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# INTEGRATING MATERIAL PERFORMANCE AND PEDESTRIAN EXPERIENCE IN SRI LANKA: A REVIEW OF BIO-BASED WOOD-CLAY COMPOSITES IN LANDSCAPE ARCHITECTURE

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## *ABSTRACT*

*Assessing the urban potential of bio-based materials requires a transdisciplinary evaluation framework that bridges the mechanical durability of civil engineering with the sensory microclimatic and aesthetic goals of Landscape Architecture. Using a systematic literature review following the PRISMA 2020 guidelines, this study synthesizes global knowledge on wood-clay composites (WCC) as low-impact pedestrian paving systems. Peer-reviewed studies published between 2010 and 2025 were analysed to synthesize knowledge on material properties and composition, mechanical and thermal behaviour, and aesthetic and sensory qualities. Findings indicate that appropriate incorporation of sawdust enhances porosity, reduces thermal conductivity, and maintains structural stability. Thereby offering a dual benefit of environmental adaptation and pedestrian comfort. Surface attributes such as texture, roughness, and visual coherence were identified as critical mediators of walking satisfaction and safety perception. Despite these advances, gaps persist in integrating multi-dimensional evaluation frameworks that link structural performance, microclimate adaptation, and human-centered design, particularly in real urban contexts. The study proposes a Multi-Dimensional Pedestrian Pavement Framework (MDPPF)***,** *emphasizing the interplay of material properties, thermal and hydrological behaviour, and sensory-aesthetic parameters to inform evidence-based landscape architectural decision-making. Future research should prioritize field-based validation, pedestrian-centered design interventions, and low-energy bio-based material stabilization strategies to foster paving systems that simultaneously advance walkability, urban thermal regulation, and aesthetic quality. This review contributes to a transdisciplinary understanding of sustainable paving, bridging technical feasibility with human experience and urban design excellence, and offers conceptual pathways for integrating bio-based composites into pedestrian-oriented landscapes.*


***Keywords:*** *Landscape Architecture; Material Performance; Regenerative Design; Sustainable Paving; Wood-clay composites (WCC).*

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# 1. INTRODUCTION

Sustainability and climate adaptation have become central challenges within contemporary construction and urban development. That requires systematic changes in product design and societal consumption patterns (Huisingh et al., 2015). In landscape architectural discourse, the ground surface is not merely a technical layer but a spatial and experiential element that contributes to placemaking, visual coherence, and public realm quality. It encompasses thermal comfort, tactile feedback, visual rhythm, and the emotional response evoked by material expression for paving (Fonseca et al., 2025).

Pedestrian walkability is compromised by thermal discomfort and aesthetic monotony in urban environments. Pavement surface temperatures reach as high as 48-67 °C under high solar exposure (Santamouris et al., 2012). Standard Walkability Indexes ignore surface temperature, which is a primary deterrent in tropical climates like Sri Lanka. High solar radiation, monsoon rainfall, and humidity significantly influence pavement performance and pedestrian comfort. Advanced paving solutions, such as high albedo, permeable, and heat handling materials, have demonstrated effectiveness in mitigating urban heat island (UHI) in developed countries (Lin et al., 2013).

While most of the current literature covers concrete and natural stone, there is a significant gap in bio-composites such as WCC. WCC has emerged as a promising paving material that uses waste wood and natural clay. Substantial quantities of wood waste end up in landfills, limiting reuse and recycling opportunities (Falk, 2002). Converting wood waste into manufactured composites enhances material performance and aligns with sustainability, enabling versatile applications (Maier, 2021). In addition, the utilization of wood waste in WCC supports circular economy principles by reducing material disposal while creating value-added products for sustainable urban infrastructure.

The aim is to review and synthesize existing knowledge on WCC through a multidisciplinary approach that bridges material science, structural performance, and landscape design principles. This research undertakes a conceptual evaluation of WCC within climate-responsive and pedestrian-centered landscape architectural frameworks. The study examines their environmental responsiveness, thermal and mechanical characteristics, and their implications for pedestrian-scale spatial experience, thereby assessing their suitability for sustainable landscape applications.

