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Article

Evaluation Matrix for Assessing the Sustainability of Wall Panels for Rural India

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Abstract: There is an increasing need for sustainable construction materials worldwide to reduce carbon emissions. Walling, being one of the most significant components of a building, has had various innovations and reinventions from traditional techniques. Although many sustainable alternatives exist for walling materials, they are mostly innovated for an urban context. An appropriate walling technique for a rural context remains challenging, as most often "one fits all" notion is applied in construction. Multiple parameters decide whether a material is suitable for a particular context, such as its technical, socio-economic and environmental characteristics. This paper reviews the various wall panels proposed for or used in rural areas as per identified parameters using the Multi-Criteria Decision-Making method of TOPSIS. The panels are ranked based on their suitability for the rural context of India. The study indicates that the Ekra wall panels are most appropriate, followed by the CSEB technique. This system aids stakeholders in selecting sustainable and appropriate walling systems and making informed choices suitable for their contexts.

Keywords: rural housing; conventional walling; innovative walling technology; evaluation matrix; sustainability; multi-criteria decision-making

1. Introduction

The United Nations recognizes shelter as a fundamental human right, alongside access to water, food, and clothing. However, providing adequate housing remains a significant challenge for developing countries, including India, where approximately 66.7% of the population resides in rural areas (Singh, Swaminathan and Ramachandran, 2013; Chandramouli C, 2011). The rural housing crisis in India is characterized by a severe shortage of homes, poor construction quality, inadequate infrastructure, and a high prevalence of temporary and kutcha houses (Census 2011, 2011). This housing deficit affects quality of life and hinders economic growth and employment opportunities. Government initiatives, such as the Pradhan Mantri Awas Yojana (PMAY), aim to address these challenges through mass housing schemes. However, these programs often rely on conventional materials and technologies that are expensive, labour-intensive, and poorly suited to rural contexts. Consequently, there is an urgent need to develop sustainable, cost-effective, and locally appropriate construction technologies that can alleviate the rural housing crisis. Walling systems play a pivotal role in housing construction, accounting for significant portions of material costs, labour requirements, and thermal performance. While government initiatives such as the Building Materials and Technology Promotion Council (BMTPC) and Global Housing Technology Challenge (GHTC) have introduced innovative technologies, these solutions are often inaccessible in rural markets. Many such emerging technologies promoted through these initiatives are primarily developed for urban mass housing and often may not be suitable for the unique socio-economic and environmental challenges of rural India. Furthermore, the "one size fits all" approach used in these initiatives fails to account for the unique socio-economic and environmental conditions of rural India. Thus, the selection of appropriate walling technologies plays a crucial role in ensuring the sustainability, affordability, and feasibility of rural housing. The walling technologies used or proposed for rural housing can be categorised as traditional, conventional, and emerging walling systems.

1.1. Traditional Walling Systems

While traditional walling techniques have been time-tested for their durability, thermal performance, and local adaptability, their declining use due to labour shortages and longer construction timelines has led to the increased adoption of conventional and innovative alternatives. Traditional walling systems have been used for centuries in India and have proven to be cost-effective, comfortable, and environmentally friendly, but they have a few challenges regarding maintenance, quickness, and scalability. Therefore, an increase in the use of modern materials, such as RC, burnt brick and steel, can be visible throughout the country. Using earthen materials for housing in India is a suitable solution for the rising costs of conventional construction materials (Kulshreshtha et al., 2020).

Methods such as Cob, involves shaping soil, sand, and straw into solid walls as depicted in Figure 1. Its porous nature offers excellent thermal mass and insulation, ideal for warm climates (Akinkurolere et al., 2006). However, the compressive strength is only 1.29 MPa, necessitating thicker walls (450-600 mm) to bear loads. Despite this, cob structures have endured 100-400 years with proper design (Agarwal, 1981). In-situ measurements show cob walls' U value ranges from 0.76-1 W/m²k (Rye and Scott, 2012). Other traditional techniques like stone walls as shown in Figure 2, boast durability and resilience to extreme temperatures. These walls typically exceed 350mm in thickness, providing effective insulation against harsh climates (Venu et al., 1997). In-situ measurements indicate stone walls exhibit U values ranging from 2.7 to 1.27 W/m²k (Rye and Scott, 2012). The strength of stone masonry varies based on mortar strength; found an average compressive strength of 33.2 MPa, with stone blocks at 100.6 MPa and mortar joints at 3.3 MPa (El Ezz, Moretti and Nollet, 2017). Wattle and daub construction as portrayed in Figure 3. involves weaving bamboo or twigs plastered with mud. This method is prevalent in the North Eastern States, parts of West Bengal, and the Andaman Islands, utilising abundant bamboo and cane resources (NIRDPR, 2005). Maintenance is simple, often requiring mud and straw without skilled labour. The compressive strength is 1.56 MPa and is suitable for earthquake-prone regions (Cuitiño, Maldonado and Esteves, 2015). With a U value of 1-2 W/m²k, the thickness can be adjusted by adding daub or plaster as needed for insulation. Bamcrete or Ekra panels as shown in Figure 4, are a modified version of the traditional wattle and daub panels plastered with cement plaster instead of mud, a common construction method in Northeast India (Dash and Gupta, 2022). These panels have been documented to have a life of approximately 100 years in the cold, dry climatic zone. The thermal properties of these panels have been recorded to be 6.2 w/m²k which is poor compared to conventional brick walls due to their low thickness (Dash, 2018).

