

# Sustainable Materials and Intelligent Monitoring for Capillary Barrier Systems in Reinforced Soil Structures: A PRISMA-Based Review

Juan C. Guzmán-Martínez<sup>1,2,\*</sup>, Ivan P. Damians<sup>2,3,4</sup> and Sebastia Olivella<sup>2,3</sup>

<sup>1</sup>*Environmental School, School of Engineering, Universidad de Antioquia-UdeA, Calle 67 # 53-108. A. A. 1226 Medellín, Colombia*

<sup>2</sup>*Department of Civil and Environmental Engineering (DECA), Universitat Politècnica de Catalunya – Barcelona Tech (UPC), 08034 Barcelona, Spain*

<sup>3</sup>*International Centre for Numerical Methods in Engineering (CIMNE), Campus Nord UPC, 08034 Barcelona, Spain*

<sup>4</sup>*VSL Construction Systems / VSL International Ltd., 08908 L'Hospitalet del Llobregat, Barcelona, Spain*

**Abstract:** Capillary barrier systems (CBS) improve geotechnical structures by controlling water infiltration under unsaturated conditions. By exploiting hydraulic contrasts between fine and coarse layers, CBS effectively diverts water flow and reduces excess pore-water pressure. When integrated with reinforced soil structures (RSS), CBS enhances stability by maintaining matric suction and mitigating rainfall-induced softening, thereby offering a climate-resilient and resource-efficient alternative to traditional drainage methods. Driven by sustainability and circular economy objectives, the adoption of recycled and marginal geomaterials—such as reclaimed asphalt pavement, recycled concrete aggregate, and local soils—has increased. In addition, recent advances in measurement technologies and data analytics enable intelligent monitoring of CBS-RSS systems, representing a significant advancement in geotechnical engineering innovation.

However, the specific contributions and limitations of sustainable materials and data-driven monitoring approaches for CBS-RSS remain unclear, hindering their wider adoption in practice. Therefore, this study employed a PRISMA-compliant systematic review to identify, screen and synthesize 82 studies on CBS in RSS, focusing on two thematic clusters: sustainable and alternative materials, and monitoring technologies and data-driven/intelligent approaches. The study shows that recycled materials such as Reclaimed asphalt pavement, recycled concrete aggregate and steel slag can provide the hydraulic contrast required for CBS layers, but that multi-year field validation, leachate characterization and standardized SWCC testing protocols for recycled geomaterials are largely missing. In addition, the review exhibit that instrumented CBS-RSS systems equipped with tensiometers, moisture sensors, piezometers and, more recently, sensor-embedded geosynthetics and wireless or fiber-optic networks can deliver rich datasets, yet these data are rarely assimilated into digital-twin or physics-informed machine-learning frameworks for real-time performance assessment and design optimization. The review connects CBS technology with sustainability and intelligent monitoring, establishing CBS-RSS as a climate-resilient, resource-efficient, and intelligent alternative to conventional retaining systems, and delineating key research priorities for broader implementation.

**Keywords:** Reinforced soil structures, Capillary barrier system, Monitoring and intelligent structures, Recycled materials, Sustainable materials, Geosynthetics.

## 1. INTRODUCTION

Capillary barrier systems (CBS) have emerged as an important strategy in geotechnical engineering for controlling infiltration and preserving unsaturated conditions in earth structures exposed to intense or prolonged rainfall [1]. Their performance relies on the contrast in hydraulic conductivity and water-retention behaviour between fine and coarse layers, which diverts downward flow, delays wetting fronts and limits pore water pressure accumulation. This capillary mechanism is particularly relevant in reinforced soil structures (RSS), where a loss of matric suction can weaken soil-reinforcement interaction and trigger deformation or instability during extreme climatic events [2,3].

The increasing frequency of climate-related loading-prolonged droughts, high-intensity storms and larger temperature swings has intensified The imperative for earth-retaining systems extends beyond mechanical reliability to encompass resilience under variable hydrological regimes. In this context, CBS are gaining attention as climate-adaptive components within reinforced slopes or walls, drainage and cover systems, due to CBS can reduce rainfall-induced pore-pressure build-up while remaining compatible with geosynthetic reinforcement strategies. At the same time, sustainability and circular-economy objectives are promoting the use of recycled and locally available geomaterials—such as reclaimed asphalt pavement (RAP), recycled concrete aggregate, steel slag and marginal soils—as alternative fine and coarse components in CBS layers and reinforced backfills, thereby reducing reliance on virgin aggregates and lowering embodied energy and greenhouse-gas emissions when their performance is acceptable [4,5].

\*Address correspondence to this author at the Environmental School, School of Engineering, Universidad de Antioquia-UdeA, Calle 67 # 53-108. A. A. 1226 Medellín, Colombia; E-mail: juanc.guzman@udea.edu.co

Simultaneously with these developments in material using in CBS, the broader field of intelligent geotechnical engineering has seen rapid advances in monitoring and sensing technologies. Field implementations such as the GeoBarrier System in steep slopes have demonstrated that CBS-type configurations can be instrumented with tensiometers, moisture sensors, piezometers and inclinometers to track suction, water content, pore-water pressure and deformations in real time [6]. Moreover, [7] realized a review on smart geosynthetics and sustainable foundations highlight the emergence of sensor-embedded geotextiles and geogrids, fiber-optic and wireless sensor networks, and ICT-based life-cycle management as core elements of intelligent reinforced earth and foundation systems. Additionally, machine-learning and physics-informed approaches have begun to exploit such monitoring data for predicting hydraulic and mechanical responses in unsaturated soils, offering a pathway toward digital-twin-style management of geotechnical assets [8,9].

Despite these advances, the literature on CBS in reinforced soil structures remains fragmented across several largely separate themes. Previous review articles on geosynthetic capillary barriers have primarily concentrated on fundamental hydraulic mechanisms, laboratory performance and geotextile behaviour, with limited attention to sustainable materials or intelligent monitoring within reinforced soil applications [10,11]. In parallel, syntheses on geosynthetic- reinforced soil walls and sustainable foundations have examined recycled geomaterials, geosynthetics and life-cycle assessment, but they do not explicitly focus on capillary barrier mechanisms or systematically address their integration into reinforced soil structures [7,12,13].

Building on a broader PRISMA-compliant systematic review of CBS in RSS, the present article narrows its scope to four underdeveloped thematic clusters; mechanisms/design, numerical approaches, sustainable materials, and monitoring/data-driven methods-and highlighted important gaps in long-term field validation of sustainable CBS materials and in the use of monitoring and Artificial Intelligence (AI) for real-time performance management examines how these can be combined to support the design and operation of climate-resilient, low-carbon CBS-RSS systems. In this way, the review moves beyond generic drainage or reinforcement concepts and positions CBS as a distinct, sustainable and intelligent option within reinforced soil design.

The systematic literature review addresses that gap by concentrating exclusively on two PRISMA-derived

clusters-sustainable and alternative materials, and monitoring technologies and data-driven approaches-for CBS in reinforced soil structures. Its primary focus is to synthesize evidence on the hydraulic, mechanical, durability and environmental performance of recycled and marginal materials used as CBS components and reinforced backfills, and to review monitoring and sensing strategies (including sensor-embedded geosynthetics, wireless and fibre-optic networks) that can generate data streams suitable for intelligent analysis and life-cycle management. By explicitly bridging CBS mechanisms with sustainable materials and intelligent monitoring within reinforced soil applications, this review aims to clarify the performance of CBS in RSS systems can be credibly promoted as sustainable and intelligent alternatives to conventional drainage and retaining solutions.

## 2. METHODS

A systematic literature review (SLR) on capillary barrier systems in reinforced soil structures was conducted, following the PRISMA 2020 guidelines [14]. The SLR was conducted using the Systematic Research agent by SciSpace to support literature discovery and initial screening, while Perplexity Computer AI was used to structure the review workflow, organise the evidence base, and assist in thematic synthesis. All records flagged by the AI-assisted screening stage were then manually verified by the reviewer through title, abstract, and full-text inspection, and final eligibility decisions were confirmed using the predefined inclusion and exclusion criteria.

Searches were conducted in SciSpace, Google Scholar, Scopus, and through manual reference tracking, using a PICO-based protocol to ensure transparency and reproducibility. Predefined Boolean queries grouped into targeting CBS with sustainable materials and monitoring. No publication-year restriction was applied, and records were limited to English and Spanish publications, with conference papers included only when published in indexed proceedings. Screening was performed in sequential stages, including duplicate removal, title and abstract screening, full-text eligibility assessment, and methodological quality appraisal, with explicit inclusion and exclusion criteria applied at each stage.

