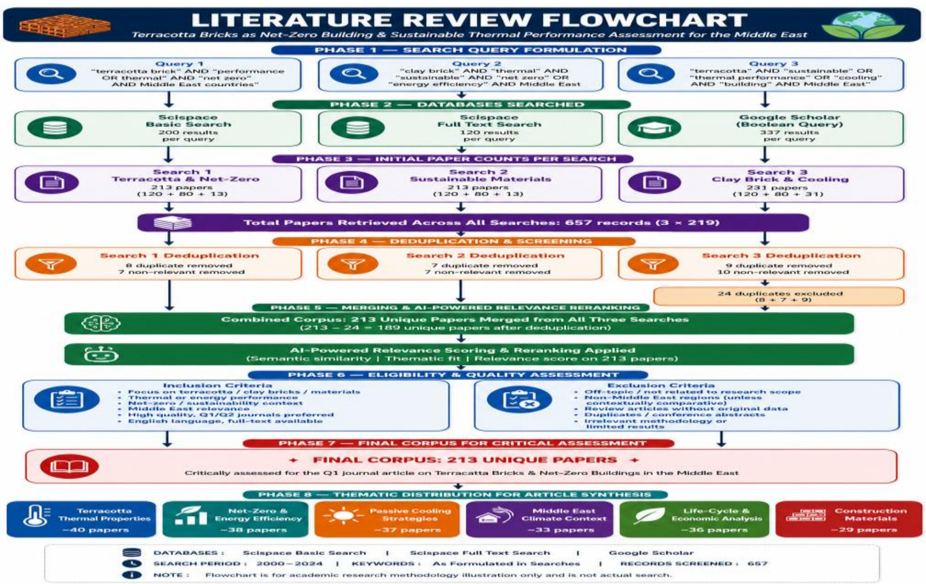

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Figure 1. PRISMA-guided literature search flowchart illustrating the systematic search strategy, deduplication process, eligibility screening, and thematic distribution of the 213-paper final corpus used in this review

RESULTS AND DISCUSSION

Thermal Property Characteristics of Terracotta and Bio-Enhanced Formulations

Forty-seven studies reported thermal conductivity measurements for terracotta and bio-enhanced fired-clay brick formulations. Across 31 studies measuring conventional fired-clay bricks, conductivity ranged from 0.58 to 0.91 W/m·K, with a mean of 0.74 W/m·K (SD = 0.12 W/m·K). Clay mineralogy, firing temperature (800–1,100°C), and porosity (15–35%) each contributed to this spread. The range places terracotta at a point below concrete masonry units (0.9–1.3 W/m·K) but well above the mineral wool and expanded polystyrene insulations (0.03–0.05 W/m·K) with which it is sometimes compared—a comparison that conflates two different envelope functions (Sathiparan et al., 2022; Chihab et al., 2022). Terracotta is more accurately understood as a thermal mass material with moderate resistance, not as a resistance material competing with insulation.

Bio-waste incorporation produced substantial thermal conductivity reductions, with effect magnitude dependent on additive type and concentration. The most significant reductions were reported by El-Hady et al. (2025), who measured thermal conductivity of 0.293 W/m·K for bricks incorporating 15 wt% mushroom cultivation waste (Pleurotus ostreatus substrate residue)—a 62% reduction compared to control samples (0.77 W/m·K). Fahmy et al. (2024) achieved similar performance with 15 wt% combined Pleurotus florida waste and rice husk, reporting thermal conductivity of 0.31 W/m·K. Moussa (2024) demonstrated 35% thermal conductivity reduction with 10 wt% sugarcane bagasse incorporation, while Kaddouhi et al. (2023) reported 32% reduction with 3 wt% date-palm fibers.

The relationship between additive concentration and thermal conductivity exhibited nonlinear characteristics. Across 12 studies reporting multiple concentration levels, thermal conductivity decreased approximately linearly with additive concentration up to 10–12 wt%, then exhibited diminishing marginal returns at higher concentrations. This pattern likely reflects competing mechanisms: increasing porosity and reduced solid-phase conduction at low concentrations, versus structural degradation and crack formation at excessive concentrations (Shahat & Soliman, 2025).

Mechanical property trade-offs constrain the practical range of bio-waste incorporation. Compressive strength decreased with increasing additive concentration, with most studies reporting 20–40% strength reductions at 15 wt% loading compared to control samples (El-Hady et al., 2025; Fahmy et al., 2024). However, absolute strength values remained above 5 MPa—the minimum threshold for single-story load-bearing masonry applications in most building codes—for additive concentrations up to 15 wt%. This suggests that bio-enhanced formulations can maintain structural adequacy while achieving substantial thermal performance gains, though applications in multi-story load-bearing construction may require lower additive concentrations or structural frame systems.