Research objectives (RO) are based on,

- RO 1- Establish a multi-dimensional landscape evaluation framework for pedestrian paving systems using a systematic, PRISMA-compliant literature review strategy
- RO 2- Review the existing knowledge of composition, material properties, and manufacturing methods of WCC.
- RO 3- Examine how pavement aesthetics and sensory qualities have been conceptualized and assessed within landscape architectural theory and practice.
- RO 4- Identify knowledge gaps, technical limitations, and research opportunities for multidisciplinary applications.

# 2. METHODOLOGY

## 2.1 RESEARCH APPROACH

This study builds a systematic literature review, following the 'PRISMA 2020' guidelines, to synthesize knowledge on bio-based WCC as sustainable paving materials. The review integrates materials science, sustainability considerations, and landscape architectural perspectives on paving materials to provide a comprehensive understanding of existing research directions and to understand knowledge gaps.

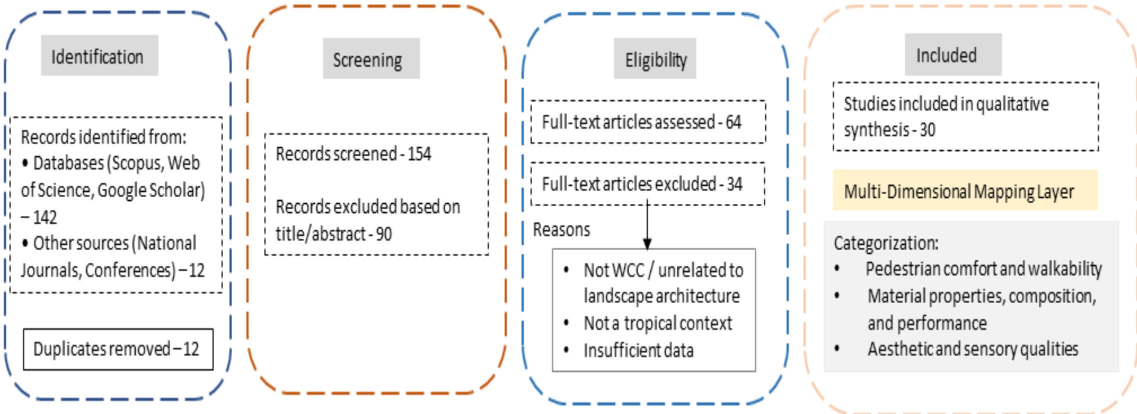


*Figure 1: PRISMA 2020 flow diagram adapted for the systematic review*

*Note: During the initial title and abstract screening, 90 records were excluded due to lack of relevance. Of these, 54 studies focused on WCC applications for heavy vehicular loads or structural masonry walls, while 36 examined non-clay polymer-based systems (Wood-Plastic Composites), which did not align with the focus of the study on pedestrian landscape paving.*

## 2.2 SEARCH STRATEGY

Given the niche focus of WCC relevant to landscape architecture aspects, the literature search included Scopus and Web of Science, Google Scholar, peer-reviewed national journals, and relevant conference proceedings to ensure a comprehensive coverage of all available studies. In order to ensure methodological reproducibility, the exact search string used in the primary search was formulated based on the following keywords:

(ALL("wood-clay composite*") OR ALL("sawdust-clay") OR ALL("bio-brick*")) AND ALL("paving" OR "pavement*" OR "walkability" OR "landscape architecture" OR "urban design")

## 2.3 ARTICLE SELECTION CRITERIA

The articles were selected according to the criteria mentioned in Table 1 to ensure quality, relevance, and alignment with the research objectives.