The search strategy found 1,000 raw records identified across the three databases and manual reference searching, followed by deduplication using title and DOI matching to remove 154 duplicates. Title screening then used topical keywords such as “capillary barrier,” “capillary break,” “unsaturated,” “reinforced soil,” “geosynthetic,” “geotextile,” and

“suction,” while abstract screening retained only studies explicitly addressing CBS mechanisms, sustainable CBS materials, or monitoring and AI applications. The review combined database searching with reference tracking and forward/backward citation chasing of key papers, especially the Zornberg, Rahardjo, Portelinha, and related research groups.

The screening process followed a staged PRISMA workflow: identification, deduplication, title screening, abstract screening, full-text eligibility assessment, and quality appraisal. All exact queries are reported to enable independent replication of the searches. Screening was conducted in staged phases with quantitative thresholds: automatic deduplication by title and DOI, title screening based on a predefined keyword list, abstract screening requiring explicit reference to CBS mechanisms, numerical modelling, sustainable CBS materials or monitoring/AI, full-text eligibility assessment using five inclusion and two exclusion criteria, and a final methodological quality appraisal. The Title/abstract screening criteria are defined via a keyword list (e.g. “capillary barrier”, “unsaturated”, “geosynthetic”), and abstract inclusion conditions (CBS mechanism, numerical modelling, sustainable materials, or monitoring/AI) are explicitly stated.

Furthermore, a single-reviewer-with-audit protocol was adopted: the first author performed title, abstract and full-text screening, while borderline cases flagged in the eligibility table (INC\* codes) and any potential conflicts of interest were re-checked against the operationalized criteria to ensure consistent decisions. Eligibility criteria were defined around four inclusion domains: CBS integrated with reinforced soil structures, sustainable geomaterials, monitoring or AI approaches, and field or practical design relevance. Exclusion criteria removed non-geotechnical capillary barrier applications, traditional saturated drainage systems without an unsaturated capillary break, and papers lacking the required CBS-RSS connection. Finally, the numbers of records excluded at each stage (title, abstract, full text) are given and tied to the PRISMA flow diagram.

Methodological quality of the included studies was assessed using the Mixed Methods Appraisal Tool-MMAT [15], which is designed for quantitative, qualitative, and mixed-methods evidence syntheses. First, each study was screened for eligibility under the MMAT design-specific criteria, and then appraised against the relevant five-item checklist for its study type; for mixed-methods studies, both the qualitative and quantitative components were assessed separately, and the overall judgment was constrained by the weakest component. To support comparability

across studies, a predefined threshold was applied, with studies scoring at least 60% (equivalent to at least 3 of 5 applicable MMAT criteria) considered to have acceptable methodological quality for inclusion in the synthesis. Studies below this threshold were either excluded or retained only for contextual interpretation, depending on their relevance and the amount of evidence available. After the initial SciSpace Systematic Research agent screening, all records flagged as eligible or borderline were manually verified by the reviewer through title, abstract, and full-text inspection. Final inclusion and exclusion decisions were confirmed by human judgment using the predefined eligibility criteria, and uncertain cases were rechecked to ensure consistency and reproducibility.

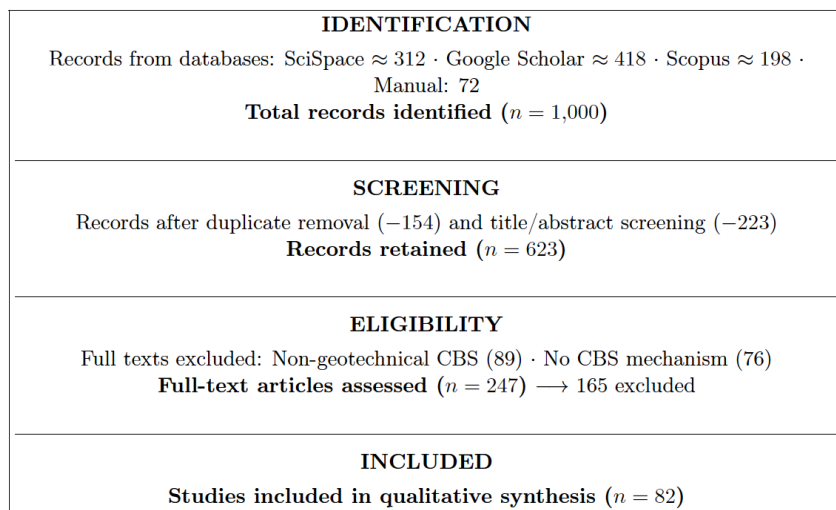
Risk of bias was considered alongside methodological quality to identify limitations related to study design, measurement reliability, model calibration, incomplete reporting, and potential selection bias. In accordance with PRISMA guidance, the appraisal process should be reported by stating the tool used, the number of reviewers, whether assessments were conducted independently, and how the appraisal influenced synthesis. In this review, quality concerns were used to interpret the strength of evidence rather than to statistically exclude studies, thereby preserving thematic coverage while still distinguishing robust findings from tentative ones.

Finally, the evidence gaps were identified through thematic coding of the final included studies and comparison of evidence coverage across the predefined review questions and thematic clusters. The gap analysis classified not only what evidence was missing, but also why it was missing, distinguishing gaps due to lack of field validation, limited long-term monitoring, insufficient sustainability data, and weak transferability across climates or structure types. The resulting gap map can therefore be used to justify future research priorities and to show where the literature remains underdeveloped despite a substantial number of studies.

### 3. RESULTS AND DISCUSSION

#### 3.1. Systematic Literature Review: Capillary Barrier in Reinforced Soil Structures

A PRISMA-compliant systematic literature review (SLR) was conducted to comprehensively evaluate and synthesize the current state of knowledge on capillary barrier systems (CBS) integrated with reinforced soil structures (RSS). Searches were performed in SciSpace, Google Scholar and Scopus using PICO-structured query families targeting (i) sustainable and recycled materials, and (ii) monitoring and



**Figure 1:** PRISMA 2020 flow diagram for record identification and selection.

AI-based approaches; inclusion criteria required explicit CBS mechanisms in geosynthetic-reinforced slopes, walls or embankments, and peer-reviewed publication, machine or deep learning (ML/DL). From approximately 1,000 initial records, 82 studies met the eligibility criteria after duplicate removal and full-text screening, and these were clustered into thematic domains that structure the results and discussion that follow.

The Figure 1 presents the PRISMA 2020 flow diagram illustrating the study selection process. Of the 1000 records identified across three databases, 223 were excluded at abstract screening and 165 at full-text review, leaving 82 studies in the final synthesis. Furthermore, Table 1 shows the distribution of included studies by thematic cluster corresponding on two thematic clusters: sustainable materials and monitoring technologies and data-driven/intelligent approaches including 22 and 15 studies, respectively.

### 3.1.1. Fundamental Mechanisms of capillary barrier

#### Keys to Understanding of Capillary Barriers

Capillary barrier systems (CBS) form when an unsaturated fine-grained layer overlies a porous medium with significantly larger pores, such as coarse sand, gravel, or a nonwoven geotextile [16]. The key mechanism is the capillary break that develops at the interface between materials with contrasting hydraulic properties: at moderate suctions, the fine soil can transmit infiltrating water, while the coarse material or geosynthetic remains at very low hydraulic conductivity

because its large pores are still air-filled [10]. As long as matric suction in the fine layer near the interface is greater in magnitude than the water-entry suction of the underlying layer, downward liquid flow into the coarse medium is strongly inhibited and water is stored above the interface [17].

From capillary theory, this behaviour follows from the curvature of air-water menisci and the resulting pressure difference across the interface [16]. The equilibrium height of capillary rise is inversely proportional to pore radius and depends on the contact angle between fluid and solid; fine soils with small pores therefore sustain larger suctions and higher capillary rise than coarse soils or porous geosynthetics [18], as cited in [16]. In granular CBS, the coarse layer is chosen so that its maximum capillary rise (or water-entry head) is much smaller than that of the overlying fine soil, ensuring that water remains hydraulically disconnected from underlying layers until a critical suction is reached [19]. This counter-intuitive inversion of hydraulic conductivity with respect to grain size allows an unsaturated fine layer to divert flow laterally while the underlying coarse or geosynthetic layer remains comparatively impermeable until breakthrough conditions are reached [10].