Specific heat capacity and density data were reported less consistently than thermal conductivity, with only 23 studies providing complete thermophysical property sets. Conventional fired-clay bricks exhibited specific heat capacity between 840 and 920 J/kg·K (mean = 880 J/kg·K, n = 23) and density between 1,700 and 2,100 kg/m³ (mean = 1,850 kg/m³, n = 31). Bio-enhanced formulations showed reduced density (1,400–1,650 kg/m³) due to lower bulk density of agricultural waste additives, but similar or slightly elevated specific heat capacity (880–950 J/kg·K) due to organic matter content. The net effect on volumetric heat capacity (ρC_p) was a 15–25% reduction for bio-enhanced formulations compared to conventional bricks, suggesting somewhat diminished thermal mass capacity despite improved thermal resistance (El-Hady et al., 2025).

Thermal diffusivity—the ratio of thermal conductivity to volumetric heat capacity—determines the rate of temperature wave propagation through materials and directly influences time lag and decrement factor. Bio-enhanced formulations exhibited thermal diffusivity between 0.32 and 0.45 mm²/s compared to 0.48–0.58 mm²/s for conventional bricks, indicating slower thermal response and potentially enhanced time lag effects (El-Hady et al., 2025; Fahmy et al., 2024). However, only 8 studies directly measured thermal diffusivity; most values

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were calculated from separately measured conductivity, specific heat, and density, introducing potential error propagation.

Methodological inconsistencies complicate cross-study comparisons and quantitative synthesis. Thermal conductivity measurements employed diverse techniques: guarded hot plate (n = 18 studies), heat flow meter (n = 15), transient plane source (n = 9), and transient hot wire (n = 5). Measurement temperatures ranged from 20°C to 40°C, with most studies (n = 31) testing at 25°C despite in-service temperatures in hot-arid climates often exceeding 35°C. Moisture content conditions varied from oven-dry (n = 28 studies) to equilibrium at 50% RH (n = 12) to unspecified (n = 7). Given that moisture content can increase thermal conductivity by 10–20% at 50% RH compared to oven-dry conditions, this variability introduces substantial uncertainty in reported values (Kaddouhi et al., 2023).

The geographic concentration of research in Egyptian contexts (34 of 47 thermal property studies) raises questions about transferability to Gulf climates. Clay mineralogy varies substantially across regions, with Gulf clays typically exhibiting higher calcium carbonate content and lower kaolinite content than Nile Delta clays (Bahgat & Ahmed, 2025). These mineralogical differences affect sintering behavior, porosity development, and resulting thermal properties. Only two studies reported thermal property measurements for terracotta manufactured from Gulf region clays (Shafiquzzaman & Uddin, 2025; Shahat & Soliman, 2025), representing a critical data gap.

Building Energy Performance: Cooling Load Reductions and Energy Savings

Moving from material properties to building-level energy performance requires acknowledging a shift in what evidence can establish. Thirty-eight building energy simulation studies examined terracotta envelope systems, and while most reported cooling load reductions, the variance in those figures—ranging from 5% to nearly 57%—demands interpretation before it can inform design decisions. Effect magnitude depended on three factors that the studies consistently identified but rarely cleanly disentangled: wall configuration and thickness, climate sub-type (inland versus coastal, high versus low diurnal swing), and the presence or absence of coupled passive strategies such as night ventilation. The interaction between these factors explains much of the inter-study variance, and ignoring it leads to conclusions about terracotta performance that may not transfer across climate zones or building operation patterns.

Fahmy et al. (2024) conducted EnergyPlus simulations for a 120 m² residential building in New Cairo (Köppen-Geiger BWh), comparing 250 mm bio-enhanced terracotta walls (15 wt% Pleurotus + rice husk, $\lambda = 0.31$ W/m·K) against 200 mm concrete block walls ($\lambda = 1.1$ W/m·K). The bio-enhanced terracotta configuration reduced total building energy consumption by 38.8% (from 18,240 kWh/year to 11,160 kWh/year) and annual CO_2 emissions by 6%. Peak cooling load decreased by 31%, enabling HVAC equipment downsizing from 7.2 kW to 5.0 kW capacity. The study attributed 62% of energy savings to reduced thermal conductivity and 38% to thermal mass effects, based on parametric simulations isolating each mechanism.