*Table 1: Selection criteria with rationale*

| Inclusion | Exclusion | Rationale |
|---|---|---|
| Peer-reviewed articles published in English | Non-English publications | Ensures scientific rigor and accessibility, avoids translation errors |

| Inclusion | Exclusion | Rationale |
|---|---|---|
| Published between 2010 and 2025 | Published before 2010 | To capture advances in mineral-bonding stabilizers and ecological urban drainage, earlier studies (pre-2010) mainly treated WCC as high-temperature fired industrial blocks, overlooking newer ambient-cured, low-carbon methods and user-experience factors important in modern landscape design. |
| Focus on WCC, wood waste, or clay-based paving, paving materials, durability, and pedestrian comfort | Studies unrelated to WCC paving, landscape architecture, or urban walkability | Ensures relevance to the research topic and ROs |
| Studies evaluating material properties, sustainability, aesthetic qualities, or pedestrian comfort | Conference abstracts only | Ensures sufficient detail for systematic analysis and thematic synthesis |

*(Source: Compiled by author)*

### 2.4 DATA EXTRACTION AND ANALYSIS

Data were extracted from each selected study, including details on author(s) and year, country or region, material composition (wood and clay), manufacturing methods, sustainability and performance, and aesthetic or pedestrian comfort assessments. The thematic synthesis was structured into three main codes directly linked to the research objectives:

- Pedestrian comfort, walkability indices, and tactile baselines, derived from established environmental psychology frameworks
- Material composition, properties, and manufacturing performance (including fired vs. ambient-stabilized pathways)
- Aesthetic qualities and sensory indicators

The results were interpreted within the framework of landscape architectural principles and sustainable urban design, complemented by insights from engineering knowledge.

## 3. RESULTS AND DISCUSSION

### 3.1 PEDESTRIAN COMFORT AND WALKABILITY

Walkability is defined as the degree to which a built environment supports and encourages people to move, socialize, and spend time comfortably within a particular area (Rafiemanzelat et al., 2017). Several studies review strategies designed to enhance pedestrian safety and comfort in urban fabric. It highlights key design interventions such as expanding sidewalks, creating pedestrian-only zones, and integrating green spaces into urban layouts (Seferoğlu & Allahverdiyev, 2025).

In addition, research on campus landscapes emphasizes that four core factors shape pedestrian comfort and walkability (Harun & Nashar, 2017) which are comfort, connectivity, safety, and accessibility. These factors stress the importance of climate-responsive streetscapes, adequate shading, continuous pedestrian networks, and safe crossings to enhance mobility and overall well-being. Under streetscape physical elements, pavement plays a fundamental role in determining pedestrian comfort and walkability.

Different urban landscape qualities are categorized into three main categories (Salem et al., 2022), which are safety and security, comfort, and level of interest. Adequate lighting, traffic calming measures, separation from vehicles, clear wayfinding, unobstructed visibility, durable materials, and well-maintained, non-slip paving collectively enhance pedestrian safety and security (Salem et al., 2022). Indicators like 'comfort' and 'interest' root back to restorative environment theories, suggesting pedestrians subconsciously seek spaces that minimize psychological fatigue (Kaplan, 1995). Consequently, features like greenery and clear wayfinding act as essential environmental affordances that reduce cognitive load, rather than merely serving aesthetic functions (Kaaronen, 2017).

Comfort is increased by continuous, connected sidewalks and environmental affordances for all users. Thermal regulation through shade-providing trees, which ensures a pedestrian-friendly environment across different seasons (Vasilikou & Nikolopoulou, 2020).The presence of greenery, particularly street trees, improves visual preference, softens harsh urban features, and creates a sense of enclosure and restorative potential. In turn, encourages longer and more frequent walking trips (Scopelliti et al., 2019). Integrating these qualities in urban landscapes creates an environment that supports pedestrian movement and enhances the walking experience. It also promotes sustainable and walkable streetscapes (Hadavi et al., 2015).

## 3.2 MATERIAL PROPERTIES, COMPOSITION AND MANUFACTURING PERFORMANCE

Scholars have demonstrated that pore-forming organic waste, such as sawdust, fly ash, rice husk, and sugarcane bagasse, increases porosity and reduces bulk density. That is a potential to enhance thermal insulation (Benjeddou, 2025; Dondi et al., 2010; Faria et al., 2012). Sawdust content of 10% achieve compressive strength of 21.2 MPa while maintaining a permeability coefficient of 0.0556 m/s. That condition is suitable for paving of light-weight traffic and pedestrians. Also, scholars found that small additions of sawdust (1%) improved tensile and shear strength and reduced swelling potential of clay by 20% to 32% (Abu Zeid, 2020). It suggests that the mechanical threshold varies with the indentation application.