The traditional method of burnt clay bricks and lime mortar takes longer to set, but it enhances durability. Suitable for temperate climates with moderate temperatures and low fire risk, this method has an average compressive strength of 8.9 MPa (Costigan and Pavía, 2013) and a U value of around 2 W/m²k (Camino-Olea et al., 2019) Adobe blocks depicted in Figure 5, is commonly seen in Indian rural areas. They are easily produced on-site and require no firing (Kulshreshtha et al., 2020). Formed by mixing mud with materials like straw or husk, the compressive strength of adobe varies from 0.5 MPa to 7 MPa (Dormohamadi and Rahimnia, 2020). The International Building Code mandates an average compressive strength of 2 MPa for adobe units. Adobe walls provide moderate insulation with a U value of around 2 W/m²k (Heathcote, 2011).

These discussed vernacular walling techniques use locally available resources and skills for construction, lasting up to a century with proper maintenance. Utilising materials like soil, stone, bamboo, and timber, abundant in respective regions, these methods offer cost-effectiveness and thermal comfort. However, societal shifts and perceptions of poverty, coupled with the demand for rapid construction and skilled labour scarcity, have led to their decline.

Figure 1. Cob wall making. (NIRDPR, 2005).

Figure 2. Stone masonry house. (NIRDPR, 2005).

Figure 3. Wattle & Daub. (Cuitiño, Maldonado and Esteves, 2015).

Figure 4. Ekra wall panel. (Dash and Gupta, 2022).

Figure 5. Adobe bricks. (NIRDPR, 2005).

1.2. Conventional Walling Systems

The current practices of walling in rural construction schemes are focused on "Pucca" materials such as burnt brick or stone packed with lime/cement mortar, cement bricks or concrete walls (National statistical office, 2018). Standardised materials like burnt brick, RCC, fly ash brick, and AAC blocks dominate mass housing projects, often overlooking local climate, geography, and resources. As government agencies prioritise cost-effective technologies, they promote pre-casting, cement blocks, and rattrap walling.

Burnt brick remains a staple in present day construction, with techniques like rat-trap bonds gaining popularity in PMAY and Nirmiti Kendra projects. Rat-trap bonds as depicted in Figure 6, involve placing bricks on the edge, reducing brick usage by 20% and cutting costs significantly. This technique enhances thermal comfort, supported by a U value of 1.4 w/m^2k and a masonry strength of approximately 3.5 MPa, attributed to the staggered joints (NIRDPR, 2005). Various government programs such as "Standupmitra" and PMAY, in India promotes fly ash blocks, made from waste by-products of thermal power stations. These blocks as shown in Figure 7 offer eco-friendly construction with less embodied energy than traditional bricks. These blocks provide superior thermal comfort with a U value of 1.79 w/m^2k and have three times the compressive strength of red or clay bricks, with a minimum strength of 10–12 N/mm^2 (Prabhat et al., 2019). Solid concrete blocks, commonly used in low-cost housing, offer cost-effectiveness and easy on-site casting, reducing transportation efforts (Bureau of Indian Standards, 2005). According to IS code specifications, these blocks vary in dimensions, but ensuring a minimum compressive strength of 4–5 MPa.

Hollow concrete blocks as shown in Figure 8 offer the advantages of lightweight and affordability. They can be conveniently cast on-site, reducing transportation efforts and fostering local economies (Bureau of Indian Standards, 2005). Typically made of cement and fly ash, these blocks feature two or three-hole cavities and are moulded using hydraulic presses. According to standards, their compressive strength ranges from 3.5 to 15 MPa. The U value is generally around 3 W/m^2K, attributed to the air cavity insulation (Bureau of Energy Efficiency, 2017). Precast concrete panels are a walling technology cast in a controlled environment before being transported to a construction site for installation. These panels are manufactured in a factory setting, under strict quality control measures, and are made to exact specifications. While these panels' strength varies with the design, they range between 27-55 MPa. In the present construction field, the materials used are mainly cement-based as they are weather resistant and fast setting, allowing for quick constructions.

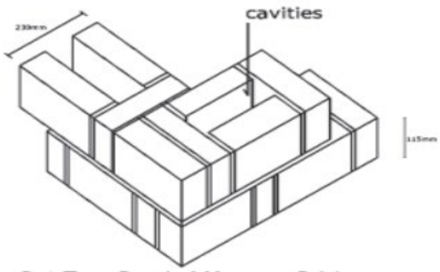

Figure 6. Rattrap Bond technique. (NIRDPR, 2005).

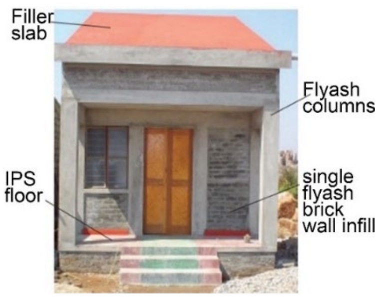

Figure 7. Fly ash house. (NIRDPR, 2005).

Figure 8. Hollow concrete block. (Ministry of Housing & Urban Affairs, 2021).

