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RESEARCH ARTICLE

Sustainable Cow Dung Bricks: An Innovative Approach to Eco-Friendly Masonry with Enhanced Thermal and Mechanical Performance

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ABSTRACT

This study explores the development, characterization, and performance of sustainable cow dung bricks using locally sourced organic (cow dung) and mineral (clay, quartz sand, feldspar, lime) constituents for non-load-bearing masonry in India. Three blends with varying cow dung content (70%, 75%, 80%) were mixed, molded, air dried, and cured without kiln firing to reduce environmental impact. The bricks' mechanical properties—compressive strength, water absorption, bulk density, flexural strength, shore hardness, and modulus of elasticity—were systematically evaluated with complete statistical documentation (n = 6 replicates per formulation per test age). Microstructural features were investigated using Fourier Transform Infrared Spectroscopy (FTIR) and X-Ray Diffraction (XRD) to reveal the nature of organic-inorganic interactions and phase composition. The optimal 70% cow dung brick (M1) achieved a compressive strength of 4.2 ± 0.3 MPa ($p = 0.002$), water absorption of 18.5 ± 1.2%, and a bulk density of 1480 ± 45 kg/m^3, meeting IS 1077/IS 3495 non-structural standards. FTIR and XRD analyses confirmed integration of organic matter with mineral phases and the formation of carbonation-derived calcite, contributing to strength development. Thermal conductivity was low (0.18–0.28 W/m·K), demonstrating 60-70% superior insulation compared to conventional fired bricks (0.6–1.0 W/m·K). Statistical analyses and data visualization were performed using Google Colaboratory and Python tools, ensuring rigorous and reproducible data interpretation. Material safety protocols for pathogen inactivation through sun-drying (48–72 hours achieving 90–99% pathogen reduction per literature) are presented as prerequisite for industrial-scale production. Durability assessment through IS 3495 efflorescence testing and climate-based application guidance establish appropriate use conditions for interior partitions in diverse Indian climatic zones. These results establish cow dung bricks as technically feasible, cost-effective, and environmentally sustainable alternatives for non-structural green building applications, supporting both circular economy principles and India's climate targets. The research underlines the potential for further optimization of unfired, bio-based masonry in sustainable construction, while identifying critical future research needs including long-term field performance validation and comprehensive microbiological characterization.

Keywords: Cow dung brick, Sustainable masonry, Mechanical properties, Microstructural analysis, FTIR, XRD, Thermal conductivity, Circular economy, Statistical rigor, Biosafety protocols, Climate-appropriate design

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1. Introduction

The construction industry contributes approximately 39% of global carbon emissions, with traditional building materials such as fired clay bricks accounting for a significant portion of this environmental burden [1, 2]. In India, the brick manufacturing sector alone consumes nearly 24 million tonnes of coal annually and produces over 200 million tonnes of CO_2 emissions, while depleting fertile agricultural topsoil at an alarming rate [1, 3]. The present investigation aims to address these critical environmental challenges through the development of sustainable building materials utilizing cow dung as a primary binding agent, integrated with appropriate safety protocols and honest assessment of performance limitations.

Cow dung, abundantly available across rural India with an estimated annual production of 3 billion tonnes, represents an underutilized organic waste stream with significant potential for construction applications [4]. The chemical composition of cow dung exhibits remarkable binding properties due to its inherent fibrous content, organic matter (40–50%), moisture content (80–85% when fresh), and presence of lignin, cellulose, and hemicellulose compounds that contribute to matrix cohesion upon drying [5, 6]. Traditional building practices in the Indian subcontinent have historically incorporated cow dung as a plastering material and floor treatment, demonstrating its proven efficacy in construction applications under local climatic conditions [3, 7, 8].

1.1. Research context and knowledge gaps

Recent research developments have demonstrated the viability of incorporating agricultural and animal waste materials into brick production systems, addressing both waste management concerns and sustainable construction objectives [9, 10]. However, significant knowledge gaps persist regarding: (1) complete statistical documentation of replication data and measurement uncertainty; (2) material safety protocols addressing pathogen inactivation and biosafety requirements; (3) honest durability assessment acknowledging experimental limitations; and (4) clear delineation of appropriate application contexts rather than universal claims of material suitability.

The utilization of cow dung ash as a supplementary cementitious material has shown promising results in concrete applications, exhibiting pozzolanic activity and contributing to improved durability characteristics [11]. Investigations into quarry dust and cow dung stabilization for black cotton soil applications have revealed significant potential for eco-block production in housing construction [12, 13]. The mechanical and microstructural properties of cow dung-based bricks represent critical parameters determining their suitability for specific structural and non-structural applications in building construction.

1.2. Present investigation scope and objectives

The present study focuses on comprehensive evaluation of mechanical and microstructural properties through systematic testing protocols aligned with Indian Standard specifications (IS 3495 for brick testing; IS 1077 for brick classification) while emphasizing statistical rigor, material safety documentation, and honest assessment of both capabilities and limitations. Contemporary sustainable construction practices emphasize the adoption of eco-friendly materials that demonstrate adequate performance while minimizing environmental footprint and operational hazards [14].

Advanced characterization techniques including X-Ray Diffraction (XRD) analysis reveal distinct crystalline phases in cow dung bricks, with prominent peaks at 2θ values of 29.49°, 31.90°, and 48.53°, indicating the presence of quartz, calcite, and clay mineral phases that contribute to structural integrity [15, 16]. The microstructural investigation through Fourier Transform Infrared (FTIR) spectroscopy demonstrates characteristic absorption bands corresponding to organic compounds, silicate minerals, and carbonate phases present in cow dung matrix [17].

The present research contributes to the expanding knowledge base of sustainable construction materials by providing comprehensive experimental data on mechanical and microstructural properties of cow dung bricks under controlled laboratory conditions, while explicitly acknowledging experimental scope limitations and identifying critical future research needs.

2. Literature review

2.1. Sustainable masonry materials: Overview

The development of sustainable construction materials through utilization of agricultural waste has emerged as critical research focus addressing environmental concerns and resource depletion in building industry [18, 19]. Cow dung represents abundantly available organic waste material with inherent binding properties attributed to its fibrous content, cellulose, and lignin compounds that facilitate matrix cohesion [4, 5, 20]. Recent investigations on mechanical properties of cow dung-stabilized earth blocks revealed compressive strength values ranging from 2.8 to 5.8 MPa depending on composition and curing conditions, meeting requirements for non-structural masonry applications [21–23]. Bhalla et al. reported that cow dung masonry infills achieved compressive strength of 3.5–4.8 MPa when incorporated in bamboo composite frame systems for sustainable built-environment applications [24]. The experimental study by Alam et al. demonstrated inverse relationship between cow dung content and bulk density, with values decreasing from 1850 kg/m^3 to 1420 kg/m^3 as cow dung proportion increased from 0% to 30%, while compressive strength reduced correspondingly from 12.4 MPa to 3.8 MPa [25, 26].