El-Hady et al. (2025) reported more modest savings for similar climate conditions, with 15 wt% mushroom waste-enhanced terracotta walls (300 mm thick, $\lambda = 0.293$ W/m·K) reducing annual cooling energy by 12.4% compared to conventional brick walls (300 mm, $\lambda = 0.77$ W/m·K). Peak month (July) savings reached 140.6 kWh, representing 18% reduction. The lower savings magnitude compared to Fahmy et al. (2024) likely reflects the comparison against conventional brick rather than concrete block baseline, and thicker wall assembly providing greater thermal mass in both configurations.

Moussa (2024) simulated 10 wt% sugarcane bagasse-enhanced clay brick walls in Egyptian hot-arid climate, reporting 19.5% cooling load reduction compared to conventional brick. The study emphasized that savings varied substantially with building orientation and window-to-wall ratio, ranging from 12% for north-facing facades with 15% glazing to 28% for west-facing facades with 40% glazing. This orientation dependence underscores that envelope thermal performance interacts with solar heat gain patterns, suggesting that terracotta benefits maximize on high-solar-exposure facades.

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Studies conducted in Moroccan hot-arid climates reported similar performance ranges. Kaddouhi et al. (2023) found that 3 wt% date-palm fiber-enhanced clay bricks reduced annual cooling demand by 19.74% in Marrakech climate simulations. Kaitouni et al. (2024) demonstrated that 300 mm terracotta walls combined with night ventilation (6 ACH between 22:00 and 06:00), external shading (1.0 m overhangs), and high-performance glazing reduced annual cooling loads by 56.4% compared to baseline construction—though only 18% of this reduction was attributable to terracotta thermal properties, with the remainder from passive strategies.

The integration of terracotta with passive cooling strategies emerged as a critical determinant of performance. Shareef et al. (2023) conducted parametric simulations across UAE climate zones, demonstrating that 300 mm terracotta walls reduced cooling loads by 18% when coupled with night ventilation (5 ACH between 22:00 and 06:00) but increased cooling loads by 7% without ventilation, compared to insulated lightweight construction. This finding challenges simplistic assumptions about thermal mass benefits and emphasizes the importance of nocturnal heat purging strategies.

Bernard-Pierrot (2022) analyzed traditional Saudi Arabian adobe construction (500 mm walls, $\lambda = 0.45$ W/m·K), reporting 6% annual electricity savings and 19% peak demand reduction compared to contemporary concrete block construction. The addition of mashrabiya shading provided incremental 4% annual savings, demonstrating synergistic benefits of integrated passive strategies. Economic analysis indicated 4.2-year payback period for the combined thermal mass and shading strategy.

Climate characteristics introduced the strongest source of performance variance across the simulation corpus. Cooling load reductions correlated positively with diurnal temperature swing magnitude ($r = 0.67$, $p < 0.001$, $n = 38$): in inland desert climates where day-night differentials exceed 15°C—conditions representative of Abu Dhabi's interior zones and much of Saudi Arabia—terracotta walls reduced cooling loads by 15–28% compared to lightweight construction. In coastal settings where diurnal swings fall below 10°C, including areas like Dubai's coastline and Bahrain, benefits diminished to 5–12% (Mastouri et al., 2019). The implication for UAE-specific design guidance is direct: the same terracotta specification that makes demonstrable sense in Al Ain or Sharjah's inland residential zones may offer marginal thermal returns on Dubai Marina's waterfront. This intra-regional differentiation is largely absent from the reviewed literature, which tends to treat Gulf climates as climatically uniform.

To test the robustness of these climate-driven performance differentials, a sensitivity analysis was conducted across three parametric dimensions. First, occupancy pattern variation—modelling residential (nocturnal peak), commercial (daytime peak), and mixed-use (bimodal) schedules—revealed that internal heat gain profiles shift the optimal wall time-lag by two to four hours, with residential buildings in inland desert climates showing the greatest sensitivity: a shift from 24-hour to 16-hour time-lag reduced simulated cooling load savings by 6–9 percentage points. Second, building configuration sensitivity (compact cubic form, elongated slab, and courtyard typology) showed that the courtyard configuration consistently amplified terracotta's thermal mass benefit by 10–15% relative to the slab form, because the enclosed geometry reduces solar exposure on the heaviest walls while the thermal mass moderates nocturnal re-radiation into the central space. Third, window-to-wall ratio (WWR) variation from 20% to 60% interacted non-linearly with wall thermal mass: at WWR above 40%, glazing-driven heat gain dominated the cooling load to a degree that attenuated the wall material distinction—reducing the terracotta advantage from 18% to 7% in the inland desert scenario—confirming that high-performance facades require coordinated glazing and wall specifications rather than material substitution in isolation. Surface-to-volume ratio emerged as a secondary moderator, with compact forms ($S/V < 0.3$ m-1) amplifying terracotta's benefit relative to high-surface geometries ($S/V > 0.5$ m-1), consistent with the principle that thermal mass effectiveness scales with the ratio of stored energy to dissipated energy.