However, these materials and skillsets to employ it may not be available in remote areas. Another primary reason for its mass usage is that these technologies are characterised as “Pucca”, which appeals to the aspirations of the beneficiaries even though it may not be appropriate for the climate and geographic location and may not be economically viable.

1.3. Innovative Walling Systems

Innovations in the construction sector, driven by initiatives like the Global Housing Technology Challenge (GHTC) and Building Materials and Technology Promotion Council (BMTPC), aim to address the housing crisis. Many new technologies designed for urban housing are later applied to rural housing, overlooking the unique needs of rural communities. The new panels innovated through BMTPC, GHTC and institutional research are mainly aimed at government housing schemes and low-cost housing to address the housing shortage crisis. They have identified and standardised various innovative technologies the government aims to introduce into the mainstream housing construction sector. The BMTPC's Performance Appraisal Certificate documents were analysed to assess various aspects of innovative wall panels. The innovations prioritise thermal comfort, faster execution, and construction quality to align with present-day requirements.

The gypcrete rapid wall systems as shown in Figure 9 is constructed from gypcrete reinforced with micro-strand glass rovings, utilize phosphor-gypsum, water, and other chemicals (BMTPC, n.d.). With a compressive strength of 7.79 MPa and a flexural strength of 2.12 MPa, they offer reduced water absorption, sound transmittance, and fire retardation properties.

The QuikBuild panel system comprises a polystyrene insulating core laced into a welded wire space frame. The wall panel is positioned, and both sides are covered with concrete. The diagonal cross wires soldered to the welded-wire cloth on either side give the wall panel strength and stiffness. A truss behaviour is created due to this combination, providing stiffness and shear terms for a complete composite behaviour. They have a compressive strength of 350 kN/m and a thermal transmittance of 0.8 W/m^2K.

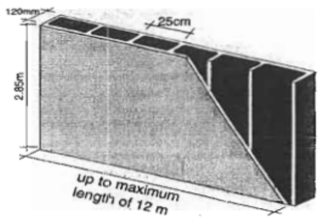

Figure 9. Gypcrete Rapid wall panel (BMTPC, n.d.).

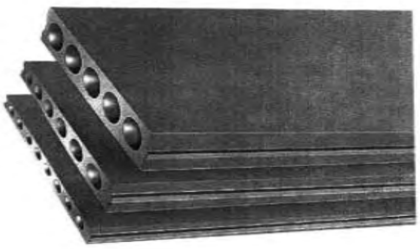

Figure 10. Walltec Hollow. (BMTPC, n.d.).

Walltec wall panels shown in Figure 10 are non-load bearing extruded concrete hollow core wall panels with a compressive strength of only 3.9 MPa and a flexural strength of 1.8 MPa.

Lightweight concrete comprised of river sand, crushed stone aggregate, lightweight aggregate, and regular Portland cement is used in the industrial production of Walltec wall panels. To minimise weight and enable mechanical, electrical, and plumbing services, hollows are integrated into Walltec walls, improving their ability to insulate against sound and heat. All panels have tongue and groove sides to aid in secure jointing. Aerocon panels are composite structures consisting of two fibre-reinforced cement face sheets enclosing a lightweight concrete core. With a compressive strength of 121 kN/m and flexural strength of 58 kg/m², they boast impressive thermal transmittance at 0.21 W/m²K and a fire resistance of 3 hours (BMTPC, n.d.). Rising EPS Cement Panels are lightweight composite sandwich panels consisting of EPS granule balls, cement, sand, fly ash, and bonding agents. Hollow in structure, they feature a front-facing of thin fibre cement/calcium silicate board. They offer a compressive strength of 5 MPa and flexural strength of 4.27 MPa. With a U value of 0.88 W/m²K and fire resistance of 4 hours, they provide efficient thermal insulation and robust fire protection. In the PIR Dry Wall Pre-Fab Panel system, two FCBs with a 10 mm thickness are filled in situ with polyisocyanurate insulation material to create straight, finished walls as demonstrated in Figure 11. The system must be combined with traditional columns and beams for pre-engineered column structures as the compressive strength is only 2.1 MPa and flexural strength is 4.7MPa. Effective insulation provided by the insulation core gives a U value of 0.033 W/mK (BMTPC, n.d.). Bamboo mat boards portrayed in Figure 12, are fabricated following IS:13958-1994 and can be used as infill walls. They are eco-friendly and consume less energy in production. These boards are 5-15mm thick and are estimated to have a life of 15 years (Ministry of Housing & Urban Affairs, 2021). Compressed stabilised earth blocks (CSEB) are made by mixing local soil with a small quantity of cement (up to 5%), sand, and water to stabilise it as demonstrated in Figure 13. It provides a sustainable alternative to burned clay bricks and cement concrete blocks since it is made from local soil. To achieve the appropriate strength, these blocks are compressed in a press and cured for 28 days.

Figure 11 Dry wall prefab. (BMTPC, n.d.).

Figure 12. Bamboo mat wall. (Ministry of Housing & Urban Affairs, 2021).

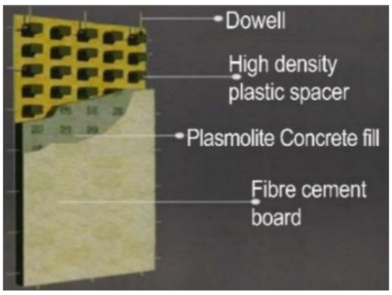

Figure 13. CSEB and machine. (Ministry of Housing & Urban Affairs, 2021).