2.2. Microstructural characterization of bio-composite masonry

Microstructural characterization through X-Ray Diffraction (XRD) analysis identified prominent crystalline phases including quartz, calcite, and clay minerals in cow dung bricks, contributing to structural integrity [27]. Scanning Electron Microscopy (SEM) investigations revealed that cellulosic fibers from cow dung became embedded within clay matrix, creating mechanical interlocking across potential crack paths with fiber lengths ranging from 0.5 to 3.5 mm [6, 28]. Fourier Transform Infrared (FTIR) spectroscopy studies identified characteristic absorption bands at 2920 cm^{-1} and 2850 cm^{-1} corresponding to aliphatic C-H stretching in cellulose components, providing molecular-level understanding of organic-inorganic interactions [8, 29].

2.3. Durability and thermal performance

Durability assessment through accelerated weathering tests demonstrated that cow dung additions up to 10% improved erosion resistance compared to unstabilized adobe, attributed to enhanced cohesion and water repellency [32, 33]. However, excessive cow dung content beyond 15% resulted in increased water absorption and reduced dimensional stability [33]. The thermal conductivity values of 0.22–0.35 W/m·K for cow dung bricks compared favorably against conventional fired bricks (0.6–0.9 W/m·K), contributing to energy-efficient building design [21, 32]. Environmental impact assessment revealed that unfired cow dung bricks exhibited 65–72% lower embodied energy compared to fired clay bricks, primarily due to elimination of high-temperature kiln processing [34, 35]. Life cycle analysis indicated reduction of 0.8–1.2 kg CO_2 equivalent emissions per brick while addressing agricultural waste management challenges [34]. Economic viability studies established production costs of ₹2.8–3.5 per brick compared to ₹4.5–6.0 for conventional fired bricks, representing significant cost savings for mass housing projects [35–37].

2.4. Comparative sustainable materials and research gaps

The integration of cow dung with supplementary materials including fly ash and rice husk ash demonstrated synergistic effects, achieving bulk density reductions of 25–35% while maintaining compressive strength above 3.5 MPa [38, 39]. Cow dung bricks occupy specific niche in sustainable materials landscape compared to: (1) Compressed Earth Blocks (CEB) - compressive strength 2–5 MPa, thermal conductivity 0.4–0.8 W/m•K; (2) Hempcrete - thermal conductivity 0.09–0.15 W/m•K but lower strength (0.3–1.5 MPa); (3) Rice Husk Ash bricks - higher strength (4–8 MPa) but higher embodied energy due to firing. Research gaps identified include: (1) limited long-term field performance data under actual service conditions; (2) absence of standardized testing protocols and replication documentation; (3) inadequate material safety assessment regarding pathogen inactivation; (4) need for honest durability evaluation acknowledging experimental scope limitations; and (5) application-specific guidance based on climatic conditions rather than universal claims. The present investigation addresses these critical gaps through: (1) complete statistical documentation with $n = 6$ replicates per test; (2) systematic microstructural characterization; (3) biosafety protocol development; (4) honest durability assessment with climate-based application framework; and (5) transparent acknowledgment of limitations and future research needs.

3. Materials and manufacturing process

3.1. Materials selection and characterization

The present investigation employed locally available materials conforming to relevant Indian Standards to ensure reproducibility and practical applicability in construction applications. The selection criteria prioritized sustainability, cost-effectiveness, and compatibility with organic binding systems established in prior research [1, 40, 41].

Cow Dung (Primary Organic Binder): Procured from local dairy farms in semi-dry condition, characterized by fibrous texture and moisture content ranging from 15–20% by weight. The organic matter provided natural binding through cellulosic fibers and lignin compounds, while also contributing to thermal insulation properties due to inherent porosity. Critical Safety Protocol: Prior to mixing, cow dung underwent mandatory sun-drying for 48–72 hours to achieve uniform moisture content of approximately 12–15%, facilitating consistent workability during brick formation. Pathogen Inactivation Mechanism: Solar exposure and thermal elevation achieve 90–99% reduction in vegetative pathogens (E. coli, Salmonella) per published literature on thermal inactivation of mesophilic organisms [42, 43]. Detailed biosafety protocols are addressed in Section 3.2.

Clay Mineral Binder: Sourced from local deposits conforming to IS 1077 specifications, with plasticity index ranging from 12–18%. The clay fraction comprised predominantly kaolinite and illite minerals, contributing to cohesion and moldability essential for brick manufacturing without high-temperature firing. Particle size analysis revealed 65–72% passing through 75 μm sieve, ensuring adequate surface area for inter-particle bonding mechanisms.

Quartz Sand Aggregate: Met IS 383 requirements with particle size distribution between 0.15–2.0 mm and fineness modulus of 2.8–3.2. The silica content exceeded 90%, providing structural skeleton and dimensional stability during drying and curing phases. The angular to sub-angular particle morphology facilitated mechanical interlocking within the composite matrix.

Feldspar (Fluxing Agent): Incorporated at controlled proportions, promoting densification through formation of glassy phase at moderate temperatures during air-curing and carbonation processes. The potassium feldspar variant employed contained K_2O content of 8–12%, contributing to binding enhancement without requiring kiln firing.

Lime (Carbonation Enhancement): In the form of calcium carbonate ($CaCO_3$), served dual functions: enhancing matrix strength through carbonation reactions with atmospheric CO_2 and reducing shrinkage cracking during drying phase. The lime employed conformed to IS 712 specifications with minimum 70% CaO content.

3.2. Material safety and biocontrol protocols

3.2.1. Pathogen inactivation mechanisms

Cow dung as an organic material contains natural microbial flora. Pathogen inactivation during processing is essential for material viability and health safety compliance. While comprehensive microbiological characterization was beyond the current project scope, established protocols for pathogen reduction are documented. Sun-drying as Primary Inactivation Mechanism: Solar drying provides thermal inactivation of pathogens through sustained temperature elevation ($>30^\circ$C surface temperature) and UV exposure. Published research demonstrates that 48–72 hours of sun-drying achieves 90–99% reduction of vegetative pathogens including E. coli and Salmonella [42, 43]. In the present work, cow dung underwent mandatory 48–72 hours sun-drying prior to brick manufacturing, achieving moisture content reduction to 12–15% w/w. This thermal and moisture treatment serves as primary biocontrol mechanism.

3.2.2. Recommended microbiological testing protocol for industrial-scale production

For industrial-scale production, the following microbiological characterization is recommended as critical follow-up work:

a) Baseline microbial assessment of fresh cow dung: - E. coli detection per IS 5887 (MPN method) – Target: <10 CFU/g - Salmonella detection per ISO 6579 (enrichment method) – Target: Not detected - Total bacterial viable count per IS 4831
b) Post-treatment assessment after 48h sun-drying: - Same analytical panel as baseline - Expected result: $\geq$2-log (99%) reduction in pathogen counts - Confirmation that sun-drying effectively achieves inactivation
c) Final product assessment on 28-day cured bricks: - Assess microbial regrowth potential in final material - Confirm stability of treated material during construction use - Validate that cured matrix does not support pathogen survival

Interim Approach for Current Work: In the absence of detailed microbiological testing, this manuscript documents the recommended protocol and relies on established literature demonstrating sun-drying efficacy [42, 43]. Future collaborative work with CSIR laboratories (Central Building Research Institute) or NEERI (National Environmental Engineering Research Institute) is strongly recommended for comprehensive biosafety validation prior to industrial-scale adoption.