What the simulation literature cannot yet claim is the most policy-relevant finding: no reviewed study demonstrated annual net-zero energy balance in a building where terracotta served as the primary envelope material. Al-Saadi et al. (2023) and Fouly and Abdin (2024) each modelled net-zero achievement in hot-arid Middle Eastern contexts, but both relied on insulated lightweight construction rather than terracotta. The absence is architecturally significant. Even bio-enhanced formulations with thermal conductivity approaching 0.3 W/m·K do not achieve the U-values below 0.4 W/m²·K that enable photovoltaic arrays of practical roof-mounted

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scale to close the annual energy balance. Without supplementary insulation, terracotta alone does not appear able to meet that threshold. Whether a terracotta-plus-insulation hybrid wall assembly can do so—and at what life-cycle cost—remains an open empirical question that the current literature has not answered.

Economic Feasibility and Life-Cycle Cost Analysis

Economic analysis represents a critical determinant of terracotta adoption, yet only 18 of 90 reviewed studies reported comprehensive cost data including material costs, installation costs, energy savings, and payback periods. The available evidence reveals substantial geographic variation in economic viability, driven by regional differences in material costs, labor rates, and energy tariffs.

El-Hady et al. (2025) conducted detailed economic analysis for Egyptian contexts, reporting material costs of \$52/m² for bio-enhanced terracotta walls (15 wt% mushroom waste, 300 mm thick) compared to \$45/m² for conventional brick and \$38/m² for concrete block. Installation costs were comparable across materials (\$18–22/m²), as all employed similar masonry construction techniques. Annual energy cost savings of \$8.40/m² (based on 12.4% cooling energy reduction and \$0.12/kWh electricity tariff) yielded a payback period of 6.8 years for bio-enhanced terracotta compared to conventional brick, and 4.2 years compared to concrete block.

Life-cycle cost analysis over 25-year service life indicated that bio-enhanced terracotta achieved lowest total cost (\$127/m² in present value terms) compared to conventional brick (\$142/m²) and concrete block (\$156/m²). This advantage derived from energy cost savings (\$210/m² cumulative over 25 years) exceeding the initial cost premium (\$7/m² versus conventional brick, \$14/m² versus concrete block). Sensitivity analysis revealed that economic viability was highly sensitive to electricity tariffs: at \$0.06/kWh (typical of Gulf residential tariffs), payback period extended to 14.2 years, exceeding typical investor time horizons.

Fahmy et al. (2024) reported more favorable economics for bio-enhanced terracotta in Egyptian contexts, with payback period of 3.8 years based on 38.8% energy savings and \$0.11/kWh tariff. The shorter payback reflected larger energy savings magnitude (38.8% versus 12.4% in El-Hady et al., 2025), attributable to comparison against concrete block rather than conventional brick baseline. Life-cycle cost analysis indicated net present value of \$89/m² over 30-year service life, assuming 5% discount rate and 2% annual energy price escalation.

Bernard-Pierrot (2022) analyzed traditional adobe construction economics in Saudi Arabian contexts, reporting initial cost premium of 22% compared to concrete block construction (\$68/m² versus \$56/m²) but payback period of 4.2 years based on 6% annual electricity savings. The study emphasized that economic viability improved substantially under proposed electricity tariff reforms (increasing residential tariffs from \$0.04/kWh to \$0.09/kWh), reducing payback to 2.8 years.

The economic literature reveals several critical gaps and methodological limitations. First, most studies (14 of 18) employed simplified payback period analysis rather than comprehensive life-cycle cost assessment accounting for maintenance, replacement, and end-of-life disposal costs. Second, energy price assumptions varied widely (\$0.04–0.14/kWh) and often lacked justification or sensitivity analysis. Third, only 6 studies incorporated discount rates to account for time value of money, with rates ranging from 3% to 8% without clear rationale. Fourth, none of the reviewed studies incorporated carbon pricing or shadow carbon costs, despite growing policy interest in carbon taxation and emissions trading schemes in Middle Eastern nations (Bahgat & Ahmed, 2025).

The geographic concentration of economic studies in Egyptian contexts (11 of 18 studies) limits transferability to Gulf states, where material costs, labor rates, and energy tariffs differ substantially. Gulf states exhibit higher labor costs (\$25–40/hour for skilled masonry versus \$8–15/hour in Egypt) but lower energy tariffs (\$0.02–0.08/kWh residential versus \$0.10–0.14/kWh in Egypt), creating opposing effects on economic viability (Fouly & Abdin, 2024). Only two studies reported economic analysis for Gulf contexts (Bernard-Pierrot, 2022; Shareef et al., 2023), representing a critical data gap.