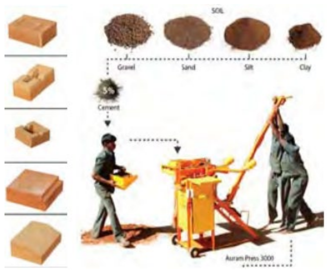

Figure 14. Plasmolite Wall panel. (BMTPC, n.d.).

Plasmolite Panels, employing High Impact Moulded Inserts, are formwork solutions featuring Fibre Cement Board sheets filled with lightweight foam concrete as illustrated in Figure 14. Offering a compressive strength of 70.35 kg/cm^2 and a U value of 0.25 W/mK, they integrate seamlessly with conventional column and beam construction, ideal for partition wall applications. Aerated Concrete Reinforced Panels are autoclaved aerated concrete panels made with fly ash, cement, gypsum, lime, sand, steel reinforcement, and anticorrosive paint. Ranging from 1 to 6 meters in length, they offer compressive strength ranging from 1.6 MPa to 5.6 MPa. Ideal for multi-story buildings, warehouses, shopping centres, and hospitals, AAC panels serve both load-bearing and non-load-bearing applications. With a U value of 0.7 W/m^2K, they are suitable for extreme climates, employing drywall construction without water for masonry (Bureau of Energy Efficiency, 2017). Ferrocement offers a much higher tensile strength-to-weight ratio than traditional reinforced concrete and improves cracking. It can be shaped into any form.

The technologies discussed above are utilized in both rural and urban areas, with their adoption often influenced by factors such as labour availability, local climate, perception, cost-effectiveness, and other considerations discussed above. However, determining the most appropriate walling systems for the rural Indian context requires a comprehensive evaluation. The need for tailored sustainability assessment tools that incorporate and prioritise social dimensions has been emphasized in research on social sustainability in rural contexts. Various studies have identified the unique challenges faced by rural communities and proposed indicators to evaluate social sustainability (Wan and Ng, 2018). To address this, the study develops a comprehensive evaluation matrix to assess the suitability of various traditional, conventional, and innovative walling technologies for rural housing. The matrix incorporates parameters spanning technical, environmental, and socio-economic dimensions, providing a robust framework for ranking walling systems based on their sustainability and contextual relevance. By identifying the most suitable walling solutions, this study aims to inform stakeholders and policymakers in selecting materials that enhance the quality and sustainability of rural housing.

The novelty of this study lies in its application of the multi-criteria decision-making method to evaluate and rank walling techniques most appropriate for rural, areas as well as sustainable tier 2 and tier 3 cities. This integrative approach combines a comprehensive literature review, expert surveys, and established benchmarks like ECBC, NBC, and IS codes to identify and rank walling systems across technical, environmental, and socio-economic parameters.

By bridging the gap between policy-driven innovations and practical realities, the research contributes to sustainable rural development, offering a replicable framework to guide construction practices in rural areas.

2. Literature Review

The Multi-Criteria Decision-Making method allows a framework to analyse various options based on a set of parameters important to the situation and context. This section dwells into the TOPSIS method used for evaluating construction materials, providing a foundation for the methodological approach adopted in this study.

2.1. Selection of MCDM method for evaluation

MCDM comprises of a range of methodologies designed to evaluate multiple, often conflicting, criteria in decision-making. These methods facilitate the selection, ranking, classification, or assessment of alternatives within a structured framework. MCDM is particularly well-suited for this study as it enables the integration of both quantitative and qualitative factors influencing housing affordability and sustainability into a single, comprehensive evaluation process. With a wide range of MCDM methods available, no single approach is universally applicable to all decision-making scenarios (Mulliner, Smallbone and Maliene, 2013). Additionally, the chosen MCDM technique should be intuitive and easy to implement, ensuring that stakeholders can readily adopt and apply the methodology in practical decision-making contexts (Mousavi-Nasab and Sotoudeh-Anvari, 2018). This study employs the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method to evaluate the sustainability of various walling techniques across technical, environmental, and socio-economic parameters. TOPSIS was chosen for its ability to rank alternatives based on their proximity to an ideal solution and distance from a negative-ideal solution, making it particularly suited to evaluations where target values are critical benchmarks (Zhang et al., 2010).

2.2. Establishing of Criteria for Evaluation

The criteria for evaluation were derived through an extensive literature review and organized into three dimensions, Technical, Environmental and Socio-Economic. Research conducted by various authors offers a thorough insight into the factors impacting urban and rural areas. Studies in highlight the equilibrium needed among technical, environmental, and socio-economic factors in choosing materials and designing processes (Akadiri, Olomolaiye and Chinyio, 2013).