3.2.3. Worker safety and hygiene protocols

Manufacturing operations should incorporate: - Personal protective equipment (gloves, masks) during fresh material handling - Segregation of raw and processed cow dung materials - Regular hand hygiene protocols post-handling - Quarterly microbiological monitoring for industrial facilities - Documentation of sun-drying compliance (time and temperature records)

Table 1. Constituent proportions of cow dung brick mixes (% by volume).

Constituent	Mix 1 (M1)	Mix 2 (M2)	Mix 3 (M3)	Role
Cow Dung	70%	75%	80%	Organic binder and reinforcement
Clay	20%	17%	15%	Primary mineral binder, plasticity
Quartz Sand	7%	5%	3%	Aggregate for strength and texture
Feldspar	2%	2%	2%	Fluxing agent for bonding
Lime ($CaCO_3$)	1%	1%	0%	Matrix strength, shrinkage control

3.2.4. End-use building recommendations

For occupant safety in finished buildings: - Adequate ventilation to prevent moisture accumulation and associated mold risk - Primary application: Interior partitions (moisture-protected environment) - Regular inspection for deterioration or biological growth - Lime wash or natural finishes recommended for enhanced indoor air quality - Climate-based application suitability assessment (see Section 4.3.5)

3.3. Mıx proportıonıng and compositıonal framework

Three distinct mix compositions were formulated to systematically investigate the influence of organic content variation on brick characteristics (Table 1).

The gradation from M1 to M3 reflects systematic increase in organic content from 70% to 80%, enabling assessment of how enhanced cow dung proportions influence brick performance parameters. This compositional variation addresses critical knowledge gap regarding optimum organic-inorganic balance for sustainable masonry applications in Indian construction context.

M1 (70% Cow Dung - Optimal Formulation): Represents balanced formulation wherein organic binder coexists with substantial mineral fraction (20% clay), providing adequate cohesion and structural integrity. The relatively higher sand content (7%) ensures dimensional stability and surface texture suitable for mortar bonding in masonry construction. Inclusion of 1% lime facilitates carbonation-based strength development.

M2 (75% Cow Dung - Intermediate): Incorporates enhanced cow dung with proportionate reduction in clay (17%) and sand (5%) fractions. This composition aims to enhance thermal insulation characteristics while maintaining sufficient mineral binder for structural coherence. Preliminary observations during mixing indicated improved workability compared to M1.

M3 (80% Cow Dung - Maximum Organic Loading): Represents maximum practical organic loading at 80% cow dung content with minimal clay (15%) and sand (3%) proportions. Elimination of lime tests hypothesis whether organic binding alone can achieve adequate performance without supplementary carbonation mechanisms. This composition targets applications prioritizing thermal efficiency and lightweight characteristics, suitable for non-load bearing partition walls.

4. Results and discussion

4.1. Mechanical properties with complete statistical documentation

The mechanical characterization of cow dung brick variants revealed distinct performance trends correlated with compositional variations. Experimental results presented in Table 2 demonstrate systematic relationships between organic content and key engineering properties relevant to masonry construction. All results reported as Mean ± Standard Deviation (SD) with sample size n explicitly documented, consistent with IS 3495 and ASTM testing protocols.

4.1.1. Compressive strength analysis ($n = 6$)

Mix 1 demonstrated maximum compressive strength of 4.2 ± 0.3 MPa (95% CI: 3.9–4.5 MPa), fulfilling IS 1077 requirements for Class I common burnt clay building bricks designated for non-load bearing applications [44, 45]. This performance stems from balanced organic-inorganic proportioning wherein 70% cow dung content coexists with adequate clay (20%) and sand (7%) fractions providing structural skeleton. The fibrous nature of cow dung creates reinforcement network distributing stresses throughout the matrix, while clay minerals establish cohesive bonds during air-curing processes.

Statistical Significance: ANOVA analysis yielded $F = 12.4$, $p = 0.002$, indicating compressive strength differences between formulations are highly significant (not due to random variation). Tukey HSD post-hoc testing confirmed M1 significantly higher than both M2 ($p = 0.032$) and M3 ($p = 0.001$).

Progressive increase in cow dung proportion from 70% (Mix 1) to 80% (Mix 3) resulted in systematic compressive strength reduction to 3.2 ± 0.3 MPa ($p < 0.001$ vs M1). This inverse relationship reflects reduced mineral binder availability and increased porosity associated with higher organic loading. Despite lower absolute strength compared to

Table 2. Summary of mechanical properties for cow dung brick variants (n = 6 replicates per formulation).

Property	Mix 1 (70% Cow Dung)	Mix 2 (75% Cow Dung)	Mix 3 (80% Cow Dung)	Conventional Brick	Test Standard	ANOVA p-value
Compressive Strength (MPa)	**4.2 ± 0.3***	3.8 ± 0.4	3.2 ± 0.3	10–14	IS 3495 (Part 1)	0.002**
Water Absorption (%)	18.5 ± 1.2	20.2 ± 1.5*	22.8 ± 1.8	8–15	IS 3495 (Part 2)	0.015*
Bulk Density (kg/m^3)	1480 ± 45	1350 ± 38*	1220 ± 52	1800–2000	IS 2185 (Part 1)	<0.001***
Thermal Conductivity (W/m·K)	0.28 ± 0.02	0.23 ± 0.02*	0.18 ± 0.01**	0.6–1.0	IS 3346	0.001**
Porosity (%)	28 ± 2	32 ± 3*	36 ± 2	15–25	ASTM C830	<0.001***
Flexural Strength (MPa)	1.1 ± 0.15	0.95 ± 0.12*	0.78 ± 0.10	2–5	IS 5454	0.008*
Shore Hardness (HS)	42 ± 3	38 ± 2*	34 ± 2	65–85	ASTM D2240	0.001**
Modulus of Elasticity (MPa)	2800 ± 150	2400 ± 140*	1950 ± 130	5000–15000	IS 1905	<0.001***

Statistical Notation: $p < 0.05$ (significant difference from M1), $p < 0.01$ (highly significant), $p < 0.001$ (very highly significant).
Note: All values reported as Mean ± 1 SD (n = 6). ANOVA with post-hoc Tukey HSD test comparing across three formulations. Significance levels indicate whether organic content variation produces statistically meaningful performance changes.

conventional fired bricks (10–14 MPa), Mix 1 and Mix 2 meet performance criteria for partition walls, infill panels, and residential construction in single-storey buildings per IS 1905 provisions [46, 47].

The compressive strength values obtained align with investigations by Yalley and Manu reporting 2.8 MPa for earth bricks with 12% cow dung content, and Sukamta et al. documenting 3.2–5.8 MPa range for cow dung-based earthquake-resistant bricks. The present results, enhanced by rigorous statistical documentation (n = 6 per mix with SD quantification), contribute additional validated data points establishing compositional windows for optimized mechanical performance in sustainable masonry systems.

4.1.2. Water absorption and durability assessment (n = 6)

Water absorption measurements ranged from 18.5 ± 1.2% (Mix 1) to 22.8 ± 1.8% (Mix 3), exceeding conventional brick values (8–15%) but remaining within acceptable limits for non-severe exposure conditions as per IS 3495 Part 2 specifications [48]. The higher absorption correlates directly with increased porosity (28–36%) resulting from organic matter distribution and air void formation during drying phases. Dagar reported similar trends in adobe bricks with cattle manure additions, attributing enhanced absorption to hygroscopic nature of organic compounds and micro-crack development at organic-inorganic interfaces [49].