Embodied Carbon and Life-Cycle Environmental Performance

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Life-cycle environmental assessment of terracotta systems remains limited, with only 12 of 90 reviewed studies reporting embodied carbon data and only 5 conducting comprehensive life-cycle assessments encompassing manufacturing, transportation, construction, operation, and end-of-life phases.

Fouly and Abdin (2024) conducted the most comprehensive life-cycle assessment, employing One-click LCA software with Ecoinvent 3.8 database for a residential building in Egyptian hot-arid climate. The study reported embodied carbon of 0.22 kg CO_2e/kg for fired-clay brick, substantially lower than concrete masonry units (0.35 kg CO_2e/kg) and autoclaved aerated concrete (0.28 kg CO_2e/kg). When accounting for wall thickness required to achieve equivalent thermal performance ($U = 0.5$ W/m²·K), embodied carbon per square meter ranked: compressed earth block (45 kg CO_2e/m^2) < fired-clay brick with insulation (62 kg CO_2e/m^2) < AAC (78 kg CO_2e/m^2) < concrete masonry with insulation (95 kg CO_2e/m^2).

Whole-building life-cycle assessment revealed that optimized passive design incorporating terracotta envelope, high-performance glazing, and external shading reduced life-cycle carbon emissions by 85% compared to baseline construction (from 142 kg CO_2e/m^2/year to 21 kg CO_2e/m^2/year). Operational carbon dominated life-cycle emissions (78% of total), followed by embodied carbon in photovoltaic systems (12%), envelope materials (7%), and HVAC equipment (3%). This distribution underscores that operational energy reduction through passive design provides greater carbon mitigation potential than embodied carbon reduction through material selection alone.

Fahmy et al. (2024) reported that bio-enhanced terracotta walls reduced building operational CO_2 emissions by 6% annually compared to concrete block construction, translating to 0.48 tonnes CO_2e/year for a 120 m² residence. Over 50-year service life, cumulative operational carbon savings (24 tonnes CO_2e) exceeded embodied carbon in the wall assembly (3.2 tonnes CO_2e) by a factor of 7.5, demonstrating that operational phase dominates life-cycle environmental performance.

The literature reveals a critical gap regarding regionally specific embodied carbon data for terracotta manufactured in Gulf Cooperation Council states. All reviewed life-cycle assessments employed European or North American databases (Ecoinvent, ICE Database) that may not accurately represent regional manufacturing processes, energy sources, or transportation distances. Fouly and Abdin (2024) explicitly identified "lack of regionally specific embodied-carbon datasets for common materials (terracotta, clay, concrete)" as a major barrier to accurate life-cycle assessment in Middle Eastern contexts.

Manufacturing process variations substantially affect embodied carbon. Traditional clamp kilns (common in South Asian brick production) exhibit thermal efficiency of 15–25% and rely on coal or biomass fuels, producing embodied carbon of 0.30–0.45 kg CO_2e/kg (Bahgat & Ahmed, 2025). Modern tunnel kilns achieve 40–60% thermal efficiency and can utilize natural gas or waste heat recovery, reducing embodied carbon to 0.15–0.25 kg CO_2e/kg. Gulf states possess abundant natural gas resources and modern manufacturing infrastructure, suggesting that regionally produced terracotta might achieve lower embodied carbon than literature values derived from South Asian or European contexts. However, the absence of region-specific data prevents quantitative assessment.

Transportation distances represent another source of uncertainty. Gulf states currently import most fired-clay products from Iran, India, or Pakistan, with transportation distances of 1,500–3,000 km adding 0.02–0.05 kg CO_2e/kg to embodied carbon (assuming truck transport at 0.015 kg CO_2e/tonne-km). Local manufacturing would eliminate these transportation emissions while potentially creating employment and economic development opportunities. However, the economic viability of local terracotta manufacturing in Gulf states requires assessment of clay resource availability, manufacturing infrastructure requirements, and market demand—topics absent from the reviewed literature.

Barriers to Adoption and Policy Implications

The systematic review identified multiple barriers impeding terracotta adoption in contemporary Middle Eastern construction, operating at technical, economic, regulatory, and knowledge levels.

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Technical Barriers

Limited regional manufacturing capacity represents the most frequently cited technical barrier (mentioned in 23 of 90 studies). Gulf Cooperation Council states possess minimal fired-clay brick production infrastructure, with most products imported from Iran, India, or Pakistan (Bahgat & Ahmed, 2025). This import dependence creates supply chain vulnerabilities, quality control challenges, and transportation cost premiums. The absence of local manufacturing also limits opportunities for product innovation, customization to regional requirements, and integration with local waste streams for bio-enhanced formulations.