The base clay used across these studies is typically characterized by high concentrations of silica ($SiO_2$) and alumina ($Al2O_3$), reporting levels 50.47% and 19.14%, respectively (Shafiquzzaman et al., 2022). This profile is suitable for brick manufacturing due to its stability during firing. Raw sawdust is enriched with cellulose and organic matter. This acts as a combustible pore-forming agent during firing that increases porosity from 7.4% to as high as 56.7% at a 20% sawdust mixing ratio. Sawdust ash functions as a chemical stabilizer. It possesses a lower specific gravity compared to clay.

While raw sawdust is valued for its ability to reduce thermal conductivity and bulk density, dropping from 2090 kg/m3 to ~1398 kg/m3 in fired bricks (Benjeddou, 2025). It inherently compromises mechanical strength as the organic fibres create voids. This differs from ash-stabilized systems, where, at low concentrations (4%), the chemical integration actually boosts California Bearing Ratio (CBR) values by over 103%. Sawdust particle sizes also affect the properties of paving. Table 2 categorizes the effects of different gradations on the structural and functional performance of WCC.

*Table 2: Particle size performance grid*

| Category | Particle Size | Primary Material Application | Impact on Mechanical Strength | Impact on Physical/Functional Properties |
|---|---|---|---|---|
| Fine | 0.5 mm (Shafiquzzaman et al., 2022)<br>212-300 µm (Jannat et al., 2021)<br><600 µm ash (Butt et al., 2016) | Fired permeable bricks<br>Unfired clay blocks<br>Subgrade stabilization | 21.2 MPa at 10% sawdust (Shafiquzzaman et al., 2022)<br>4.09 MPa at 2.5% (Jannat et al., 2021)<br>+26% Unconfined Compressive Strength (UCS) at 4% Sawdust ash (Butt et al., 2016) | Higher Porosity, absorption, and permeability<br>↓ Density<br>Swelling reduction (Abu Zeid, 2020) |
| Medium | 0.75-1.0 mm (Shafiquzzaman et al., 2022)<br>425-600 µm (Jannat et al., 2021) | Permeable pavement units<br>Lightweight fired bricks<br>Optimized unfired blocks | **Optimal strength-porosity balance**<br>4.74 MPa UCS (Jannat et al., 2021)<br>21.2 MPa at 10% Sawdust (Shafiquzzaman et al., 2022) | Controlled porosity<br>Moderate permeability<br>Improved thermal performance (Benjeddou, 2025) |
| Coarse | 1.5 mm (Shafiquzzaman et al., 2022)<br>1.18-2.00 mm (Jannat et al., 2021) | Experimental permeable blocks | Strength reduction<br>10.2 MPa (1.5 mm) (Shafiquzzaman et al., 2022)<br>3.90 MPa at 2.5% (Jannat et al., 2021) | Excessive porosity<br>Highest permeability<br>Reduced structural integrity |

*Note: Locally available Sri Lankan timber wastes may exhibit different physical, chemical, and hygroscopic behaviours compared to species such as Deodar (*Cedrus deodara*) or Kail (*Pinus wallichiana*) used in previous studies.*

### 3.3 AESTHETIC AND SENSORY QUALITIES

Aesthetic and sensory qualities extend beyond functional safety to influence emotional comfort and a sense of place. Material selection for the particular landscape should balance functionality, aesthetics, and heritage preservation (da Silva & Pereira, 2022). Pedestrian comfort involves emotional responses to paving materials and the quality of the walking environment. A Pilot Study introduced paving attributes in Braga (Silva et al., 2025). The study evaluated five primary surface parameters (Table 3).