Technical criteria serve as foundational standards for walling technologies to be recognized as viable by organizations such as BMTPC and BIS. These criteria encompass several essential parameters, including strength, thermal properties (K-value), fire resistance and durability (BSi, 1992; Bureau of Energy Efficiency, 2017; BMTPC, n.d.). Compliance with these standards is critical for ensuring safety and efficiency. Traditional construction techniques in India, have been employed for centuries, showcasing strength, durability, and adaptability to local climates. However, these methods often lack standardization according to modern building codes, which can hinder their broader acceptance and application in contemporary construction practices (Ministry of Housing & Urban Affairs, 2021). Another major aspect is the ease of construction or the buildability using the technique, that needs to be contextual based on the changing times (Calkins, 2009). The necessity of selecting materials that can withstand environmental pressures and reduce the need for frequent replacements has been increasingly recognized for long-term sustainability (Singhaputtangkul et al., 2014) (Pawar, 2021). Further, the Government Orders for rural structures state that the constructions should be made using local and alternative technologies and that the reliance on cement and steel should be reduced (Ministry of Rural Development, 2016). The environmental impact of materials, particularly in terms of energy consumption, embodied energy, and pollution effects, has gained increasing attention in sustainability evaluations (Sánchez-Garrido, Navarro and Yepes, 2022). Further the impact created during the disposal of the material or demolition of the structure should be minimal (Beder, 2006). Implementation of construction methods that promote recycling and reuse of materials, is being promoted through various government guidelines in rural infrastructure (Yuan et al., 2021; Paryavaran Bhawan, Road and Delhi, n.d.).

In rural areas socio-economic factors play a crucial role in ensuring project feasibility and community acceptance, with particular emphasis on cost effectiveness and cultural significance. The overall cost implications of different technologies, including initial investment, maintenance and affordable solutions are crucial for rural communities with limited financial resources (Wong et al., 2006; MoRD, 2022). The image perception of certain technologies being symbols of poverty and certain other techniques like cement and steel being status symbols encourage people to make choices in construction even though it may not be suitable, appropriate for their context (Kulshreshtha et al., 2020). Utilizing traditional materials and techniques can help preserve local architectural heritage and cultural identity, which is particularly important in rural areas where community history is closely tied to its built environment (Manandhar, Kim and Kim, 2019). Further, the use of local material is essential especially in rural context due to supply chain disruptions and to reduce transportation costs (KR and GP, n.d.).

Thus, combining the understandings from the literature review, Table 1 consolidates the various sub-criteria within socio-economic, environmental, and technical dimensions pertaining mainly to the appropriateness of walling methods within rural areas.

Table 1. Sustainable assessment parameters for building material selection. (By Authors)

Technical criteria *(BSi, 1992; Bureau of Energy Efficiency, 2017; BMTPC, n.d.), (Calkins, 2009)*	**Environmental criteria** *(Singhaputtangkul et al., 2014), (Pawar, 2021), (Ministry of Rural Development, 2016), (Sánchez-Garrido, Navarro and Yepes, 2022)*	**Social-economic criteria** *(Wong et al., 2006)*,*(MoRD, 2022), (Kulshreshtha et al., 2020), (Manandhar, Kim and Kim, 2019), (KR and GP, n.d.)*
• Strength/Force • K value • Fire resistance	• Potential for recycling and reuse	• Maintenance cost • Cultural Preservation • Image/ Aesthetics

• Durability • Ease of Construction	• Environmentally sound disposal options • Pollution created • Embodied energy	• Use of local material • Labor availability

This examination of the literature highlights the importance of modifying rural construction practices to be more integrated, sustainable, and buildable. It requires decision-making matrixes that can successfully incorporate technical efficiency, environmental sustainability, and socio-economic consequences.

3. Methodology

This study employs the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to evaluate the sustainability of 23 walling techniques for rural housing. The methodology involved is demonstrated in Figure 15.

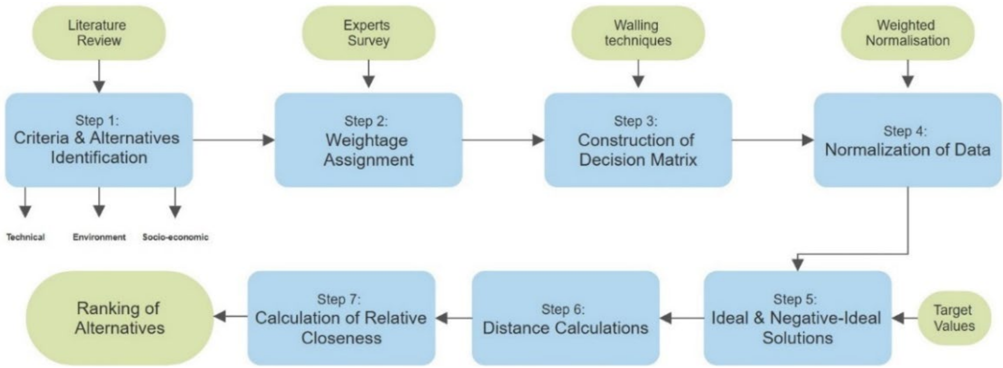

Figure 15. Methodology for developing matrix using TOPSIS. (By Authors).

3.1. Criteria and Alternatives Identification

The comprehensive literature review conducted were able to establish the evaluation criteria and alternatives as discussed in Table 1. The alternatives include 23 walling techniques, spanning traditional methods (e.g., Cob, Wattle and Daub), conventional methods (e.g., Brick and Cement), and innovative panels (e.g., GFRG, Quik Build Panels).