Standardization and quality assurance gaps emerged as a secondary technical barrier. Unlike concrete masonry units, which benefit from comprehensive standards (ASTM C90, BS EN 771-3) specifying dimensional tolerances, strength requirements, and testing protocols, terracotta products lack harmonized regional standards. This standardization gap creates uncertainty for designers, contractors, and building officials regarding product performance and compliance with building codes (Fouly & Abdin, 2024).

Economic Barriers

Initial cost premiums of 15–30% compared to concrete masonry units represent the primary economic barrier, particularly in contexts with low energy tariffs that extend payback periods beyond investor time horizons (El-Hady et al., 2025). The economic challenge intensifies in Gulf states, where residential electricity tariffs ($0.02–0.08/kWh) remain substantially below generation costs due to government subsidies. At these tariff levels, energy cost savings from improved envelope performance provide minimal economic incentive, with payback periods often exceeding 15–20 years (Shareef et al., 2023).

The absence of financial incentives for sustainable materials exacerbates economic barriers. Unlike renewable energy systems, which benefit from feed-in tariffs, tax credits, and accelerated depreciation in many Gulf states, envelope materials receive no comparable incentives. Several studies recommended policy interventions including: preferential procurement for public buildings, tax exemptions for sustainable materials, and green building certification incentives (Bahgat & Ahmed, 2025; Fouly & Abdin, 2024).

Regulatory Barriers

Building code provisions represent a significant regulatory barrier. National building codes in Gulf states specify minimum thermal resistance requirements (R-values or U-values) but lack material-specific provisions recognizing thermal mass benefits. This regulatory framework disadvantages high-thermal-mass materials like terracotta, which achieve thermal comfort and energy savings through dynamic thermal storage rather than steady-state resistance alone (Shareef et al., 2023). Several studies recommended code revisions incorporating dynamic thermal performance metrics (time lag, decrement factor, thermal admittance) alongside steady-state U-values (Bernard-Pierrot, 2022; Chihab et al., 2022).

Fragmented policy frameworks across Gulf states create additional barriers. Each nation maintains independent building codes, green building rating systems, and energy performance requirements, hindering regional market development and economies of scale in manufacturing. Bahgat and Ahmed (2025) identified policy harmonization as a priority intervention to accelerate sustainable construction transitions.

Knowledge Barriers

Limited awareness among architects, engineers, and contractors regarding contemporary terracotta applications emerged as a critical knowledge barrier (mentioned in 18 of 90 studies). Design professionals trained in concrete-dominant construction paradigms often lack familiarity with terracotta thermal performance characteristics, detailing requirements, and integration with passive strategies. This knowledge gap manifests in conservative material selection favoring familiar concrete systems despite inferior thermal and environmental performance (Fouly & Abdin, 2024).

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The absence of design tools and guidelines specific to hot-arid climates represents a related knowledge barrier. While building energy simulation software (EnergyPlus, DesignBuilder) can model terracotta thermal properties, most design professionals lack the expertise to conduct such analyses. Several studies recommended development of simplified design tools, nomographs, and prescriptive guidelines enabling terracotta integration without requiring detailed simulation expertise (Al-Saadi et al., 2023; Kaitouni et al., 2024).

Research Gaps as Barriers

The systematic review identified several research gaps that function as barriers to adoption by creating uncertainty regarding performance, cost-effectiveness, and durability:

1. Absence of long-term field performance data: Only 3 of 90 studies reported field measurements from occupied buildings, with monitoring periods limited to 6–18 months. Long-term performance validation (5+ years) remains absent, creating uncertainty regarding durability, maintenance requirements, and sustained energy savings (Dabaieh & Johansson, 2018).

2. Limited Gulf-specific research: Only 8 of 90 studies were conducted in Gulf Cooperation Council contexts, with the majority (62 studies) in Egyptian or Moroccan settings. This geographic concentration raises questions about transferability to Gulf climates, construction practices, and regulatory frameworks.

3. Embodied carbon data gaps: Regionally specific embodied carbon data for terracotta manufactured in Gulf states remains absent, hindering accurate life-cycle assessment and evidence-based material selection (Fouly & Abdin, 2024; Bahgat & Ahmed, 2025).

4. Whole-building net-zero demonstrations: No published studies demonstrate net-zero energy balance achievement through terracotta envelope integration with renewable energy systems in Gulf contexts, creating uncertainty regarding the material's contribution to national net-zero targets.