*Table 3: Paving attribute measuring parameters*

| Parameter | Description | Measuring method |
|---|---|---|
| Roughness | Surface unevenness | 3m straightedge + laser sensor |
| Friction | Slip resistance | British Pendulum Tester (BPT) |
| Texture | Surface depth and drainage capacity | Laser profilometer (ETD value) |
| Heat retention | Surface temperature and thermal comfort | Infrared thermometer |
| Maintenance | Cracks, damage, wear | Visual inspection |

*Source: Silva et al. (2025)*

Tactile and visual attributes such as texture, roughness, and surface regularity were highly rated (M = 4.79). That indicates smooth, stable, and visually uniform pavements enhance walking satisfaction (Silva et al., 2025). Computational texture analysis shows that physical texture features influence perceived aesthetic qualities, indicating that material properties can shape emotional and perceptual responses to surfaces (Liu et al., 2015). Surface colour and reflectivity affect visual and thermal perception, and influence how pedestrians experience urban landscapes (Rosso et al., 2016). Pedestrians often walk barefoot or in thin-soled sandals in cultural landscapes in the Sri Lankan context. Low thermal effusivity of WCC is a major sensory advantage over asphalt.

Moderate slip risks are presented by the Portuguese pavement, which combines aesthetic and historical value (Benson et al., 2023). The selection of walkability paving materials is directly related to the UHI (Kasim et al., 2018). The albedo value in paving materials is the primary factor in mitigating the effects of UHI. Several researchers have proven colours and textures of paving play an important role in reducing the temperature (Kasim et al., 2018). During the monsoon, algal growth diminishes visual appeal and slippery surfaces, posing a safety risk for pedestrians. Conditions that encourage algal colonization include high light exposure, neutral pH, nutrient availability, and low electrical conductivity and total dissolved solids (Munyai et al., 2019).

The Ancol Art Market study examined landscape hardscape aesthetics using a descriptive-analytical approach. Variables included building, site structure, and pavement (Adhitya et al., 2020) analyzed through form, texture, and colour. Aesthetic indicators (Adhitya et al., 2020), including unity, symmetry, balance, harmony, and contrast. The findings of these studies can inform the development of improved landscape design strategies and optimize site aesthetics through the identified parameters and indicators. These aesthetic principles are particularly relevant for evaluating pedestrian paving systems, where surface expression directly influences user perception and spatial experience. In the context of WCC, such indicators provide a useful lens to assess how material texture, colour variation, and surface consistency contribute to visual coherence and landscape identity.

## 4. INTEGRATED SYNTHESIS AND RESEARCH GAPS

### 4.1 INTEGRATED SYNTHESIS

Analysis of Sections 3.1-3.3 suggests that pedestrian walkability is not solely a function of design geometry but is critically mediated by the properties of the materials employed.

Existing walkability frameworks identify comfort, safety, accessibility, and connectivity as core determinants (Rafiemanzelat et al., 2017; Salem et al., 2022). This review demonstrates that these dimensions are directly influenced by the physicochemical and mechanical behaviour of paving materials. There is a need for an integrated, climate-responsive framework that explicitly addresses tropical environmental pressures characteristic of Sri Lanka.

Empirical evidence shows 10% sawdust replacement achieves approximately 21.2 MPa compressive strength in fired systems. It maintains permeability near 0.0556 m/s (Shafiquzzaman et al., 2022), fulfilling structural requirements for pedestrian and light-load applications. However, reliance on high-temperature firing (850-900°C) increases carbon footprint and requires specialized laboratory conditions, limiting scalability in the resource-constrained construction sector in Sri Lanka. Reductions in density from 2090 $kg/m^3$ to approximately 1398 $kg/m^3$ (Benjeddou, 2025) enhance thermal regulation, contributing to UHI mitigation, as highlighted by Kasim et al. (2018).

Pavement surface temperatures frequently exceed pedestrian comfort thresholds, intensifying heat stress and discouraging walkability in dense urban areas such as Colombo. Therefore, the reduced thermal conductivity associated with lightweight WCC should be positioned as a climate-adaptive requirement rather than an optional sustainability feature. Contents exceeding 15-20% or particle sizes above 1.5 mm result in significant strength loss (~10.2 MPa). Therefore, environmental benefits achieved through increased porosity must be balanced against mechanical stability. The optimal performance window can be summarized as follows.