Breakthrough of capillary barrier occurs when suction at the interface is reduced to the water-entry head of the coarse material or geosynthetic, at which occurs fails locally and water begins to enter the underlying layer [20,21]. Depending on infiltration rate, soil properties and geometry, this may happen

**Table 1:** Distribution of Included Studies by Thematic Cluster ( $n = 82$ )

Theme	$n$	%	Focus
Sustainable Materials	22	27	RAP, RCA, steel slag, marginal backfill, industrial by-products
Monitoring & AI/ML	15	18	Sensor networks, Intelligent or technology system, ML/DL for performance prediction

progressively-water entering locally and spreading-or rapidly once the wetting front reaches the interface under near-saturated conditions [22]. Mainly, column tests with geosynthetics show that after drying, the capillary break can re-establish, implying that CBS can sustain repeated wetting-drying cycles while maintaining their barrier effect over the long term [4].

The capillary break effect has two main effects. First, it increases the water storage capacity of the overlying soil beyond the level associated with gravity drainage alone, which is critical for surface covers that rely on temporary storage and evapotranspiration to limit net percolation [23]. Second, it promotes lateral diversion of infiltrating water along inclined interfaces, which is essential for sloping applications where the barrier is intended to direct water toward drains or outside sensitive zones [24].

#### Applications in Reinforced Soil Structures

Capillary barrier systems are now used in a range of reinforced soil structures as both hydraulic control layers and structural components, exploiting unsaturated flow to preserve suction while providing drainage and stability. Applications include geosynthetic-reinforced slopes, GeoBarrier systems (GBS) for steep slopes, MSE walls or GRS, and retaining walls backfilled with fine-grained soils that would otherwise be hydraulically problematic under rainfall. Technologies range from classical two-layer soil CBS, through dual/three-layer capillary barriers and covers with unsaturated drainage layers (UDL), to

geotextile drains, geocomposite drains, and geobag-based GBS that combine capillary barrier effects with geogrid reinforcement and recycled aggregates.

The Table 2 illustrate that capillary barrier concepts have been adapted to a wide range of reinforced soil structures, from relatively simple retaining walls to complex geogrid-reinforced slopes and GeoBarrier systems (GBS). CBS typologies range from classical two-layer soils, through dual/three-layer capillary barriers and covers with unsaturated drainage layers (UDL), to geotextile drains, geocomposite drains, and geobag-based GBS that combine capillary barrier effects with geogrid reinforcement and recycled aggregates

In all cases, the basic mechanism remains the same: a fine-grained layer with relatively small pores is underlain by a coarser or more porous medium (often a geosynthetic), so that capillary forces at the interface temporarily halt downward flow, increase storage in the fine layer and promote lateral diversion, thereby preserving matric suction and shear strength in the structural backfill.

In retaining walls backfilled with fine-grained soils, Chen et al. [25] propose an internal capillary barrier formed by a silt backfill over a sand-nonwoven geotextile assembly, installed within the wall and sloping slightly to promote lateral drainage. Under intense but finite rainfall, this typology acts predominantly as a barrier: infiltrating water is stored in

**Table 2: Capillary Barrier Systems Employed in Reinforced Soil Structures**

Type of RSS implemented	Typology of capillary barrier system (CBS)	Functionality (drainage / barrier / stabilisation)	Reference
Retaining wall backfilled with fine-grained soil (silty backfill wall).	Internal sand-geotextile CBS inside the wall (single capillary barrier).	Internal sand layer provides lateral drainage while the geotextile acts as a capillary break.	Chen et al. [25]
Slopes / embankments protected by capillary barrier covers.	Capillary barrier cover (CBC) with unsaturated drainage layer (UDL.)	CBC stores water in the fine layer and delays breakthrough; the UDL provides preferential unsaturated drainage.	Li et al. [26]
Steep residual soil slopes with geogrid-reinforced zone and geobag facing (near-vertical GBS wall).	GeoBarrier System (GBS): three-layer capillary barrier with vegetated geobag facing (multi-layer CBS).	system acts simultaneously as retaining wall, hydraulic cover and stabilisation measure.	Rahardjo et al. [3]
Geosynthetic-reinforced slopes with internal drains (GRS embankments).	Nonwoven geotextile drains sandwiched in sand cushions.	The sand-geotextile assemblage acts as a drain, dissipating pore pressures in the soil above reinforcement layers.	Thuvo et al. [27]
Mechanically stabilised earth (MSE) / GRS walls with geocomposite drains.	Geocomposite drain (geonet core with nonwoven geotextile filters).	Local capillary-barrier effects at the soil-geotextile interface influence effective saturation near the drain, but the primary role is drainage.	Chinkulkijniwat et al. [28]
Geotextile-reinforced walls and slopes (GRS structures).	Geosynthetic capillary barrier: fine soil over nonwoven geotextile.	Nonwoven geotextiles beneath fine backfill develop capillary barriers in unsaturated stages.	Zornberg et al. [10]

the overlying silt and sand, while the geotextile prevents penetration into the main silt backfill so that suction and factor of safety remain essentially unchanged compared with the initial condition.

For steep slopes and near-vertical walls, typologies become more integrated with the reinforcement layout. The GeoBarrier System (GBS) combines geobag facing units filled with fine recycled asphalt (RAP) or concrete aggregate (RCA) and an underlying coarse recycled layer to form a three-layer capillary barrier placed directly on the face of a geogrid-reinforced residual soil slope. This arrangement acts simultaneously as a retaining wall, hydraulic cover and stabilizing measure: rainfall is largely intercepted and stored in the fine and vegetated layers, lateral diversion occurs within the coarse recycled layer and sump, and the reinforced residual soil behind the GBS remains nearly unaffected in terms of suction even during extreme rainfall sequences Rahardjo et al. [2].

Internal drainage typologies for geosynthetic-reinforced slopes and walls include nonwoven geotextile drains sandwiched between sand cushions and geocomposite drains with geonet cores, both of which can exhibit capillary-barrier behaviour during unsaturated stages. In the sandwich system proposed by Thuo et al. [27], a thin nonwoven geotextile is placed between two thin coarse sand layers within a silty sand backfill; during infiltration the soil above each geotextile may temporarily experience increased moisture and reduced suction due to a capillary break, but once the wetting front moves through and pore pressures become less negative, the sand-geotextile assemblage behaves as a drain that dissipates pore pressures and improves stability in the upper part of the reinforced slope.

In MSE walls with geocomposite drains, Chinkulkijniwat et al. [28] show that the geonet geotextile core provides hydraulic conductivity one to two orders of magnitude greater than the compacted sand backfill, controlling the phreatic surface and keeping effective saturation in the reinforced zone significantly lower than in comparable walls without geocomposites. Here the capillary barrier effect at the soil-geotextile interface is secondary to the drainage function, but it still affects local saturation and suction near the drain and thus must be considered when interpreting unsaturated flow and stability.

Collectively, these typologies highlight that capillary barrier systems in reinforced soil structures are best viewed as tunable hydro-mechanical elements whose role can be shifted between barrier, drain and stabiliser through appropriate selection of fine and coarse materials, geosynthetics and geometry.

In reinforced soil structures, the choice of backfill, drainage layer, and barrier material governs hydraulic conductivity, retention capacity, stiffness, and compatibility with reinforcement elements. Consequently, sustainable alternatives, including marginal soils and recycled asphalt pavement, necessitate rigorous evaluation not merely for their environmental merits, but also for their capacity to uphold the functional specifications mandated by Capillary Barrier System (CBS). Consequently, the materials discussion naturally follows the application discussion, because implementation in the field is ultimately constrained by material behavior and durability.

### **3.1.2. Sustainable and Alternative Materials**

An expanding body of research indicates that capillary barrier systems can be engineered using sustainable and alternative materials while maintaining their hydraulic performance, provided their unsaturated properties are properly characterized and integrated into design. The PRISMA-compliant systematic review on CBS in reinforced soil structures identifies a distinct “sustainable materials” cluster (22 studies) and synthesizes their performance in a comparative analysis that contrasts reclaimed asphalt pavement (RAP), recycled concrete aggregate (RCA), steel slag, marginal soils and industrial by-products against conventional gravel in terms of water-entry value (WEV), saturated hydraulic conductivity and typical CBS role. The table presents the main characteristics of the sustainable materials used in the CBS and also describes the limitations of their application. This comparison shows that several recycled materials achieve WEV contrasts of roughly one order of magnitude relative to typical fine layers, together with saturated conductivities within the  $10^{-3}$ – $10^{-5}$  m/s range, making them viable coarse layers in CBS, whereas marginal silts and fly ash emerge as candidate fine layers when blended into approved soil mixes. At the same time, the review stresses that long-term field validation, standardized SWCC testing protocols for recycled geomaterials and leachate assessments remain major gaps before routine adoption in regulated infrastructure.