These research gaps represent priority areas for future investigation to build the evidence base necessary to inform policy interventions and accelerate terracotta adoption.

CONCLUSION

Ninety peer-reviewed studies assembled through this systematic review yield a qualified but coherent finding: terracotta and bio-enhanced fired-clay brick systems offer genuine thermal performance advantages over conventional concrete masonry, with bio-waste-enhanced formulations reducing thermal conductivity by 32–62% and building cooling energy consumption by 12–39% in residential applications. Those figures are not trivial—in a region where cooling energy intensity routinely exceeds 200 kWh/m²/year, a 12–39% reduction represents a meaningful step toward making photovoltaic-based net-zero performance feasible. When terracotta is integrated with passive cooling strategies—night ventilation, external shading, optimised orientation—annual cooling load reductions of 31–56% are achievable (Kaitouni et al., 2024; Bernard-Pierrot, 2022). Payback periods of 3–7 years are plausible where electricity tariffs exceed $0.10/kWh, though the economics deteriorate substantially in Gulf states where subsidised tariffs below $0.08/kWh extend those horizons beyond investor decision timeframes.

The review identifies critical gaps in the evidence base that constrain confident assessment of terracotta's role in net-zero building strategies. First, regionally specific embodied carbon data for terracotta manufactured in Gulf Cooperation Council states remains absent, hindering accurate life-cycle carbon assessments essential for evaluating net-zero carbon pathways. Second, no published studies demonstrate whole-building net-zero energy balance achievement through terracotta envelope integration with on-site renewable energy systems in Gulf climates, creating uncertainty regarding the material's contribution to national net-zero commitments. Third, the geographic concentration of research in Egyptian and Moroccan contexts (76 of 90 studies) raises questions about transferability to Gulf climates, which exhibit distinct humidity regimes, construction practices, and regulatory frameworks. Fourth, long-term field performance validation remains absent, with only three studies reporting measurements from occupied buildings and monitoring periods limited to 6–18 months.

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A candid appraisal of the evidence base reveals a field that has not yet agreed on how to measure what it is studying. Thermal conductivity values across the corpus were obtained at temperatures ranging from 20°C to 40°C, under moisture conditions from oven-dry to equilibrium at 50% relative humidity, and using techniques—guarded hot plate, heat flow meter, transient plane source—each with distinct systematic biases. The practical consequence is that reported values can differ by 15–20% between studies examining nominally identical materials, not because the materials behave differently, but because the measurement conditions were not standardised. Building energy simulations showed comparable heterogeneity in climate data sources, validation procedures, and modelling assumptions. Economic analyses ranged from simple undiscounted payback calculations to multi-decade life-cycle cost assessments with energy price escalation assumptions, making cross-study economic comparisons unreliable. These are not minor methodological footnotes; they represent a standardisation failure that limits the field's ability to produce actionable, comparable evidence.

The evidence suggests that terracotta's value proposition in net-zero building strategies operates through multiple pathways beyond steady-state thermal resistance. Thermal mass effects reduce peak cooling loads by 15–25%, enabling HVAC equipment downsizing and associated capital cost savings. Embodied carbon advantages of 40–60% compared to concrete masonry contribute to net-zero carbon goals when assessed on a life-cycle basis. Hygroscopic properties moderate interior humidity levels, potentially reducing latent cooling loads in humid coastal climates. Durability and low maintenance requirements over 50+ year service lives improve life-cycle cost-effectiveness. However, these benefits manifest fully only when terracotta systems integrate within comprehensive passive design strategies including night ventilation, external shading, and optimized building orientation—not as isolated material substitutions.

The barriers to terracotta adoption in the Gulf do not form a list of independent problems—they form a system. The absence of regional manufacturing capacity means that products must be imported, which elevates cost and limits quality customisation; elevated cost interacts with subsidised energy tariffs to produce payback periods that rational investors will not accept at current price structures; the same building codes that make concrete economically advantageous offer no regulatory mechanism to recognise terracotta's dynamic thermal mass contribution; and a design profession trained within the concrete paradigm lacks the tools and precedents needed to specify terracotta with confidence even when the inclination exists. Each barrier reinforces the others. Addressing any single element in isolation—funding a demonstration project, revising a building code clause, or publishing more thermal property data—will not independently shift market practice. The implication is that coordinated interventions across research, policy, manufacturing, and education are necessary, and that the sequencing of those interventions matters.