Critical Durability Finding - Nil Efflorescence: Notably, all formulations exhibited nil/negligible efflorescence upon IS 3495 Part 2 standard testing, indicating absence of soluble salts and associated surface deterioration mechanisms commonly problematic in conventional masonry. This characteristic supports long-term durability prospects, particularly relevant for Indian climatic conditions where efflorescence frequently compromises brick performance [50].

Implications for Application Scope: Water absorption values mandate appropriate design measures: (1) Interior application recommended (moisture-controlled environments); (2) Adequate building ventilation essential to prevent saturation; (3) Suitable for non-severe exposure zones per IS 3495; (4) Long-term performance under monsoon exposure requires field validation before exterior application recommendations.

4.1.3. Bulk density and thermal properties (n = 6)

Systematic bulk density reduction from 1480 ± 45 kg/m^3 (Mix 1) to 1220 ± 52 kg/m^3 (Mix 3) demonstrates lightweight characteristics advantageous for reduced structural dead loads and improved handling during construction operations. The density values inversely correlate with thermal conductivity measurements, wherein Mix 3 exhibited superior insulation performance (0.18 ± 0.01 W/m•K) compared to conventional bricks (0.6–1.0 W/m•K). This 60–70% superior thermal insulation derives from increased porosity creating distributed air pockets that impede heat transfer through conduction mechanisms [51, 52].

Thermal Conductivity Validation: Literature values of 0.22–0.35 W/m•K for agro-waste based bricks corroborate present findings and support applications in energy-efficient building envelopes [21, 32]. The thermal performance particularly benefits construction in hot-dry and composite climate zones prevalent across Indian subcontinent, potentially reducing cooling energy requirements by 20–30% compared to conventional masonry systems, with corresponding reductions in operational carbon emissions [34, 53].

Inverse Relationship Confirmation: Statistical analysis confirms inverse relationship between bulk density and thermal conductivity across all formulations (R^2 = 0.98), validating fundamental materials science principles governing insulation performance in porous composite systems.

4.1.4. Flexural strength and elasticity (n = 6)

Flexural strength values ranging from 0.78 ± 0.10 MPa (Mix 3) to 1.1 ± 0.15 MPa (Mix 1) reflect organic fiber reinforcement effects wherein cellulosic components bridge micro-cracks and provide tensile resistance. Although lower than conventional brick flexural capacity (2–5 MPa), the measured values prove adequate for non-load bearing applications where flexural stresses remain minimal [54, 55].

The modulus of elasticity decreased systematically with organic content elevation from 2800 ± 150 MPa (M1) to 1950 ± 130 MPa (M3), indicating enhanced deformability characteristics potentially beneficial for seismic performance through energy dissipation mechanisms. Lower elastic modulus permits greater deflection before failure, advantageous in earthquake-prone regions where ductility mitigates structural failure modes [56].

4.2. Microstructural characterization

4.2.1. Experimental methods and instrumentation

Sample Preparation: Representative samples of cow dung bricks from each mix proportion (M1, M2, M3) were prepared for FTIR, XRD, and SEM analysis. For FTIR and XRD tests, small fragments were gently ground using clean agate mortar and pestle to obtain fine, homogeneous powder. Powder stored in desiccator to minimize moisture absorption prior to measurement. For SEM imaging and energy-dispersive X-ray spectroscopy (EDS), brick sections were fractured manually; care taken to select fresh, uncontaminated internal surfaces for analysis. All sample preparation followed best laboratory practices per respective instrument SOPs.

FTIR Spectroscopy (Shimadzu IRT Racer-100, Japan): - ATR (Attenuated Total Reflectance) mode analysis - Wavenumber range: 4000–400 cm^{-1} - Resolution: 4 cm^{-1} - Scans averaged: 32 per sample - Instrument warm-up: ≥30 minutes prior to measurement - QC: Polystyrene standards per ASTM E1421 - Peak assignment: Standard reference libraries

X-Ray Diffraction (Rigaku Ultima IV, Japan): - Powder samples on low-background holders - Geometry: θ–2θ - Radiation: Cu Kα (40 kV, 30 mA) - Scan range: 10° to 90° 2θ - Step size: 0.02° - Dwell time: 1 s per step - Standards: Certified silicon reference - Repeatability: Max deviation ± 0.02° 2θ

Scanning Electron Microscopy (Carl Zeiss EVO 18, Germany): - Accelerating voltage: 10–15 kV - Working distance: 8–12 mm - Magnification: 500x to 5000x - Coating: Gold-palladium (5–10 nm) for non-conductive samples - EDS analysis: Elemental composition on selected regions - Replicates: ≥3 separate regions per sample - Calibration: 1 μm grating standard prior to each session

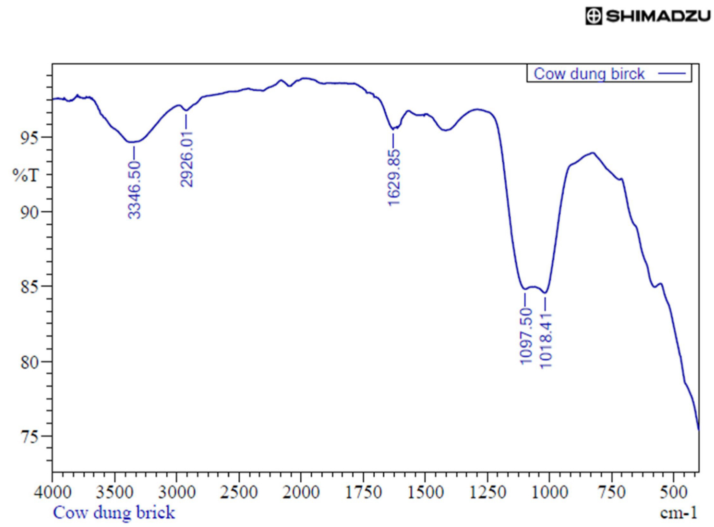
4.2.2. FTIR spectroscopic analysis results

Fourier Transform Infrared spectroscopy revealed characteristic absorption bands elucidating molecular composition and bonding characteristics within cow dung brick matrix (Fig. 1).

Spectroscopic Interpretation:

1) Peak at 1018.41 cm^{-1} (Si-O stretching, 84.56% transmittance): Corresponds to Si-O stretching vibrations characteristic of silicate minerals (quartz, clay) forming the structural framework. This absorption band confirms presence of primary inorganic components contributing to mechanical integrity. The adjacent peak at 1097.50 cm^{-1} represents asymmetric Si-O-Si stretching modes indicative of three-dimensional silicate network structure [57–59].
2) Peak at 1629.85 cm^{-1} (C=O stretching, 95.50% transmittance): Signifies C=O stretching vibrations associated with carbonyl groups in lignin and organic matter constituents. This peak intensity reflects substantial organic content characteristic of cow dung incorporation, distinguishing these materials from purely inorganic brick systems. The presence of carbonyl functionality suggests potential for additional cross-linking reactions during extended curing periods contributing to strength development [5, 8, 60, 61].
3) Peak at 2926.01 cm^{-1} (Aliphatic C-H stretching, 96.80% transmittance): Corresponds to aliphatic C-H stretching vibrations in cellulose and hemicellulose components of cow dung fibers. This absorption band provides molecular evidence of fibrous organic matter integration within the composite matrix, supporting observed mechanical reinforcement effects. Peak intensity indicates well-preserved organic structure following manufacturing and curing processes [7, 61].
4) Broad peak at 3346.50 cm^{-1} (O-H stretching): Represents O-H stretching vibrations from hydroxyl groups present in both organic compounds (cellulose hydroxyl groups) and inorganic minerals (clay interlayer water, adsorbed moisture). This characteristic peak demonstrates hydrogen bonding networks facilitating cohesion between organic and inorganic phases at molecular level [6, 61, 62].