#### Marginal and Locally Available Soils

Marginal and locally available soils have received renewed attention as sustainable fine layers and backfills in reinforced soil structures incorporating capillary barrier concepts, driven by the need to replace imported select fills and valorise local resources [31-33]. The PRISMA-based SLR identifies marginal silts, lateritic soils and fly ash as alternatives for the moisture-retention layer (MRL) in CBS-RSS, provided that their soil-water characteristic curves (SWCCs) and

**Table 3: Sustainable Materials for Capillary Barrier Systems and their Hydraulic Characteristics**

Material	Type	CBS layer	Limitations
RAP	Recycled aggregate	Coarse layer	Bitumen coating may alter long-term hydraulic response; clogging and durability require validation <sup>a</sup>
RCA	Recycled aggregate	Coarse layer	Hydraulic response depends strongly on gradation and fines content; long-term chemical stability needs assessment <sup>a</sup>
Steel slag	Industrial by-product	Coarse layer	Leachate chemistry and volumetric stability need further study <sup>b</sup>
Natural gravel	Virgin aggregate	Coarse layer reference	Higher environmental cost than recycled alternatives <sup>b</sup>
Marginal soil / silt	Natural soil	Fine layer	Hysteresis, shrink–swell, and moisture sensitivity may reduce reliability <sup>b</sup>
Fly ash geotextile / amended fine layer	Industrial by-product / engineered layer	Fine layer	Long-term soil-water retention stability remains uncertain <sup>b</sup>
Wicking geotextile	Geosynthetic	Interface / drainage layer	Performance depends on interface suction <sup>c</sup>
Nonwoven geotextile	Geosynthetic	Interface / capillary break	May trap moisture above the interface and reduce drainage if lateral transport is limited <sup>d</sup>

<sup>a</sup>Source values reported for RCA and RAP unsaturated properties and water-entry behaviour [29]. <sup>b</sup>Values are synthesized from the PRISMA review summary; the report notes promising performance but limited long-term validation. <sup>c</sup>Wicking geotextile behaviour and suction thresholds are reported in the numerical study of [30]. <sup>d</sup>Capillary-barrier persistence and moisture buildup for nonwoven geotextiles are reported in the field/lysimeter study [10].

hydraulic conductivities are characterized and, where necessary, adjusted via approved soil mixtures to achieve sufficient water-entry value contrast with the underlying coarse layer [34,35].

Numerical investigations on geogrid-reinforced soil walls using select fills, marginal soils and fly ash show that walls with marginal or fly-ash backfills can satisfy external and internal stability criteria if reinforcement length and stiffness are increased, but they are significantly more sensitive to rainfall-induced pore-pressure build-up and develop larger lateral deformations than walls with clean granular backfills [36-38]. Under high infiltration rates (for example, 80 mm/h), factors of safety for walls with marginal or fly-ash backfills can drop below unity unless additional drainage elements such as chimney drains of at least 0.3 m thickness are installed, emphasizing that capillary-barrier benefits in such systems must be combined with explicit drainage design to control hydro-mechanical response during extreme events [39].

#### Reclaimed Asphalt Pavement - RAP

Reclaimed asphalt pavement (RAP) has emerged as a leading sustainable alternative for the coarse CBS layer in reinforced slopes and walls because it combines favorable unsaturated hydraulic properties with high shear strength and the possibility of reusing road-construction waste [40,41]. Laboratory column tests on dual capillary barriers using RAP as the coarse

layer show 35-55% higher storage capacity than single barriers and delayed breakthrough until the overlying fine layer approaches near saturation, indicating that RAP can effectively increase diversion length and temporary storage compared with natural gravel [42].

In field-scale GeoBarrier System applications, slopes incorporating fine and coarse RAP as CBS materials are numerically analyzed and instrumented to show that pore-water pressures in the protected residual soil remain strongly negative during tropical storms, supporting the use of RAP-based CBS for sustainable slope and wall stabilization [2,6].

#### Recycled Concrete Aggregate - RCA

Recycled concrete aggregate (RCA) provides a similarly attractive sustainable option for CBS coarse layers, particularly in systems where both hydraulic efficiency and structural stiffness of the barrier are important [43,44]. Systematic laboratory work on RCA demonstrates that finer RCA has smaller dominant pore sizes, higher WEV and residual suction, and lower saturated hydraulic conductivity than coarser RCA, while both materials presents a suction-dependent shear strength, closely replicating the mechanical behaviour of natural gravel under saturated and unsaturated conditions [29].

In the GeoBarrier System concept, fine RCA placed in geobags as the fine layer, combined with coarse RCA as the underlying coarse layer and an approved

soil mixture as the outer vegetated layer, forms a multi-layer CBS that successfully limits rainfall-induced pore-pressure changes in the underlying residual soil and confines stress variations within the recycled layers [45]. Taken together with column and numerical studies summarized in the PRISMA review, these results support the replacement of natural aggregates by RCA in CBS layers for reinforced slopes and walls, provided that potential issues such as leachate chemistry and long-term durability are addressed in design and monitoring.

Overall, the sustainable-materials evidence indicates that RAP, RCA and steel slag can all satisfy the hydraulic contrast and shear strength requirements for CBS coarse layers, but each material presents distinct geotechnical and environmental trade-offs. Unsaturated testing shows that RAP exhibits water-entry values of the order of 10 kPa relative to typical fine layers, saturated hydraulic conductivities between  $10^{-3}$ – $10^{-4}$  m/s, and friction angles in the range of approximately 35–47°, comparable to or higher than those of natural coarse aggregates [29,42]. These properties, combined with the mild hydrophobicity imparted by the asphalt coating, support its use as a CBS coarse layer. However, its performance is sensitive to gradation, fines content and long-term changes in the bituminous binder, which may influence permeability, stiffness and clogging potential under repeated wetting-drying cycles [29,46].

Meanwhile, RCA displays similarly favourable hydraulic behaviour, with water-entry values within roughly one order of magnitude of common fine layers, saturated hydraulic conductivities in the  $10^{-2}$ – $10^{-4}$  m/s range and high shear resistance, as reflected in laboratory gyratory shear tests and California Bearing Ratio (CBR) values that are comparable to, or only slightly lower than, those of crushed stone bases [47,48]. At the same time, the presence of adhered mortar increases water absorption and reduces maximum dry density, and cementitious phases may evolve over time, necessitating attention to leachate chemistry and durability in design [49].

Steel slag offers high stiffness and adequate hydraulic contrast for CBS layers, but its volumetric stability and long-term chemical behaviour under cyclic environmental loading remain less well documented and require site-specific assessment [5]. Marginal silts and fly-ash-amended soils are promising as fine CBS layers because of their retention capacity and local availability, yet they tend to exhibit pronounced hysteresis, shrink-swell responses and greater sensitivity to rainfall-induced deformation than select granular backfills, implying that CBS benefits must be combined with explicit drainage provisions and

conservative stability checks, particularly under extreme rainfall [36]. From an environmental standpoint, RAP, RCA and steel slag all reduce dependence on virgin aggregates and landfill disposal of construction and Demolition wastes, but their net sustainability advantage should be quantified through life-cycle assessment rather than assumed solely from material reuse [46,47].

#### Wicking Geotextiles

Another alternative material to employ is called wicking geotextiles, which represent a newer class of geosynthetic materials that can be used as alternative or complementary layers in capillary barrier systems, combining capillary-break behaviour in the cross-plane direction with active lateral drainage in the in-plane direction [10]. Wicking products are engineered with multi-grooved nylon fibres that remain saturated at high suctions and provide continuous in-plane flow channels under unsaturated conditions [50].

Numerical and experimental studies on a proprietary woven wicking geotextile installed in road base courses shows that, unlike conventional hydrophobic woven geotextiles that act as persistent capillary barriers and effectively raise the groundwater table to the geotextile elevation [30,51]. Water-retention testing by [52] that woven wicking geotextiles have bimodal geotextile-water characteristic curves, with an inter-yarn air-entry value around 1–1.5 kPa controlling cross-plane capillary break and a much higher inner-yarn air-entry value (of the order of hundreds of kPa) associated with deep fiber grooves that remain water-filled and conductive over a wide suction range. Small soil-column capillary-barrier tests demonstrate that geotextiles containing 4DG wicking fibres in woven and nonwoven configurations can strongly reduce percolation to the underlying gravel (to about 5% of the imposed inflow) by laterally draining water stored above the interface and can progressively dissipate the moisture build-up associated with a capillary barrier once the vertical inflow ceases [52, 53].