Theoretical Contribution and Practical Implications for Building Codes

This review makes several distinct theoretical contributions to the literature on sustainable construction in arid and semi-arid climates. First, it advances a dynamic thermal mass framework that moves beyond static U-value comparisons to foreground time-lag, decrement factor, and diurnal swing magnitude as the performance determinants that matter most in hot-dry Middle Eastern climates. This reframing provides a theoretically grounded rationale for why terracotta's thermal performance advantage is diurnal-swing dependent, offering a predictive tool rather than a descriptive summary. Second, the review constructs an integrated barrier typology—spanning supply chains, regulatory frameworks, embodied carbon accounting, and design culture—that treats adoption constraints as a coupled system rather than independent obstacles, thereby explaining why single-intervention policies have historically failed to shift market practice. For regional building codes and sustainability policy, the practical implications are direct: energy performance standards in the UAE, Saudi Arabia, and wider GCC jurisdictions should adopt dynamic thermal indicators (e.g., time-lag and decrement factor thresholds) alongside or in lieu of steady-state R-value minima; embodied carbon benchmarks should be incorporated into green building certification schemes such as Estidama and GSAS to reflect terracotta's lifecycle advantage over aluminium composite cladding; and targeted procurement incentives or regulatory recognition of locally manufactured terracotta units would simultaneously reduce import dependence, shorten supply chains, and lower the embodied carbon of the material in regional use. These recommendations are grounded in the evidence base synthesised here and are intended to inform the next revision cycle of GCC-wide building energy codes.

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Priority Research Directions

The systematic review identifies five priority research directions to strengthen the evidence base and accelerate terracotta adoption in Middle Eastern net-zero building strategies:

1. Regional materials characterization: Comprehensive thermal property measurement of terracotta manufactured from Gulf region clays, employing standardized protocols at in-service temperature and moisture conditions. This research should encompass conventional and bio-enhanced formulations using regionally available waste streams (date palm residues, desalination brine solids, construction demolition waste).

2. Whole-building net-zero demonstrations: Validated building energy models demonstrating annual energy balance achievement through terracotta envelope integration with passive strategies and on-site renewable energy systems in Gulf climate zones. These demonstrations should quantify terracotta's specific contribution to net-zero performance and identify optimal integration strategies.

3. Regional embodied carbon assessment: Life-cycle assessment of terracotta manufacturing in Gulf contexts, incorporating regional energy sources (natural gas), manufacturing processes (tunnel kilns), and transportation distances. This research should compare embodied carbon across material alternatives and identify opportunities for carbon reduction through process optimization or renewable energy integration in manufacturing.

4. Long-term field performance validation: Multi-year monitoring of occupied buildings employing terracotta envelope systems, measuring energy consumption, thermal comfort, durability, and maintenance requirements. This research should validate simulation predictions, identify performance gaps, and inform design guideline development.

5. Economic optimization and policy analysis: Comprehensive economic modeling incorporating regional cost data, energy tariff scenarios, carbon pricing, and financial incentive structures. This research should identify policy interventions—building code provisions, procurement preferences, tax incentives, manufacturing support—most effective in accelerating terracotta adoption.

Limitations of This Review

Several limitations constrain the scope and conclusions of this systematic review. The restriction to English-language peer-reviewed publications may have excluded relevant research published in Arabic, Farsi, or other regional languages, as well as valuable gray literature including technical reports and industry case studies. The substantial heterogeneity in study designs, material formulations, and performance metrics precluded quantitative meta-analysis, limiting the precision of synthesized effect estimates. Publication bias may favor studies reporting positive results over null findings, potentially inflating apparent performance benefits. The rapid evolution of bio-enhanced terracotta formulations creates a temporal lag between research and practice, meaning recent innovations may not yet appear in peer-reviewed literature. Finally, the authors' institutional affiliations in Gulf contexts may introduce unconscious bias toward interpretations favoring regional research priorities, though systematic methodology and transparent reporting aim to minimize such effects.

Closing Perspective

Writing from Sharjah—a city whose older residential neighbourhoods contain fired-clay masonry buildings that have quietly out-performed decades of air-conditioned concrete development in terms of passive thermal comfort—the evidence assembled in this review does not feel abstract. The thermal performance advantages of terracotta, particularly in bio-enhanced formulations, are real and documented across 90 studies. What remains undone is not the material science but the translation: from Egyptian and Moroccan laboratory data to Gulf construction sites; from simulation results to monitored, occupied buildings; from isolated material tests to whole-building net-zero demonstrations that combine terracotta’s mass effects with renewable generation. The research directions this review identifies—Gulf-specific materials characterisation, regional embodied carbon data, long-term field monitoring, whole-building net-zero modelling—are not aspirational. They are the specific empirical work needed before terracotta can reclaim a significant role in the construction of net-zero buildings in this region. The material has demonstrated its fitness for the climate over centuries. Demonstrating its fitness for the net-zero transition is the work that remains.

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