3.2. Weightage Assignment through Expert Survey

To ensure that the evaluation framework reflects the practical realities of rural construction, a survey was conducted among architects, engineers, contractors, and masons working in rural and peri-urban contexts. The survey aimed to gauge their responses regarding walling techniques, identify challenges in rural construction, and assign weightages to the socio-economic parameters used in the evaluation. Participants were selected through a convenience sampling method shown in Figure 16 based on their availability and affiliation with the National Institute of Rural Development and Panchayati Raj (NIRD & PR), which is a limitation due to the sample size.

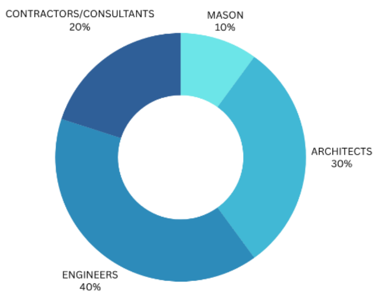

Figure 16. Survey participants. (By Authors).

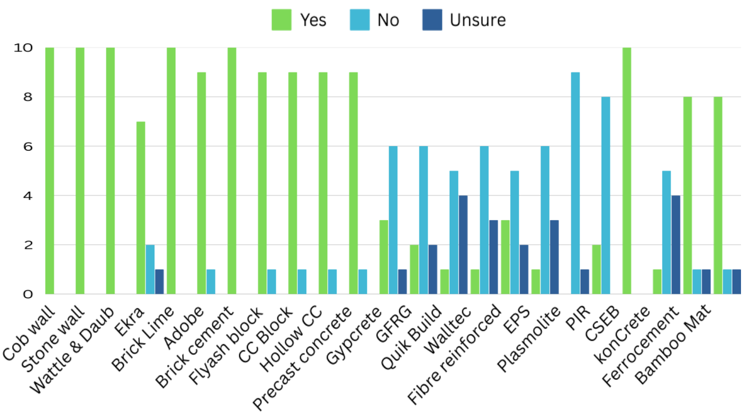

Figure 17. Awareness of the various wall panels. (By Authors).

Participants were surveyed on their awareness, usability, and the challenges of using these technologies and the results are represented in Figure 17. Participants rated each aspect as High, Medium, or Low based on their professional experience. To quantify the qualitative responses, these ratings were converted into numerical values: High = 15, Medium = 10, and Low = 5. The survey revealed significant gaps in the familiarity and adoption of innovative walling techniques such as GFRG and Quik Build Panels, while traditional methods like Cob and CSEB were more widely recognized. Additionally, challenges such as labour unavailability in remote areas, high maintenance costs, and limited material accessibility were identified as critical factors influencing construction choices. These insights were instrumental in refining the socio-economic parameters and assigning weights to reflect their relative importance in the rural context. Respondents were asked to rate the importance of socio-economic criteria on a scale of 1 to 5. The aggregated responses were used to calculate the weightages for these criteria using the TOPSIS formula:

$$W_j = \frac{\sum_{k=1}^{n} r_{jk}}{\sum_{j=1}^{m} \sum_{k=1}^{n} r_{jk}} \tag{1}$$

where W_j is the weight for the j^{th} criterion, r_{jk} is the rating given by the kth expert for the j^{th} criterion, n is the number of experts, and m is the total number of criteria.

Weightage Allocation

The weightage allocated are shown in Table 2. The technical parameters were assigned equal weightage as they are considered as fundamental requirements for any walling technology, ensuring compliance with standards set by BMTPC, National Building Code, and other guidelines. Similarly, the environmental parameters were also given equal weightage to align with increasing governmental emphasis on sustainability and the need to reduce the environmental footprint of construction practices. The socio-economic parameters, however, distinguish the suitability of technologies in the rural Indian context, where factors such as affordability, availability, accessibility, and image often dictate construction choices. The weightages for socio-economic criteria were derived from the expert survey, reflecting their relative importance in rural construction as per the given formula. This approach ensures that while technical and environmental parameters establish baseline requirements, socio-economic parameters play a pivotal role in determining overall suitability.

Table 2. Weightages assigned to criteria. (By Authors)

Criteria	Technical					Environmental				Socio-Economic					
	Strength	U-value	Fire Resistance	Durability	Ease of Construction	Embodied Energy	Reusability	Disposal Options	Impact During Harvest	Awareness of Technology	Local Producibility	Status/Image	Skill Labor Availability	Cultural Preservation	Maintenance
Final	0.0666	0.0666	0.0666	0.0666	0.0666	0.0668	0.0668	0.0668	0.0668	0.068	0.068	0.064	0.064	0.064	0.072

3.3. Construction of Decision Matrix

A decision matrix was created, listing the raw values of 23 walling techniques against the identified criteria. Data were collected from standards, certifications, and expert survey inputs as shown in Table 3.

Table 3. Data for parameter and its sources. (By Authors)

Group	Criteria	Source for Raw Values
Technical	Strength	Literature, PAC certificates
	U-value	Literature, ECBC
	Fire Resistance	Literature, PAC certificates
	Durability	Literature
	Ease of Construction	Literature, Expert survey
Environmental	Embodied Energy	Literature
	Reusability	Literature, Expert survey
	Disposal Options	Expert survey
	Impact During Harvest	Literature, Expert survey
Socio-Economic	Awareness of Technology	Expert survey
	Local Producibility	Expert survey
	Status/Image	Literature, Expert survey
	Skill Labor Availability	Expert survey
	Cultural Preservation	Literature, Expert survey
	Maintenance	Expert survey

3.4. Normalization of Data

The raw data were normalized to make them dimensionless and comparable using the formula:

$$N_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (2)$$

where x_{ij} represents the raw value of the i^{th} alternative for the j^{th} criterion.