Large-scale lysimeter and embankment simulations and recent road-embankment field trials further show that wicking geotextiles installed within silty-sand covers or base courses can both prevent undesirable capillary break under certain groundwater and rainfall scenarios and accelerate post-event drying by wicking water laterally to roadside drains, effectively acting as a thin, engineered capillary-barrier-drainage layer within the CBS [30,54].

In the broader CBS-RSS context outlined by the PRISMA review and design studies of inclined covers with capillary-barrier effect, thick or specially

engineered geotextiles are therefore increasingly recognised as viable alternatives to granular layers in the fine or coarse positions of a capillary barrier, offering tunable hydraulic response with reduced reliance on virgin aggregates in slopes, embankments and retaining structures [10,55].

The long-term performance of sustainable CBS-RSS systems must also be evaluated within the broader framework of adaptation to climate change, as the IPCC indicates an increase in the frequency and intensity of extreme precipitation events and modification to regional temperature and evapotranspiration regimes [56]. Indeed, higher rainfall intensities and longer storm clusters can accelerate wetting-drying degradation, increase the likelihood of local breakthrough and lead to more frequent or prolonged periods of elevated pore-water pressures, particularly in systems employing marginal or recycled backfills with nonstandard pore structures [1,39]. Temperature and moisture cycles may also influence the mechanical and hydraulic properties of RAP, RCA and steel slag through ageing, microcracking or chemical alteration, potentially modifying SWCCs and hydraulic conductivities over time [5,29]. These considerations underscore the need to incorporate climate-scenario loading into CBS-RSS design rainfall histories and to rely on long-term monitoring to detect gradual shifts in hydraulic response and material behaviour under evolving environmental conditions.

### **3.1.3. Materials: Research Gaps and Future Directions**

Research on sustainable alternatives for capillary barrier systems remains promising but still incomplete, particularly with respect to the characterization and standardization of recycled geomaterials, long-term field validation, and life-cycle assessment. Current evidence indicates that materials such as reclaimed asphalt pavement, recycled concrete aggregate, and steel slag can satisfy the hydraulic contrast required for capillary-barrier action, yet their soil-water characteristic curves, unsaturated hydraulic conductivity functions, and interface behaviour are not yet characterized in a sufficiently standardized manner for broad design adoption. This limitation is important because recycled materials often exhibit nonstandard particle morphology, bimodal pore structure, and time-dependent physic-chemical changes that may alter water-entry behaviour and invalidate protocols originally developed for natural soils.

A second research gap concerns durability under real operating conditions. Most available studies are laboratory based or limited to short monitoring periods, whereas multi-year field evidence on suction retention,

clogging, leachate effects, wetting-drying degradation, and breakthrough stability is still scarce for sustainable CBS configurations. The recent Bathurst lecture on geosynthetic MSE walls shows that the wider reinforced-soil community is already moving toward risk-based life-cycle evaluation, reliability assessment, and long-term sensor-supported management, which provides a clear methodological direction for CBS research as well. In this context, future sustainable CBS studies should be extended beyond proof-of-concept hydraulic tests to service-life monitoring under realistic climatic variability.

From a sustainability perspective, an important next step is the integration of life cycle impact assessment (LCIA) with conventional hydraulic performance evaluation. The PRISMA review identifies LCIA as a key future need because the environmental advantage of sustainable CBS materials cannot be assumed without quantifying transport, processing, construction, maintenance, and end-of-life effects relative to virgin granular alternatives. Miyata [13] complements this point by demonstrating that risk-based life cycle cost and  $CO_2$  emission assessment can be incorporated into geosynthetic earth structures through probabilistic failure analysis and recovery-cost estimation. Extending that framework to CBS would allow direct comparison of sustainable and virgin layer materials on a combined basis of hydraulic efficiency, economic resilience, and embodied environmental impact.

Although sustainable and alternative materials broaden the implementation possibilities of CBS, they also increase the need for long-term assessment and performance control. Materials that appear suitable in short-term tests may evolve under wetting-drying cycles, temperature variation, and reinforcement interaction, making monitoring essential for verifying their field behavior. This is where intelligent geotechnical analysis becomes relevant: real-time sensing, long-term observation, and data-driven methods can support material selection, detect performance changes, and improve predictive reliability. Therefore, monitoring and intelligence represent the final step in the review logic, transforming CBS from a passive barrier concept into an adaptive, measurable, and optimizable geotechnical system.

### **3.1.4. Monitoring and Intelligence Technologies**

Across the CBS-RSS literature, monitoring has evolved from isolated manual readings to dense sensor networks, controlled laboratory facilities and, more recently, data-driven analysis frameworks. Instrumentation now routinely targets matric suction, volumetric water content, pore-water pressure, stresses and deformations, providing time-series

datasets that can both validate numerical models and feed emerging AI-based prediction tools.

The PRISMA systematic review shows that most CBS-RSS studies rely on a common sensor palette: suction probes (high-capacity tensiometers), TDR/FDR water-content sensors and piezometers [10,57,58]. Within the Monitoring and AI/ML cluster by studies, several research deploy IoT-enabled sensor networks that stream suction, water content and pore-water pressure in real time, and a smaller group couples these data with machine-learning models for SWCC and permeability prediction, pointing toward digital-twin type applications.

Within the monitoring and AI/ML cluster of the review (15 out of 82 studies), several authors deploy distributed sensor networks with automated data acquisition, often using IoT-enabled nodes to stream suction, volumetric water content and pore-water pressure in near real time. Advanced applications also incorporate satellite or airborne interferometric synthetic aperture radar (InSAR) to track surface displacements over instrumented slopes and reinforced walls, while machine-learning models (e.g. support vector machines, gradient boosting and hybrid

neural networks) are trained on laboratory and field datasets to predict soil-water characteristic curve (SWCC) parameters, permeability and CBS performance indicators directly from index properties.

Table 4 presents a comparison of monitoring technologies reported for capillary barrier systems integrated with reinforced soil structures, including the main measured variables, advantages, limitations, recommended applications, and representative references drawn from the SLR report. The comparison indicates that no single technique is sufficient; effective monitoring generally requires a combination of direct hydraulic sensors, deformation measurements and, where feasible, distributed or remote methods that can support both local performance verification and broader asset-management objectives. A multi-sensor strategy is generally preferable because no single technology can capture suction evolution, hydraulic breakthrough, deformation, and asset-scale performance simultaneously. In practice, direct hydraulic sensors are best combined with deformation measurements and, where feasible, distributed or remote systems to support both local verification and longer-term asset management.

**Table 4: Comparison of Monitoring Technologies Reported for CBS–RSS Systems, Including Main Measured Variables, Advantages, Limitations, Recommended Applications, and Representative References**

Technology	Main variables	Advantages	Limitations	Recommended application in CBS–RSS	Representative reference(s)
High-capacity tensiometers	Matric suction	Direct measurement of unsaturated state; high temporal resolution; strong for validating wetting-front response	Cavitation risk; maintenance-sensitive; requires careful installation and calibration	Field validation of capillary barrier performance and breakthrough detection in slopes and walls	[6,59]
TDR/FDR moisture sensors	Volumetric water content	Continuous monitoring; relatively low cost; suitable for dense sensor arrays	Soil-specific calibration required; affected by installation quality and temperature effects	Tracking wetting-front progression, storage capacity, and post-rainfall drying	[60,61]
Piezometers	Pore-water pressure	Direct indicator of stability; useful for assessing drainage efficiency and safety margin	Limited sensitivity in highly unsaturated zones; point-based measurement only	Slope and wall safety assessment during rainfall and long-duration infiltration events	[6,25]
Inclinometers / LVDTs / displacement sensors	Lateral movement, settlement, deformation	Simple interpretation; useful for performance and serviceability checks	Provide indirect hydraulic information; localised response only	Monitoring deformation of reinforced slopes, facing movement, and wall serviceability	[60,62]
Fibre-optic sensing (DTS/DFOS)	Strain, temperature, moisture proxies	Distributed, long-range monitoring; suitable for embedded or continuous sensing along geosynthetics	Higher cost; installation complexity; interpretation requires advanced signal processing	Long-term intelligent monitoring of reinforcement layers and CBS functional zones	[7,13]
Wireless sensor networks / IoT nodes	Multi-sensor streams: suction, moisture, pressure, deformation	Real-time transmission; remote access; supports asset management and early warning	Power dependence; connectivity issues; cyber-security and maintenance concerns	Instrumented CBS–RSS demonstrators and digital-twin-ready monitoring systems	[9,63]

## Monitoring and Instrumentation in Capillary Barrier Systems

### *Geobarrier System*

For the GeoBarrier System (GBS) on a 70° residual-soil slope, [6] first used SEEP/W and SIGMA/W analyses to identify representative points within the fine RCA, coarse RCA and underlying residual soil where hydraulic and stress changes during rainfall would be most significant. These simulations guided a field instrumentation includes: tensiometers and soil-moisture sensors at TA-TD, earth-pressure cells at EP in three orthogonal directions, piezometers at the crest and toe to observe groundwater table fluctuations, and a weather station near the slope toe to record rainfall and evaporation for correlation with subsurface response, enabling direct assessment of GBS performance against model predictions.