*Table 4: Comparative performance of WCC mix ratios*

| Study | Optimal Mix | Processing / Methodology | Key Result |
|---|---|---|---|
| Shafiquzzaman et al. (2022) | 10% sawdust (0.5–1.0 mm) | Sieved soil (0.5 mm), mix with sawdust, mold (70×70×50 mm), air/oven dry, fire 900°C | 21.2 MPa compressive strength; 0.0556 m/s permeability |
| Butt et al. (2023) | 4% sawdust ash | -Sawdust (deodar and kail wood) is air-dried and burnt at room temperature.<br>-Ash sieved through a 600-micron sieve to remove deleterious materials. | 103% increase in CBR |
| Abu Zeid (2020) | 1% sawdust | Air-dried samples; sawdust mixed directly with clay at optimum water content and compacted at Maximum dry density; no firing of blocks | 30% increase in tensile strength, Shear strength >20%, Swelling potential ↓ 20–32% |
| Jannat et al. (2021) | 2.5% sawdust | -Dry blending of raw clay powder and sawdust particles | Best mechanical performance for unfired blocks. |

| Study | Optimal Mix | Processing / Methodology | Key Result |
|---|---|---|---|
| | (425–600 µm) | -Addition of water to the workable paste<br>-Molding into prisms (40×40×160 mm). Cured for 21 days (room temp.) and dried for 28 days before testing. | Density: ~1781 to ~1422 kg/m³<br>Capillary water absorption: increases with sawdust percentage<br>Linear shrinkage: decreases with increasing sawdust |
| Benjeddou (2025) | 4% sawdust | -Dry mixing of clay and sawdust<br>-Water added for a workable paste<br>-Moulding into plates (270×270×40 mm)<br>-Drying (staged 40–110 °C)<br>-Firing in kiln (total cycle ~23 h)<br>-Heat to 850 °C, hold 4 h – Controlled cool-down | ~4% sawdust: threshold where lightweight behaviour and thermal insulation improvements become significant while avoiding extreme porosity that may compromise mechanical function.<br>2–6% range balances improved insulation with manageable density changes |

Hygroscopic behaviour is critical under high relative humidity (>80%) and monsoon conditions in Sri Lanka. Although 1% sawdust reduced swelling by 20-32% in unfired systems (Abu Zeid, 2020), its effectiveness under prolonged wet-dry cycles remains uncertain and requires tropical durability testing. Biological resilience is also a concern. The organic content of sawdust may increase fungal or algal growth in warm, humid environments. While firing reduces this risk, the long-term performance of unfired systems needs further investigation.

Experience metrics can be strengthened by linking measurable surface properties to human perception. Particle size influences perceived texture, where finer particles create smoother impressions while coarser particles produce rougher, more natural qualities. Visual texture attributes such as coarseness and contrast influence aesthetic responses to surfaces (Liu et al., 2015). Surface treatments can further enhance these qualities. Sanding or polishing wood-chip aggregates may reveal grain patterns and improve visual coherence. Research also shows that appropriate surface roughness and coherent material design can improve pedestrian comfort, perceived safety, and the overall experience of walkable environments (Adhitya et al., 2020; Silva et al., 2025).

## 4.2 PROPOSED MULTI-DIMENSIONAL PEDESTRIAN PAVEMENT FRAMEWORK (MDPPF)

The proposed MDPPF is a comprehensive design system that integrates material composition, thermal and hydrological behaviour, and sensory perception to guide the development of user-centric, bio-based paving materials for creating walkable, healthy cities in tropical environments (Figure 2). Sustainable pedestrian pavements should be evaluated across several interrelated dimensions. User experience and visual quality must also be considered from a landscape architectural perspective. The MDPPF recognizes potential trade-offs between key properties of WCC pavements while higher organic content can enhance porosity, permeability, and pedestrian thermal comfort, it may reduce structural durability. Therefore, MDPPF encourages a site-responsive balance of material composition based on landscape use, prioritizing durability in high-traffic areas and porosity in low-traffic environments.