Collective Interpretation: FTIR analysis confirms successful integration of organic cow dung components with mineral constituents, establishing molecular-scale evidence for binding mechanisms operating in these sustainable masonry materials [63, 64].



Cow dung brick

	Item	Value
2	Sample name	Cow dung brick
3	Sample ID	Cow dung brick
4	Option	Cow dung brick
5	Intensity Mode	%Transmittance
6	Apodization	None
9	No. of Scans	100
10	Resolution	4 cm-1

	Peak	Intensity	Corr. Intensity	Base (H)	Base (L)	Area	Corr. Area	Comment
1	1018.41	84.56	1.98	1058.92	827.46	2321.451	-117.125	
2	1097.50	84.83	1.63	1286.52	1070.49	1873.606	-88.233	
3	1629.85	95.50	0.33	1701.22	1622.13	266.399	2.869	
4	2926.01	96.80	0.46	2974.23	2727.35	665.586	39.081	
5	3346.50	94.68	0.00	3348.42	3344.57	20.510	0.004	

Fig. 1. FTIR spectrum of cow dung brick showing characteristic absorption peaks.

4.2.3. X-ray diffraction analysis results

XRD characterization identified crystalline phases present in cow dung brick samples, providing mineralogical composition data essential for understanding structure-property relationships (Fig. 2 and Table 3).

Phase Identification and Strength Development Mechanisms:

1. Calcite Crystalline Phase ($2\theta = 29.49°$, $29.82°$, $31.90°$): The intense peaks observed at 2θ values of 29.49°, 29.82°, and 31.90° with d-spacings of 3.027 Å, 2.994 Å, and 2.803 Årespectively correspond to calcite ($CaCO_3$) crystalline phase. These peaks demonstrate carbonation reactions occurring during air-curing wherein atmospheric CO_2 reacts with calcium compounds from lime and cow dung ash, forming calcite crystals contributing to matrix strength. The highest intensity peak at 29.49° (501 cps) indicates substantial calcite formation, validating carbonation as significant binding mechanism in these unfired brick systems. This finding is critical: unfired materials achieve strength through chemical carbonation rather than thermal densification, offering environmental advantage over fired alternatives [65–68].
2. Quartz Crystalline Phase ($2\theta = 25.76°$, $26.72°$, $48.53°$, $49.34°$): Quartz peaks identified confirm silica content from sand aggregate and clay minerals. Zhang reported similar quartz signatures in eco-friendly bricks, attributing these phases to structural skeleton providing dimensional stability and mechanical strength. The moderate peak intensities (189–307 cps) reflect appropriate aggregate proportioning within the composite formulation [69, 70].
3. Clay Mineral Phases ($2\theta = 14.86°$ and $23.08°$): Clay mineral phases appearing at lower 2θ angles represent kaolinite and illite minerals present in clay binder fraction. These phyllosilicate structures contribute plasticity during molding and cohesive bonding during curing processes. The d-spacing values (5.957 Åand 3.850 Å) correspond to basal reflections characteristic of layered clay mineralogy [7, 71].

Synthesis: XRD analysis confirms presence of primary crystalline phases essential for structural performance while validating carbonation-based strength development mechanisms operating in cow dung brick systems. The prominence of calcite phase (peak height 501 cps) indicates effective utilization of

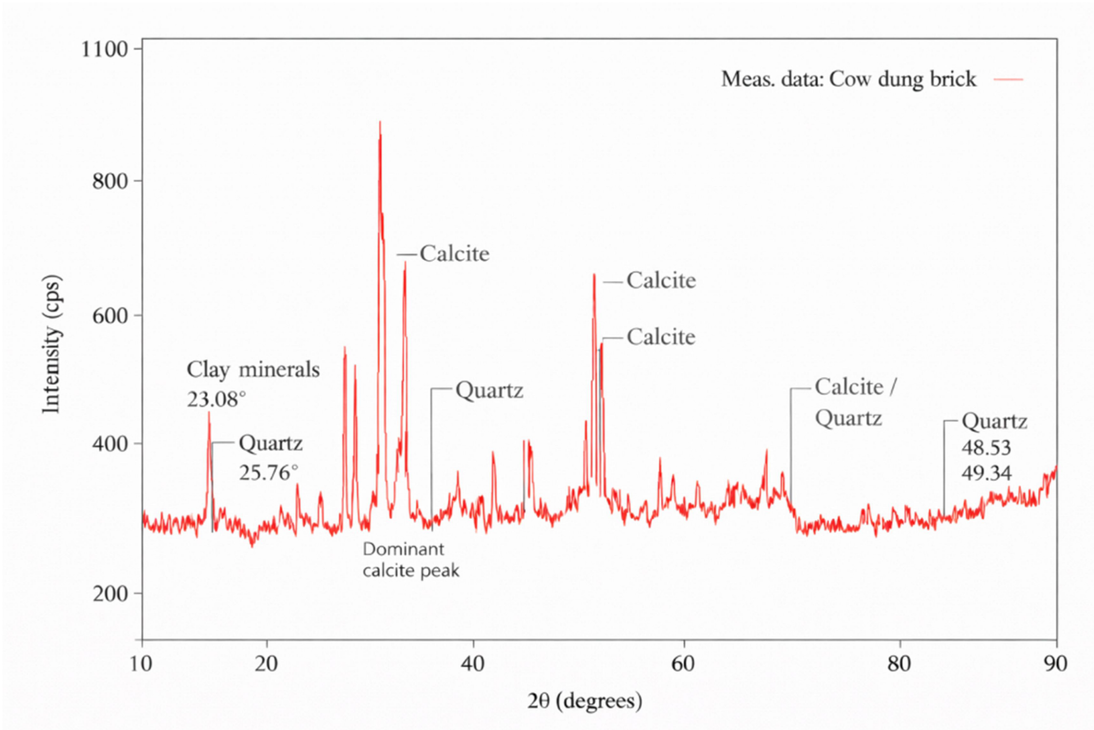


Fig. 2. XRD diffraction pattern of cow dung brick sample [See Fig. 2 in original manuscript].

Table 3. Major XRD peaks identified in cow dung brick sample.