### *Sand cushion system*

Balakrishnan and Viswanadham [62] realized centrifuge tests on geogrid-reinforced walls with marginal backfill used Linear Variable Differential Transformers (LVDT) along the crest to track settlements at 40 g and digital image analysis of high-speed photographs to obtain wall-face movements and reinforcement strain fields. A dedicated pullout box instrumented with an S-type load cell and potentiometers provided normal-stress-controlled load-displacement curves for soil-geogrid interfaces, linking centrifuge-scale deformation patterns to measurable interface properties under different moisture contents and obtain facing displacements and reinforcement strain distributions along each geogrid layer.

These combined datasets show, for example, that low-stiffness geogrids embedded in marginal soil at wet of optimum exhibit significantly reduced pullout resistance and excessive deformations, while stiffer geogrids mobilise higher interface friction and limit outward movements. Although the original study interpreted these measurements using conventional geotechnical methods, the data structure (time-stamped load-displacement histories, strain fields and settlement curves) is well suited for subsequent data-driven analysis, including inverse identification of interface parameters and pattern recognition of incipient failure modes.

Yang et al. [60] investigated GRS walls with sand cushions under artificial rainfall using an overhead nozzle array calibrated with 30 collection boxes to achieve uniform intensity, and a dense instrumentation layout measuring volumetric water content, pore-water

pressure, wall-facing displacement and reinforcement strains. Digital image correlation (DIC) on sequential wall-face images supplied full-field shear-strain maps and failure-surface evolution, while sensor data quantified how varying cushion thickness modified wetting-front progression and pore-pressure build-up inside the reinforced zone. The combined use of embedded sensors, rainfall simulators and DIC in these studies illustrates how high-resolution datasets can inform both traditional limit-equilibrium checks and more advanced, data-driven performance metrics for rain-resistant GRS walls.

### *Wicking Geotextiles*

Recent work on wicking geotextiles demonstrates how carefully instrumented laboratory setups can characterize both capillary and drainage performance, providing rich datasets for performance-based design. You et al. [61] evaluated a new wicking geotextile in loess-sand mixtures using three instrumented setups: visual capillary tests in transparent cells, evaporation tests in an environmental control box with an electronic balance, and drainage tests in acrylic columns with embedded geotextile layers and volumetric water-content sensors at three depths. Artificial rainfall was applied in controlled events, and continuous moisture monitoring allowed quantification of vertical wicking heights, evaporation rates and the temporal evolution of drainage efficiency relative to control columns without geotextile.

These experiments show that the wicking geotextile significantly accelerates water removal and that its influence extends up to several tens of centimeters above the fabric, insights that could be further leveraged in data-driven models linking fabric geometry, soil type and drainage performance.

Mohammed and Zornberg [64] designed soil columns to assess an enhanced lateral drainage (ELD) geotextile, instrumenting each column with five EC-5 moisture sensors at 2, 4, 5, 8 and 10 inches and logging data with an AZL6 datalogger to capture real-time water-content variations under water-table fluctuations and controlled surface infiltration. Sensor-calibration in the test soil and repeated wetting-drying cycles ensured accurate moisture readings, enabling precise delineation of the influence zone by geotextile and its drainage efficiency compared with a nonwoven geotextile and a no-geotextile control.

Transitioning from these macroscale and mesoscale configurations, researchers have also started to interrogate capillary barrier mechanisms at the pore scale and at the level of controlled climate

channels, thereby enriching the hierarchy of monitoring approaches available for intelligent CBS analysis.

Li et al. [65] used microfluidic chips with fine-coarse pore-network configurations to study capillary barrier effects (CBEs) at the pore scale under different injection rates and pore-size variabilities. The microfluidic devices comprised honeycomb pore lattices with distinct fine and coarse sections. High-resolution images of the evolving water-air interface were captured and processed: contrast enhancement isolated the invaded region, the perimeter of the wetted area was traced by connecting pore-body centers, and the invaded area was computed using dedicated software to obtain water saturation, trapped air patches were similarly identified to compute gas saturation. Monitoring in this context relied on high-resolution image sequences from an optical system, with image processing used to delineate invaded regions, compute water and gas saturations and track interface morphology, providing a purely visual yet quantitatively rich record of CBE development as a function of flow conditions.

At the intermediate scale between laboratory columns and field covers, [66] developed a 4 m x 0.4 m x 0.15 m 2D inclined channel equipped with a rainfall simulator (1500 needles), a calibrated solar-radiation system of metal-halide lamps, and HVAC-based control of air temperature and relative humidity to reproduce semi-arid climate sequences for landfill covers. Within the soil profile, 5TE probes measured volumetric water content, temperature and electrical conductivity at four depths, while MPS-6 probes and low-capacity tensiometers (LCT) monitored suction in clay and sand layers; runoff and bottom drainage were separately collected at dedicated outlets, allowing full water-balance assessment of conventional and capillary barrier covers over long test periods. A solar-radiation simulator consisting of eight 400 W metal-halide lamps was calibrated using a CMP-3 pyranometer to impose a target mean radiance of approximately  $440 \text{ W/m}^2$  at a distance of 27 cm from the soil surface, corresponding to typical semi-arid conditions.

Two long-term tests on a conventional compacted clay barrier and a capillary barrier (granular over clayey soil) under semi-arid climate sequences derived from Brazilian meteorological data demonstrate the capabilities of this monitoring system. Therefore, the 2D channel provides an ideal platform for coupling monitored data with hydro-mechanical models, and potentially for training data-driven surrogates or digital twins that emulate cover performance under arbitrary climate scenarios.

In combination, these studies illustrate a progression from point-based measurements to integrated, multi-scale monitoring systems—centrifuge packages, climate-controlled channels, wicking-column arrays and microfluidic visualization—which together underpin both conventional CBS performance assessment and emerging intelligent, data-driven analysis frameworks. The PRISMA highlights that the next step is to fuse such rich datasets—ranging from pore-scale microfluidic images to climate-controlled 2D channel measurements and field-scale sensor networks—into digital-twin frameworks where machine-learning algorithms assist in parameter updating, early-warning detection and optimal CBS design under uncertainty.

Despite their substantial potential, the deployment of sensor networks, fiber-optic systems, and Internet-of-Things (IoT)-based monitoring solutions for CBS-RSS applications in real-world field conditions is impeded by numerous practical constraints. For example, Tensiometers and water-content probes require careful installation to maintain good soil contact and are prone to calibration drift, cavitation and damage during construction or extreme events, which can compromise long-term data quality [6,57]. Distributed fiber-optic sensing offers high spatial resolution along reinforcement and drainage layers, but cables must be protected against mechanical damage, and the cost and complexity of signal interpretation can limit routine use [13]. Wireless IoT nodes depend on robust power supply and connectivity, which may be difficult to guarantee in remote slopes or embankments, and raise additional concerns related to data management and cyber-security [9]. These constraints suggest that intelligent monitoring should be incorporated into CBS-RSS design from the outset, with redundancy, progressive deployment and explicit maintenance strategies rather than as an afterthought.

### **3.1.5. Monitoring: Research Gaps and Future Directions**

The PRISMA review highlights two main gaps for CBS-RSS monitoring and intelligence: the lack of digital-twin integration that continuously fuses sensor data with numerical models, and the limited use of AI/ML for CBS design optimization and monitoring-based decision support. Existing field and laboratory studies show that high-quality data streams (suction, water content, Pore water pressure, stress, deformation, climate) can be collected reliably, but there is still no standardized framework to assimilate these data into predictive digital twins for CBS that update parameters and reliability metrics in real time.