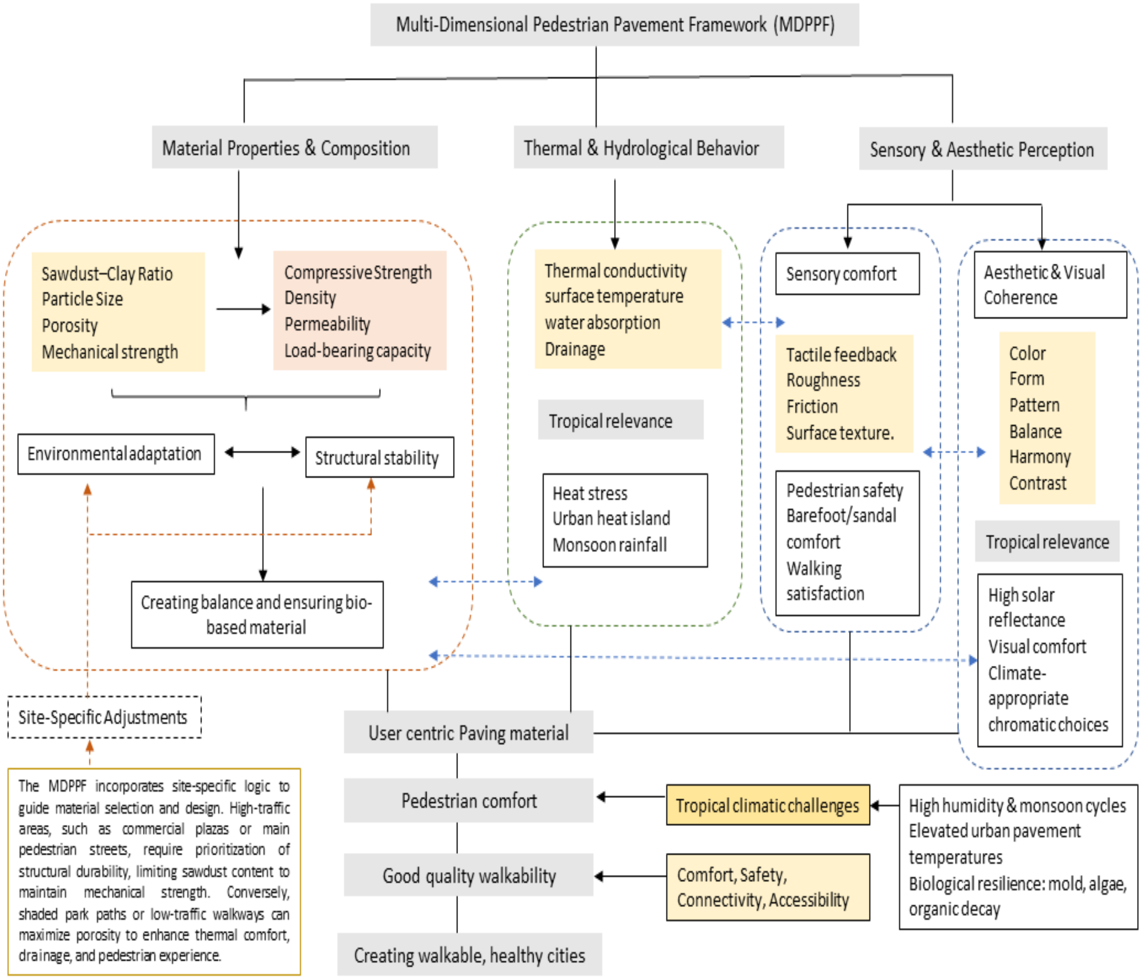


*Figure 2: Conceptual diagram of MDPPF*

## 4.3 IDENTIFIED RESEARCH GAPS

Identified research gaps under the three categories (indicated in Section 2.4) have been listed below.