3.5. Weighted Normalization

The normalized values were multiplied by the respective weights to account for the relative importance of each criterion:

$$WN_{ij} = W_j \times N_{ij} \quad (3)$$

3.6. Determination of Ideal and Negative-Ideal Solutions

The ideal positive solution (A^+) and ideal negative solution (A^-) were determined using:

1. Target values set by standards (e.g., NBC, IS codes, and ECBC), where available, as shown in Table 4. The target values serve as references to evaluate how well each walling technique aligns with the desired performance thresholds.

Table 4. Target Values for technical parameters. (By Authors)

Parameter	**Force**	**K value**	**Fire Safety**	**Durability**
Recommended Target value	800	0.09	1	50
Standard or Code	IS Code	ECBC	NBC	NBC

2. The traditional TOPSIS approach, where for beneficial criteria (e.g., strength), the ideal solution (A^+) is the maximum value, and the negative-ideal solution (A^-) is the minimum value. For non-beneficial criteria (e.g., U-value), the ideal solution (A^+) is the minimum value, and the negative-ideal solution (A^-) is the maximum value.

3.7. Distance Calculations

The Euclidean distance of each alternative from the ideal (S_i^+) and negative-ideal (S_i^-) solutions was calculated using:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (WN_{ij} - A_j^+)^2} \qquad S_i^- = \sqrt{\sum_{j=1}^{n} (WN_{ij} - A_j^-)^2} \tag{4}$$

3.8. Calculation of Relative Closeness to the Ideal Solution

The relative closeness (C_i^*) of each alternative to the ideal solution was computed:

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{5}$$

3.9. Ranking of Alternatives

The walling techniques were ranked based on their relative closeness (C_i) to the ideal solution. Techniques with higher (C_i^*) values are considered more suitable for rural housing.

4. Results and Findings

This section presents the raw data and survey findings, which serve as the foundation for evaluating the performance of various walling systems against the selected criteria. The analysis incorporates both quantitative and qualitative parameters derived from literature, performance certificates, codes, and expert surveys. For technical and environmental criteria, values were extracted from standards, performance appraisal certificates and relevant literature. In cases where qualitative data were required, assessments were conducted through the survey of experts. To quantify qualitative data, the High-Medium-Low (H/M/L) ratings assigned by experts in the survey were translated into numerical values of 15, 10, and 5, respectively. This ensured consistency and comparability across all parameters. The ideal and non-ideal values selected as per the methodology, are also given Table 5 below.

Table 5. Raw Data for the Walling techniques for various parameters (Literature & Survey) (By Authors)

WALLING		**TECHNICAL**					**ENVIRONMENTAL**				**SOCIO-ECONOMIC**					
		Force	K-value	Fire	Durability	Buildability	Embodied energy	Reusability/Recyclability	Sustainable disposal	Pollution	Awareness	Local producibility	Status/ Image	Skill Labour availability	Cultural Preservation	Maintenance
	Ideal Value	800	.092	1	50	15	0.11	15	15	5	15	15	15	5	15	5
	Least Ideal Value	45	0.8	0.33	15	5	6.8	5	5	15	5	5	5	15	5	15
	Units	kN	w/mk	hours	years	H / M/ L	MJ/kg	H / M/ L	H / M/ L	H / M/ L	H / M	H / M	H / M	H / M/ L	H /M/ L	H / M/ L

											/L	/L	/L			
1	Cob wall	774	0.18	3	100	5	0.46	15	15	5	15	15	5	15	15	15
2	Stone wall	19920	0.24	2	200	5	0.44	15	15	15	15	15	10	15	15	5
3	Wattle & daub	187.2	0.1524	0.6	35	5	1	15	15	5	15	15	5	10	15	15
4	Ekra wall	200	0.6096	1	120	15	0.3	15	15	5	15	15	15	5	15	5
5	Brick & lime	2047	0.207	0.8	80	10	6	5	5	10	10	10	15	15	15	5
6	Adobe wall	460	0.207	3	25	5	2	15	15	5	15	15	5	15	15	15
7	Brick& cement	805	0.322	2	55	15	6	5	5	15	15	10	15	15	10	5
8	Fly ash block	2750	0.414	6	75	15	0.83	10	10	10	15	5	10	15	5	5
9	CC block	337.5	0.805	5	60	15	1.3	5	5	15	15	5	15	15	5	5
10	Hollow CC	690	0.69	5	60	15	3.6	5	5	15	15	5	15	15	5	5
11	Precast concrete panel	9200	0.69	5	60	5	2.6	5	5	15	15	5	15	15	5	5
12	Gypcrete rapid wall panel	936	0.36	5	60	10	2.6	5	5	15	5	5	15	15	5	5
13	GFRG panel	160.952	0.39	4	60	10	1.3	5	5	15	5	5	15	15	5	5
14	Quik build panels	350	0.08	5	60	10	2.6	5	5	15	5	5	15	15	5	5
15	Walltec Hollow Core Concrete Wall	975	0.3	5	60	10	3.7	5	5	15	5	5	15	15	5	5
16	Prefab fibre reinforced Sandwich Panels	121	0.0252	5	65	10	6.8	5	5	15	5	5	15	15	5	5
17	Rising EPS (Beads) Cement Panels	750	0.108	0.33	90	10	2.6	5	5	15	5	5	15	15	5	5
18	Plasmolite Wall Panels	1074.4	0.0625	8	90	10	2.6	5	5	15	5	5	15	15	5	5
19	PIR dry wall prefab	189	0.000396	5	90	10	2.6	5	5	15	5	5	15	15	5	5
20	CSEB	1260	0.184	2	60	15	0.11	15	15	10	10	15	10	15	10	5
21	konCrete	720	0.07	5	60	10	2.6	5	5	15	5	5	15	15	5	5
22	Ferrocement panels	337.5	0.9	3	35	10	2.3	5	5	15	15	5	15	15	5	10
23	Bamboo mat wall	45	0.0372	0.5	15	10	4	10	10	5	15	10	5	10	10	10