From the perspective of Information and Communication Technology (ICT), Miyata [13]

mentioned to life-cycle management of geosynthetic MSE walls using long-term fiber-optic sensing combined with risk-based life-cycle cost and  $CO_2$  assessments. Translated to CBS, this suggests developing ICT-based life-cycle monitoring schemes in which distributed fiber optic sensors embedded in geosynthetics, together with conventional tensiometers and moisture probes, feed into asset-management platforms that track condition, trigger early warnings and support maintenance planning over decades rather than single storm events.

John and Pu [7] review of sustainable foundations shows that sensor-embedded, geosynthetics and intelligent soil with wireless sensor networks are already being used for real-time monitoring and predictive maintenance in broader geotechnical applications. For capillary barrier systems in Reinforced Soil Structures, this points to several promising intelligent geosynthetic configurations: wicking or enhanced-lateral-drainage geotextiles with integrated fiber-optic or electrical sensors to measure moisture and strain; geogrids and geocomposites acting simultaneously as reinforcement, capillary barrier and sensing layers; and Internet of Things (IoT)-enabled data loggers that transmit CBS state variables directly into cloud-based analytics engines. A closely related gap is AI-assisted material selection: while recycled aggregates (RCA, RAP, steel slag) and advanced geotextiles have been characterized hydraulically and mechanically, AI-based multi-criteria tools that rank candidate material combinations for CBS-balancing SWCC contrast, mechanical performance, cost and environmental footprint-are still largely conceptual and should be developed and validated using existing experimental databases.

Overall, intelligent monitoring and data-driven analysis can substantially enhance reliability based design, predictive maintenance and risk management of CBS-RSS systems. Time-series data on suction, water content, pore-water pressure, strain and displacement enable updating of resistance and load models, allowing engineers to track how factors of safety evolve under repeated storms and changing boundary conditions, and to explicitly account for uncertainties in material properties and climatic forcing [8,13]. Physics-informed machine-learning frameworks, such as hybrid VAE-GAN models for unsaturated Thermo Hydro Mechanical behaviour, offer a pathway to embed conservation laws in surrogate models trained on instrumented CBS datasets, which can then be deployed within digital twins for rapid scenario evaluation and early-warning analytics [67]. In this manner, CBS-RSS systems can evolve from static, design-only configurations into actively managed geotechnical assets, in which interventions are guided

by empirically observed performance, and risk can be managed proactively over the life cycle.

Extending such physics-informed models to CBS would allow the rich monitoring data collected from GeoBarrier slopes, climate-controlled 2D channels and instrumented wicking geotextile columns to be used not only for post-hoc interpretation, but to build surrogate models of CBS THM behaviour that can be embedded in digital twins, perform rapid scenario analyses and support AI-assisted design optimization under realistic climatic and loading conditions.

#### 4. LIMITATIONS AND FUTURE DIRECTIONS

This PRISMA-based review is constrained by its focus on peer-reviewed geotechnical journals and on studies where capillary barrier mechanisms are explicitly integrated into reinforced soil structures, which inevitably excludes some landfill covers, unreinforced slopes, grey literature and recent demonstrator projects that may contain relevant but less standardised evidence. The thematic clustering into sustainable CBS materials and intelligent monitoring/data-driven approaches remain in an early developmental stage with fragmented, case-specific coverage. In addition, the research gaps identified in the PRISMA synthesis lack of multi-year field validation for recycled CBS materials and nascent digital-twin integration for real-time monitoring underscore that the current evidence base is still insufficient to fully quantify long-term resilience and reliability under seismic, climatic and operational variability.

Future research should therefore prioritize coordinated field demonstrators of CBS-RSS systems constructed with recycled and marginal materials (e.g. RAP, RCA, steel slag) and instrumented for long-term ICT-enabled monitoring of suction, water content, pore-water pressure and deformations. Methodologically, for standardised SWCC and hydraulic testing protocols tailored to recycled geomaterials with atypical pore structures and time-dependent behaviour. At the monitoring and data-driven level, extending physics-informed data-driven frameworks-such as hybrid variational autoencoder-generative adversarial network (VAE GAN) models for unified unsaturated THM response-towards CBS-RSS applications offers a promising route to embed conservation laws within AI surrogates that are trained on instrumented CBS datasets and deployed inside digital twins for rapid scenario evaluation and early-warning analytics.

Based on of the reviewed evidence, a practical roadmap for implementing sustainable CBS-RSS systems can be articulated in four stages. First,

candidate recycled and marginal materials should be screened using SWCC, hydraulic conductivity, shear strength, durability and leachate criteria to ensure that they provide sufficient hydraulic contrast and mechanical robustness for the intended CBS function [5,29]. Second, pilot-scale test sections or small demonstrator slopes and walls should be constructed to validate CBS behaviour, breakthrough resistance and interaction with reinforcement under controlled or monitored rainfall. Third, these pilot and full-scale systems should be instrumented from the outset to capture suction, water content, pore-water pressure and deformation under real climatic variability, using robust sensor layouts tailored to the key failure mechanisms [6,62]. Finally, the resulting datasets should be assimilated into reliability-based design updates and, where feasible, physics-informed or data-driven surrogate models that support predictive maintenance, scenario analysis and climate-adaptive risk management for CBS-RSS infrastructure [13,67].

## 5. RECOMMENDATIONS

Given these constraints and gaps, CBS-RSS systems should presently be deployed as sustainable and smart alternatives with explicit recognition of their experimental status when recycled materials and advanced monitoring are used. For design practice, the review recommends that CBS-RSS schemes incorporating alternative materials treat hydraulic and mechanical properties of RCA, RAP and steel slag as uncertain and explicitly propagate this uncertainty through reliability-based or partial-factor design formats, rather than adopting deterministic parameter values derived from short-term laboratory tests. Designers should also adopt coupled hydro-mechanical analyses as the default for performance-based CBS-RSS design, reserving purely hydraulic or simplified methods for preliminary screening, and should begin to incorporate climate-change scenarios into design rainfall histories to explore marginal-backfill performance under more intense and more frequent storms.

For monitoring and data-driven implementation, the review recommends that future CBS-RSS projects be conceived from the outset as instrumented, ICT-ready assets, integrating tensiometers, moisture probes, fibre-optic sensors and IoT loggers into geosynthetics and backfill so that high-quality datasets can serve both performance verification and model calibration. In parallel, researchers should develop open, curated databases of CBS-RSS experiments and field observations-covering material properties, geometries, loading histories and sensor records-to enable benchmarking of AI/ML models for SWCC prediction, permeability estimation and CBS design optimisation, moving beyond isolated case-by-case applications.

From a practical geotechnical perspective, CBS-RSS systems are most relevant where rainfall infiltration and climate variability threaten slope stability and retaining-wall performance. Field and numerical studies on GeoBarrier Systems and internal capillary barriers in walls show that, when appropriately configured, CBS can maintain negative pore-water pressures in reinforced residual soils, limit pore-pressure build-up and reduce deformation during intense storms, even for steep slopes backfilled with marginal or recycled materials [25,45]. In slopes, this translates into higher factors of safety and delayed onset of rainfall-induced failures, while in reinforced walls it helps to control face displacements and internal stability under long-duration or repeated storm events [39,60]. Because marginal and recycled backfills are typically more sensitive to infiltration than select granular fills, combining CBS with geosynthetic reinforcement and targeted drainage should be regarded as an integral climate-resilience strategy rather than a purely hydraulic design detail [7,13].

Finally, closer collaboration between unsaturated-soil mechanicians, geosynthetic technologists and data-science specialists is essential for developing robust physics-informed AI tools and digital-twin workflows that are acceptable to practitioners and regulators for safety-critical applications in reinforced soil structures.

## 6. CONCLUSIONS

This PRISMA-compliant systematic review consolidates, the fragmented evidence on capillary barrier systems integrated into reinforced soil structures across two tightly coupled domains: sustainable and alternative materials, and monitoring technologies and data-driven approaches. By synthesizing 82 peer-reviewed studies, it provides a state-of-the-art map that links classic unsaturated-soil and geosynthetic capillary barrier research with recent advances in recycled geomaterials, intelligent geosynthetics and ICT-based life-cycle management of MSE/GRS walls. indeed, this review serves not merely as a technical synthesis but as a conceptual framework designed to facilitate the paradigm shift from traditional drainage and reinforced retaining wall methodologies toward performance-based, sustainability-driven, and data-integrated CBS-RSS systems.