*Table 5: Key research gaps*

| Thematic Domain | Identified Gap | Landscape Architectural Concern | Implication for Urban Design & Public Realm |
|---|---|---|---|
| Pedestrian Comfort & Walkability | Limited field-based validation in real pedestrian environments | Pavement performance under high humidity (>80%), monsoon rainfall, intense solar exposure, and barefoot/sandal walking remains untested | Uncertainty in long-term walkability, spatial resilience, and public realm performance |

| Thematic Domain | Identified Gap | Landscape Architectural Concern | Implication for Urban Design & Public Realm |
|---|---|---|---|
| Material Properties, Composition and Performance | Weak integration of microclimate performance and pedestrian comfort | Surface temperature and thermal perception rarely correlated with pedestrian experience | Limits the design of climate-responsive, thermally adaptive, and heat-mitigating streetscapes in dense urban areas such as Colombo |
| | Absence of a performance-based walkability material framework | No multi-criteria evaluation tool integrating structural stability, hygroscopic response, thermal behaviour, and sensory experience | Designers lack evidence-based material selection criteria for pedestrian pavements |
| | Laboratory-focused evaluation detached from site context | Mechanical properties assessed without accounting for monsoon wet–dry cycles, biological exposure, or landscape use patterns | Difficult translation into implementable urban design strategies and long-term maintenance planning |
| Aesthetic and Sensory Qualities | Fragmented evaluation of structural and aesthetic qualities | Texture, colour, and spatial rhythm are not linked with moisture behaviour, thermal comfort, or weathering patterns | Constrains holistic streetscape design and climate-sensitive place-making strategies |
| | Limited guidance on preferred pavement colours in tropical climates | Chromatic selection is not evaluated against solar reflectance, glare control, thermal absorption, or visual harmony | Weak evidence-based design for visual coherence and pedestrian experience in urban landscapes |

# 5. CONCLUSIONS AND IMPLICATIONS

## 5.1 SCHOLARLY AND PRACTICAL IMPLICATIONS

The MDPPF developed in this study provides a practical, evidence-based framework for urban designers working in hot and humid tropical environments. Rather than focusing solely on structural performance, it encourages a more holistic approach to material selection by considering both technical and sensory factors, such as how particle size distribution can influence thermal performance and pedestrian comfort. From a practical perspective, the framework supports circular economy principles by promoting the use of sawmill waste as a sustainable material for urban infrastructure. In the Sri Lankan context, this offers a low-carbon alternative for managing timber industry residues while creating value-added construction products. For policymakers, the adoption of WCC standards could contribute to municipal solid waste reduction targets by encouraging the local reuse and valorisations of wood waste streams.

Furthermore, the MDPPF bridges the traditional divide between laboratory-based material testing and real-world urban design applications by integrating engineering performance indicators with environmental and user-experience criteria. This enables designers and decision-makers to evaluate paving materials not only for their mechanical suitability but also for their contribution to pedestrian comfort, thermal adaptation, and aesthetic quality in public spaces. As a result, the framework provides a pathway for translating material science research into practical landscape architectural and urban design interventions that respond to the challenges of tropical urban environments.

### 5.2 LIMITATIONS OF THE CURRENT REVIEW

Although this review provides a strong theoretical foundation, several limitations should be acknowledged. The analysis is limited to English-language academic publications published between 2010 and 2025, which may have excluded relevant non-indexed technical reports and local studies. In addition, most existing evidence is based on laboratory experiments, resulting in limited understanding of the long-term performance of WCC under real tropical conditions, including prolonged weathering, monsoonal wet–dry cycles, high humidity, and biological growth such as algae in pedestrian environments.

### 5.3 FUTURE RESEARCH DIRECTIONS

To further optimize climate-responsive materials and enhance pedestrian walkability in tropical environments, subsequent studies should prioritize the following areas:

- Conduct long-term, multi-season field studies to assess the performance of ambient-cured stabilized pavements under actual pedestrian use.
- Explore low-energy stabilization approaches, including bio-based binders and low-temperature thermal treatments, to improve moisture resistance and durability.
- Examine how different pavement textures and layout patterns influence pedestrian perceptions, comfort, and movement behavior in tropical public spaces.

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