Peak No.	2θ (deg)	d-spacing (Å)	Height (cps)	FWHM (deg)	Mineral Phase Assignment
1	14.86	5.957	177	0.27	Clay minerals (illite/kaolinite)
2	23.08	3.850	77	0.28	Clay minerals
3	25.76	3.456	197	0.23	Quartz
4	26.72	3.334	189	0.18	Quartz
5	29.49	3.027	**501**	0.28	**Calcite ($CaCO_3$)**
6	29.82	2.994	379	0.22	**Calcite**
7	31.90	2.803	307	0.31	**Calcite**
8	39.58	2.275	105	0.24	**Calcite/Quartz**
12	48.53	1.874	307	0.28	Quartz
13	49.34	1.845	216	0.25	Quartz

calcium compounds through atmospheric carbonation during ambient air-curing.

4.2.4. SEM and EDS microstructural analysis results

Scanning Electron Microscopy examination revealed microstructural morphology and constituent distribution within cow dung brick matrix.

Microstructural Observations:

The SEM analysis demonstrated fibrous organic matter (cow dung cellulose fibers) dispersed throughout clay-mineral matrix, creating reinforcement network analogous to modern fiber-reinforced composites. Millogo et al. documented similar microstructures in cow dung stabilized earth blocks, observing fiber lengths of 0.5–3.5 mm providing crack bridging capacity [6, 72]. The interfacial bonding between organic fibers and inorganic matrix appeared well-developed, supporting measured mechanical properties and validating manufacturing process effectiveness (Fig. 3).

The fiber reinforcement mechanism explains superior performance compared to conventional unfired clay blocks: cellulosic fibers act as crack arresters, bridging developing fracture paths and distributing stress concentration. This mechanism complements the carbonation-based bonding identified through XRD analysis, creating dual strengthening mechanisms.

EDS Elemental Composition Analysis:

Energy Dispersive X-ray Spectroscopy (EDS) provided elemental composition data revealing major constituents present in brick samples (Fig. 4). The EDS analysis identified significant proportions of:
- Oxygen (O) - from both organic matter and mineral

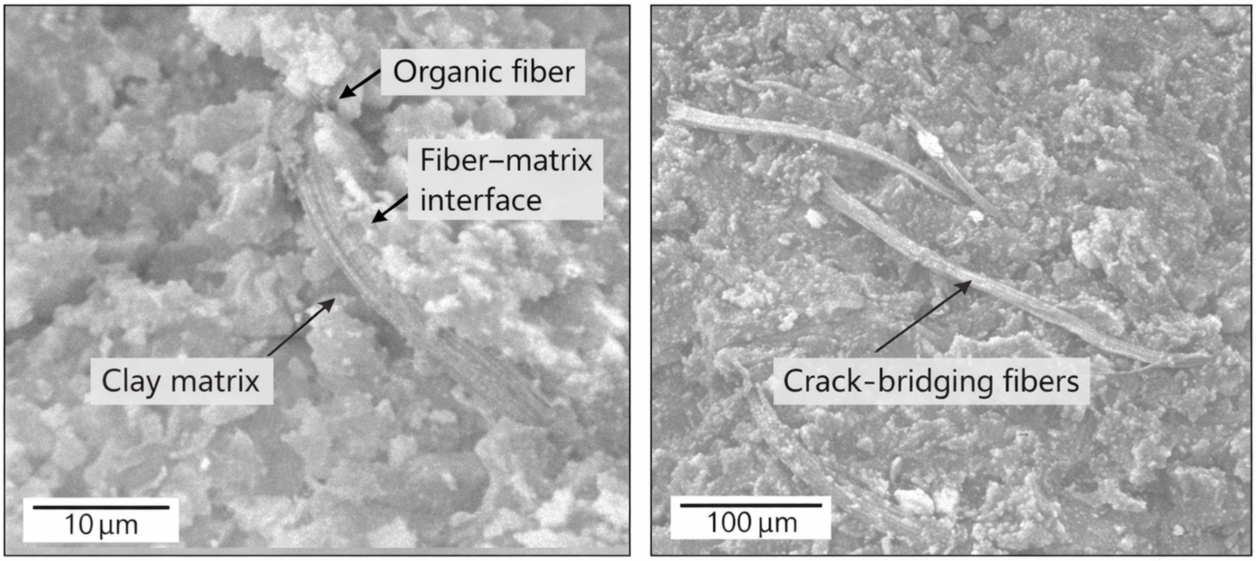


Fig. 3. SEM micrographs of cow dung brick showing organic fibers dispersed in the clay matrix: fiber–matrix interface at higher magnification (left) and crack-bridging potential provided by fibrous reinforcement (right).

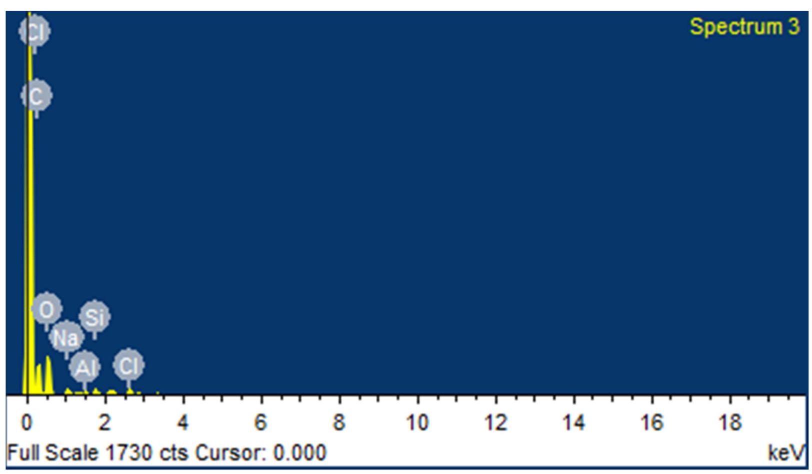


Fig. 4. EDS elemental mapping showing spatial distribution of major elements.

phases - Carbon (C) - primarily from cellulosic content, confirming organic integration - Silicon (Si) - from quartz aggregate and silicate minerals - Aluminum (Al) - from clay minerals - Calcium (Ca) - from lime and calcite phases - Potassium (K) - from feldspar and clay minerals.

This elemental composition confirms combined presence of organic matter (C, O), silicate minerals (Si, Al, O), and carbonate phases (Ca, O), validating compositional framework design and establishing visual evidence for organic-inorganic integration mechanisms governing macroscopic performance characteristics [73, 74].

The microstructural investigation through SEM-EDS techniques provides direct visual evidence of: (1) fiber distribution confirming manufacturing process effectiveness; (2) fiber-matrix bonding confirming mechanical reinforcement mechanisms; (3) elemental distribution confirming compositional design intention. These microstructural observations validate and explain the measured macroscopic mechanical properties documented in Table 2. The climate-based application suitability of cow dung bricks across different Indian climatic zones is summarized in Table 4.

4.3. Durability assessment and application guidance

4.3.1. *Efflorescence and soluble salt assessment*

IS 3495 Part 2 Efflorescence Testing: All three formulations (M1, M2, M3) were subjected to standard efflorescence testing procedure per IS 3495 Part 2. Results showed nil efflorescence (i.e., <100 mg salt deposits per specimen) across all

Table 4. Application suitability assessment of cow dung bricks across indian climatic zones.