The raw data were normalised and processed as per equations (2) and (3). Example shown in Table 6:

Table 6. Weighted normalised values. (By Authors)

	Force	**U-value**	**Fire safety**	**Durability**	**Ease of construction**	**Embodied energy**	**Reusability/Recylcability**	**Sustainable disposal**
FINAL WEIGHTS	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067
Cob wall	0.002	0.001	0.010	0.018	0.006	0.002	0.023	0.023

The weighted normalised values were then used to find the Euclidean distance of each alternative from the ideal by applying the formula (4) and (5). The resultant values are given below in Table 7. This analysis highlights the most suitable walling techniques for rural housing among those reviewed, ranking them from 1 to 10, where 1 is the best performing.

Table 7. Ranking of various walling techniques as per TOPSIS. .(By Authors)

WALL TYPE	S+	S-	C_i	RANK
CSEB	0.013	0.049	0.796	1
Ekra wall	0.015	0.056	0.792	2
Fly ash block	0.028	0.048	0.634	3
Wattle & daub	0.027	0.043	0.616	4
Cob wall	0.031	0.046	0.601	5
Adobe wall	0.029	0.041	0.592	6
Stone wall	0.065	0.083	0.562	7
CC block	0.035	0.042	0.543	8
GFRG panel	0.037	0.037	0.502	9
Precast concrete panel	0.046	0.045	0.497	10
Bamboo mat wall	0.030	0.029	0.492	11
Hollow CC	0.038	0.037	0.491	12
Plasmolite Wall Panels	0.044	0.042	0.488	13
PIR dry wall prefab panel	0.039	0.036	0.479	14
Gypcrete rapid wall panel	0.039	0.035	0.472	15
konCrete	0.039	0.035	0.471	16
Quik build panels	0.039	0.035	0.471	17
Rising EPS (Beads) Cement Panels	0.037	0.033	0.469	18
Brick & lime	0.037	0.032	0.468	19
Brick& cement	0.037	0.032	0.461	20
Ferrocement panels	0.036	0.030	0.454	21
Walltec Hollow Core Concrete Wall	0.041	0.032	0.444	22
Prefab fibre reinforced Sandwich Panels	0.048	0.029	0.380	23

The TOPSIS analysis ranked CSEB and Ekra Wall Panels as the most suitable for rural contexts due to strong socio-economic performance and satisfactory technical and environmental scores.

5. Limitation

The study is limited by the small sample size of the expert survey, which may not fully represent the broader construction industry. Additionally, the qualitative assessment of certain socio-economic parameters introduces a degree of subjectivity into the evaluation process.

6. Conclusion and Way Forward

The findings indicate that CSEB and Ekra wall panels emerge as the most suitable option for rural housing construction due to their durability and local availability. These technologies will also enable the selection of appropriate construction methods in sustainable tier 2 and tier 3 cities. Emerging technologies from organizations like BMTPC and GHTC, despite their innovative nature, appear more suited to urban contexts owing to the specialized materials and skillsets required for their manufacture and installation. Modernizations such as prefabricated concrete panels, while addressing issues of strength and durability, must account for local availability and thermal comfort, rendering them less suitable for many contexts in India. The current market approach of a "one size fits all" for wall panels does not align with the practicalities of rural areas, where diverse socio-economic factors significantly influence suitability. Addressing these gaps presents an opportunity to develop tailored technologies that are cost-effective, durable, and accessible, thus contributing substantially to solving the rural housing crisis. The proposed matrix serves as a valuable tool for material selection in such constructions, considering essential parameters, such that the materials chosen align with the specific needs of rural housing.

Developing a parameter-specific housing evaluation matrix will facilitate the identification of suitable construction technologies, enabling the development of methods that are appropriate to the geographical and social context. Further research on the social acceptance of existing wall panels is necessary to better understand the housing needs of rural populations. Future research should focus on expanding the survey scope to include a larger, more diverse participant pool and exploring dynamic weighting systems to account for regional and temporal variations. Such studies will help tailor housing solutions that not only meet technical and environmental criteria but also align with the social and economic realities of the communities they are intended to serve. In conclusion, this study underscores the importance of a multi-criteria decision-making approach in selecting sustainable and appropriate walling systems for rural contexts by incorporating a diverse set of parameters. By adopting a holistic approach that encompasses these dimensions, the rural infrastructure can progress towards a more sustainable future, supporting community well-being and growth.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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