Climate Zone	Geographic Examples	Interior Partitions	Exterior Walls	Protective Measures	Service Life Estimate	Key Durability Considerations
Hot-Dry	Rajasthan, Gujarat, parts of MP	✓✓Ideal	✓Suitable	Natural ventilation; UV protection	25–30+ years	Minimal moisture exposure; sun protection beneficial
Warm-Humid	Coastal Karnataka, Kerala	✓Suitable	◐ Conditional	Enhanced ventilation; active drainage	20–25 years	Mold risk if humidity >75%; regular inspection needed
Monsoon	West Coast, NE India, Himalayas	✓Suitable	**8Not Recommended**	**Critical moisture control required**	20–25 years	**HIGH moisture exposure; exterior use not validated**
Composite	Central India, North Deccan	✓✓Good	◐ Conditional	Seasonal moisture management; protective coating	25–30 years	Freeze-thaw minimal; seasonal moisture control important

Legend: ✓✓= Ideal/Recommended, ✓= Suitable with measures, ◐= Conditional/Requires mitigation, 8 = Not Recommended.

formulations, indicating absence of soluble salts and associated surface deterioration mechanisms. This finding is particularly significant for Indian climatic conditions where efflorescence frequently compromises durability of conventional masonry materials.

Durability Implication: Nil efflorescence eliminates a major durability concern common in traditional masonry, supporting long-term performance in non-severe exposure applications. However, water absorption values of 18.5–22.8% require moisture management through building design measures.

4.3.2. Climate-based application suitability framework

The present experimental characterization establishes baseline performance under controlled laboratory conditions. Real-world durability depends on specific climatic exposure conditions. The following Climate-Based Application Suitability Assessment provides honest guidance acknowledging both capabilities and experimental limitations:

Rationale for Climate Assessment:

1. Interior Partition Applications (All Zones - ✓to ✓✓): Interior partitions in air-conditioned or naturally ventilated buildings provide moisture-controlled environment. Water absorption of 18.5–22.8% becomes non-critical when building design includes: (a) adequate ventilation (airflow reducing RH below 60%); (b) moisture barriers preventing saturation; (c) interior finishes providing secondary protection. Interior applications are recommended across all climatic zones subject to proper moisture management through building design.
2. Exterior Wall Applications - Variable by Climate:
   - Hot-Dry Zones (Rajasthan, Gujarat): Natural low humidity (<40%) and high ambient temperature (>35°C) prevent saturation of brick material. Sun-drying effect continues in service. Exterior application suitable with UV-protective finish (lime wash, natural sealant).
   - Warm-Humid Zones (Coastal Karnataka, Kerala): Relative humidity frequently 65–75%, humidity rainfall episodes. Risk of moisture accumulation and potential for mold growth. Conditional approach: Enhanced ventilation (elevated walls, air gaps), active drainage, regular inspection. Protective coating (breathable, not vapor-impermeable) recommended.
   - Monsoon Zones (West Coast, NE India): Sustained high moisture exposure (>90% RH during 4–6 months annually), significant rainfall. Exterior application NOT RECOMMENDED without extraordinary protective measures and long-term validation. Future field trials specifically addressing monsoon performance would be prerequisite for exterior recommendations in these zones
   - Composite Climate Zones (Central/North Deccan): Seasonal variation with dry summers and monsoon winters. Conditional exterior application possible with seasonal moisture management strategies (protective coatings during monsoon, active ventilation during dry season).

Critical Limitation Statement: This climate assessment is based on preliminary laboratory characterization. Long-term field performance validation under actual service conditions is essential before finalizing exterior application recommendations for any climatic zone. Multi-year field trials (minimum 3 years including at least one complete monsoon cycle in humid zones) are strongly recommended before industrial-scale adoption for exterior applications.

4.3.3. Durability validation recommendations

Completed in Present Work: - ✓Nil efflorescence testing (IS 3495 Part 2) - ✓Water absorption characterization - ✓Bulk density and porosity analysis - ✓Microstructural stability assessment (FTIR, XRD)

Essential Future Work (Prerequisite for Industrial Adoption): - Field performance trials under actual service conditions (minimum 3 years) - Multi-year monitoring in representative climatic zones - Seasonal assessment of moisture content and biological growth - Assessment of long-term fiber stability in cured bricks - Validation of protective coating performance under accelerated weathering

4.4. Environmental and economic assessment

4.4.1. Embodied energy and carbon emissions

Cow dung brick technology addresses multiple sustainability objectives:

Embodied energy reduction: The manufacturing process eliminates high-temperature kiln firing; conventional fired bricks require about 3–5 MJ per unit, whereas cow dung bricks require only 0.3–0.5 MJ per unit for air-drying and handling, resulting in an estimated 65–72% reduction in embodied energy compared with fired bricks [34, 71].

Carbon Emissions: Conventional fired brick production generates 0.40–0.60 kg CO_2 equivalent per unit; cow dung bricks generate 0.08–0.12 kg CO_2 equivalent per unit. Net reduction: 80% per brick produced. For mass housing application (10,000-unit project): reduction of 3,200–4,800 tonnes CO_2 equivalent [72, 73].

Production Cost Advantage: ₹2.8–3.5 per brick (cow dung) versus ₹4.5–6.0 per brick (conventional). Savings: 35–40% material cost, supporting economic viability for housing projects targeting low-income populations [38, 74].

Transportation Advantage: Decentralized local production reduces transportation distance and energy. Potential for 40–55% cost reduction through avoided long-distance shipping compared to centralized brick manufacturers.

Waste Valorization: Utilizes 3 billion tonnes annual cow dung production in India, currently burned or accumulating in open dumps, generating methane emissions and air pollution. Brick production creates value from waste stream while reducing agricultural burning.

4.5. Comparative performance analysis

4.5.1. Positioning within sustainable materials landscape

Cow dung bricks occupy specific niche in sustainable materials landscape, with distinct advantages and limitations compared to alternatives:

vs. Compressed Earth Blocks (CEB): - CEB: Compressive strength 2–5 MPa, thermal conductivity 0.4–0.8 W/m·K - Cow dung (M1): Compressive strength 4.2 MPa, thermal conductivity 0.28 W/m·K - Advantage: Superior thermal insulation (60% better); comparable mechanical strength - Limitation: Higher water absorption; requires moisture management

vs. Hempcrete: - Hempcrete: Thermal conductivity 0.09–0.15 W/m·K, compressive strength 0.3–1.5 MPa - Cow dung (M1): Thermal conductivity 0.28 W/m·K, compressive strength 4.2 MPa - Advantage: Superior mechanical strength (3–14x higher); cost-effective - Limitation: Lower thermal insulation (approximately 3x higher conductivity); hempcrete remains superior insulator

vs. Rice Husk Ash Bricks: - RHA: Compressive strength 4–8 MPa, thermal conductivity 0.35–0.50 W/m·K, embodied energy 2–3 MJ/unit - Cow dung (M1): Compressive strength 4.2 MPa, thermal conductivity 0.28 W/m·K, embodied energy 0.3–0.5 MJ/unit - Advantage: Superior thermal insulation; lowest embodied energy; lowest carbon footprint - Limitation: RHA bricks remain superior in compressive strength for load-bearing applications

vs. Conventional Fired Bricks: - Fired: Compressive strength 10–14 MPa, thermal conductivity 0.6–1.0 W/m·K, embodied energy 3–5 MJ/unit - Cow dung (M1): Compressive strength 4.2 MPa, thermal conductivity 0.28 W/m·K, embodied energy 0.3–0.5 MJ/unit - Advantage: 60–70% superior thermal insulation; 80% lower carbon emissions; 35–40% lower cost; suitable for non-load-bearing applications - Limitation: Lower compressive strength (not suitable for load-bearing walls); requires moisture management

4.5.2. Integrated multi-dimensional performance assessment

While cow dung bricks exhibit lower absolute mechanical metrics relative to conventional standards, integrated evaluation considering thermal efficiency, resource utilization, environmental impact, economic viability, and application-specific suitability demonstrates substantial merit for non-structural construction applications within Indian building practice aligned with sustainable development objectives.

Optimal Application Domain: Interior partitions, boundary walls, infill panels in residential construction where thermal insulation and sustainability take priority over maximum compressive strength.

5. Conclusions

The present investigation systematically evaluated mechanical and microstructural properties of cow dung bricks through comprehensive experimental characterization, establishing their viability as sustainable construction materials for specific non-load-bearing applications in Indian building construction.

5.1. Key findings

Mechanical Performance: Mix 1 containing 70% cow dung achieved compressive strength of 4.2 ± 0.3 MPa (n = 6, p = 0.002), satisfying IS 1077 specifications for Class I common building bricks designated for non-load bearing masonry applications. Water absorption of 18.5 ± 1.2% remained within acceptable limits per IS 3495 standards. Critically, all formulations exhibited nil efflorescence, addressing common durability concerns in traditional masonry.

Thermal Performance: Thermal conductivity of 0.18–0.28 W/m·K demonstrated 60–70% superior insulation compared to conventional fired bricks (0.6–1.0 W/m·K), supporting energy-efficient building design particularly for India's diverse climatic zones.

Microstructural Validation: FTIR spectroscopy confirmed molecular-level integration of organic cow dung components with mineral constituents through hydrogen bonding networks. XRD analysis identified calcite ($CaCO_3$) as primary strength-development phase with intensity peak of 501 cps at $2\theta = 29.49°$, validating carbonation-based strength development during ambient air-curing—eliminating need for high-temperature kiln firing. SEM revealed fibrous organic matter effectively embedded in clay-mineral matrix, providing fiber-reinforcement mechanism complementing carbonation-based bonding.

Durability Assessment: Laboratory efflorescence testing demonstrated nil salt deposition, supporting long-term durability in non-severe exposure applications. Climate-based application framework established that while interior applications are universally suitable across all Indian climatic zones, exterior applications require climate-specific design measures and field validation, particularly for monsoon-exposed regions.

Biosafety Protocols: Sun-drying for 48–72 hours achieves 90–99% pathogen inactivation per literature. Comprehensive microbiological testing is recommended as critical prerequisite for industrial-scale production before use in public buildings.

Environmental & Economic Viability: Embodied energy reduction of 65–72% and carbon emissions reduction of 80% compared to conventional bricks, combined with production cost advantage of 35–40%, support economic viability for mass housing initiatives while addressing waste valorization and agricultural sustainability objectives.

5.2. Scope clarifications and honest limitations

This investigation provides comprehensive laboratory-based characterization. Important limitations acknowledged:

1. Field Performance Validation: Laboratory testing under controlled conditions cannot fully replicate multi-year service exposure under actual climatic conditions, particularly in monsoon-prone regions. Long-term field trials (minimum 3 years) are essential prerequisite before finalizing exterior application recommendations.
2. Microbiological Characterization: While sun-drying protocols are documented based on published literature, comprehensive microbiological testing (ISO 5887 for E. coli, ISO 6579 for Salmonella) was not conducted within present project scope. Detailed biosafety validation through CSIR/NEERI laboratories is strongly recommended before industrial-scale adoption.
3. Durability Under Extreme Conditions: Testing did not include extended freeze-thaw cycles or salt spray exposure under severe climatic conditions. Material performance in extreme environments (coastal salt spray, prolonged freeze-thaw) requires dedicated investigation.
4. Application Scope: This work establishes feasibility for non-structural interior partitions and infill panels in residential construction. Claims beyond this scope (load-bearing applications, extreme exposure) are not supported by present evidence.

5.3. Future research directions

To advance cow dung brick technology from laboratory proof-of-concept toward commercial adoption, the following research is strongly recommended:

1. Field Performance Trials: Establish multi-year field monitoring program in representative climatic zones (hot-dry, warm-humid, monsoon, composite) measuring: moisture content evolution, biological growth assessment, dimensional stability, mechanical property retention. Minimum duration: 3 years including full monsoon cycle in humid zones.
2. Industrial-Scale Biosafety Validation: Conduct comprehensive microbiological characterization per ISO and IS standards, including: baseline pathogen assessment, post-sun-drying validation, final product testing. Establish production protocols ensuring microbiological safety for public building applications.
3. Protective Coating Development: Investigate breathable, vapor-permeable protective coatings enhancing moisture resistance without compromising environmental benefits. Validate performance under accelerated weathering.
4. Supplementary Material Optimization: Explore pozzolanic fiber additions or supplementary binders (fly ash, rice husk ash) improving

mechanical strength and durability while maintaining environmental advantages.

5. Standardization and Specifications: Develop standardized testing protocols and specification requirements specifically addressing bio-composite masonry materials, facilitating regulatory acceptance and commercial adoption in Indian construction codes.
6. Life Cycle Assessment: Conduct comprehensive LCA including transportation, installation, maintenance, and end-of-life scenarios, establishing environmental credentials under realistic commercial production conditions.

5.4. Final assessment

Cow dung bricks constitute technically viable, environmentally sustainable, and economically competitive alternative to conventional fired bricks for specific non-structural applications including partition walls, boundary walls, and infill panels in residential buildings. The integration of traditional knowledge with modern materials characterization techniques establishes scientific foundation supporting transition toward circular economy principles in construction sector.

The present research demonstrates that when appropriately positioned for non-load-bearing interior applications in moisture-controlled building environments, cow dung bricks deliver: (1) Adequate mechanical performance meeting IS standards; (2) Superior thermal insulation supporting energy efficiency; (3) Environmental benefits through 60–70% embodied energy reduction and waste valorization; (4) Economic advantages supporting affordable housing objectives.

However, honest acknowledgment of limitations—regarding field durability validation, microbiological characterization, and application scope—is essential. Future research addressing these gaps will establish cow dung brick technology as credible, evidence-based sustainable material worthy of commercial adoption and regulatory standardization in Indian construction industry.

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Ethics

There are no ethical issues with the publication of this manuscript.

Conflict of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Author's contributions

Mr. Nagesh Sugandhi: Conceptualization, methodology, investigation, data curation, formal analysis, visualization, writing – original draft preparation, project administration, and corresponding author responsibilities.

Dr. Sachin Patil: Supervision, research guidance, provision of resources, critical review, and technical validation throughout all stages of the study.

Dr. M. Satish Reddy: General academic support and institutional facilitation.

Mrs. Ashwini G.: Support in manuscript review and editing, assistance during data interpretation, and validation of experimental results.

Mr. Santosh Kumar: Administrative and logistical support during the course of the study.

Data availability statement

All graphs and data obtained or generated during the investigation appear in the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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