From the materials perspective, the evidence shows that reclaimed asphalt pavement, recycled concrete aggregate, steel slag and marginal backfills can satisfy the hydraulic contrast and shear strength requirements of CBS layers while simultaneously reducing embodied energy, greenhouse-gas emissions and reliance on virgin aggregates when used within reinforced soil

systems. When coupled with geosynthetics that provide reinforcement, drainage and separation, these recycled materials enable hybrid CBS-RSS configurations with mechanical performance comparable to traditional solutions, but with clear advantages in life-cycle environmental metrics. At the same time, the review confirms that these sustainable CBS materials remain under-validated at field scale, with multi-year performance, leachate behaviour and standardized SWCC testing still open issues-meaning that CBS-RSS should presently be treated as a technically robust but still maturing sustainable alternative, where material uncertainties are handled explicitly in reliability-based design.

On the monitoring and data-driven side, the compiled studies demonstrate that CBS-RSS systems are inherently well suited to instrumentation, with field and laboratory work showing reliable multi-sensor monitoring of matric suction, volumetric water content, pore-water pressure, stress, deformation and climatic forcing. The Information and communication technology (ICT)-based asset management is increasingly deployed-it becomes evident that CBS-RSS can act as a natural testbed for intelligent earth-retaining structures that integrate sensing, analytics, and adaptive decision-making. Nevertheless, the review also shows that digital-twin integration and physics-informed AI for CBS remain at an early stage; sensor networks are seldom coupled to real-time numerical models, and machine learning is used mainly for property prediction rather than for full design optimization and operational decision support.

Taken together, the systematic review and the broader state-of-the-art literature support the view that capillary barrier systems incorporated into reinforced soil structures constitute a credible pathway toward sustainable and intelligent retaining solutions, provided they are designed and assessed within an unsaturated-mechanics and risk-based framework. As a sustainable alternative, CBS-RSS systems can leverage recycled and industrial by-product materials, geosynthetic reinforcement and drainage, and life-cycle assessment to reduce environmental burdens relative to conventional gravity and cantilever walls; as an intelligent alternative, they can exploit dense monitoring, ICT-based life-cycle management and emerging physics-informed, data-driven models to support digital twins, predictive maintenance and adaptive design updates. The utility of this review lies in making these linkages explicit: it provides a structured evidence base and research agenda that connect capillary barrier mechanisms and numerical tools with sustainable material innovation and smart monitoring, thereby positioning CBS-RSS as a

next-generation option for resilient, low-carbon, information-rich reinforced soil infrastructure

## 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.

## FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## REFERENCES

- [1] Li N, Jiang H, Li X. Behaviour of capillary barrier covers subjected to rainfall with different patterns. *Water* 2020; 12(11): 3133. <https://doi.org/10.3390/w12113133>
- [2] Rahardjo H, Zhai Q, Satyanaga A, Leong E, Wang C, Wong J. Numerical analyses for assessment of geobarrier system performance. In: *In PanAm Unsaturated Soils 2017*. 2017. <https://doi.org/10.1061/9780784481677.007>
- [3] Rahardjo H, Satyanaga A, Gofar N, Leong E, Kew J, Wang C, et al. Geobarrier System for Protection Against Rainfall-induced Slope Failure. *ISSMGE International Journal of Geoenvironment Case Histories* 2019; 5(1): 26-43. <https://doi.org/10.4417/IJGCH-05-01-03>
- [4] McCartney JS, Zornberg JG. Effects of infiltration and evaporation on geosynthetic capillary barrier performance. *Canadian Geotechnical Journal* 2010; 47(11): 1201-13. <https://doi.org/10.1139/T10-024>
- [5] Abishev R, Satyanaga A, Guney M, Lim A, Kim J. Use of steel slag and recycled concrete in geobarrier system for slope stabilization. *Frontiers in Built Environment* 2025; 11: 1598714. <https://doi.org/10.3389/fbuil.2025.1598714>
- [6] Rahardjo H, Kim Y, Gofar N, EC L, Wang C, JLH W. Field instrumentations and monitoring of GeoBarrier System for steep slope protection. *Transp Geotech* 2018; 16: 29. <https://doi.org/10.1016/j.trgeo.2018.06.006>
- [7] John CK, Pu JH. Sustainable foundations: Integration of recycled materials and geosynthetics in intelligent design. *Journal of Intelligent Geotechnical Engineering and Foundations* 2025; 1: 1-24. <https://doi.org/10.65904/3083-3590.2025.01.01>
- [8] Baghbani A, Choudhury T, Costa S, Reiner J. Application of artificial intelligence in geotechnical engineering: A state-of-the-art review. *Earth-Science Reviews* 2022; 228: 103991. <https://doi.org/10.1016/j.earscirev.2022.103991>
- [9] Rane N, Choudhary S, Rane J. Leading-edge artificial intelligence (ai) and internet of things (iot) technologies for enhanced geotechnical site characterization. Available at SSRN 4640926 2023. <https://doi.org/10.2139/ssrn.4640926>
- [10] Zornberg J, Bouazza A, McCartney J. Geosynthetic capillary barriers: current state of knowledge. *Geosynth Int* 2010; 17(5): 273-300. <https://doi.org/10.1680/gein.2010.17.5.273>
- [11] Zornberg J, Azevedo M, Pickles C. Evaluation of the Development of Capillary Barriers at the Interface between Fine-Grained Soils and Nonwoven Geotextiles. In: *Proceedings of the GeoChicago 2016 Conference*, Chicago, IL; vol. 2016-Janua. 2016, p. 159-67. <https://doi.org/10.1061/9780784480182.015>

- [12] Holtz R. 46th Terzaghi Lecture: Geosynthetic reinforced soil: From the experimental to the familiar. *J Geotech Geoenviron* 2017; 143(9): 1-21. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0001674](https://doi.org/10.1061/(ASCE)GT.1943-5606.0001674)
- [13] Miyata Y. Geosynthetic mse walls research and practice: past, present, and future (2023 igs bathurst lecture). *Geosynthetics International* 2025; 32(1): 62-81. <https://doi.org/10.1680/jgein.24.00054>
- [14] Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The prisma 2020 statement: an updated guideline for reporting systematic reviews. *bmj* 2021; 372. <https://doi.org/10.1136/bmj.n71>
- [15] Hong QN, Fàbregues S, Bartlett G, Boardman F, Cargo M, Dagenais P, et al. The mixed methods appraisal tool (mmat) version 2018 for information professionals and researchers. *Education for information* 2018; 34(4): 285-91. <https://doi.org/10.3233/EFI-180221>
- [16] Henry KS. The use of geosynthetic capillary barriers to reduce moisture migration in soils. *Geosynthetics International* 1995; 2(5): 883-8. <https://doi.org/10.1680/jgein.2.0040>
- [17] Stormont J, Henry K, Evans T. Water retention functions of four nonwoven polypropylene geotextiles. *Geosynth Int* 1997; 4(6): 661-72. <https://doi.org/10.1680/jgein.4.0110>
- [18] Holtz RD, Kovacs WD, Sheahan TC. *An introduction to geotechnical engineering*; vol. 733. Prentice-hall Englewood Cliffs, NJ; 1981.
- [19] Stormont JC. Incorporating capillary barriers in surface cover systems. In: *Landfill Capping in the Semi-Arid West: Problems, Perspectives, and Solutions*, Conference Proceedings, ESRF-019, Environmental Science and Research Foundation. 1997, p. 39-51.
- [20] Baker RS, Hillel D. Laboratory tests of a theory of fingering during infiltration into layered soils. *Soil Science Society of America Journal* 1990; 54(1): 20-30. <https://doi.org/10.2136/sssaj1990.03615995005400010004x>
- [21] Stormont JC, Morris CE. Method to Estimate Water Storage Capacity of Capillary Barriers. *Journal of Geotechnical and Geoenvironmental Engineering* 1998; 124(4): 297-302. [https://doi.org/10.1061/\(ASCE\)1090-0241\(1998\)124](https://doi.org/10.1061/(ASCE)1090-0241(1998)124)
- [22] McCartney JS, Kuhn JA, Zornberg JG. Geosynthetic drainage layers in contact with unsaturated soils. In: *proceedings of the international conference on soil mechanics and geotechnical engineering*; vol. 16. aabalkema publishers; 2005, p. 2301. <https://doi.org/10.3233/978-1-61499-656-9-2301>
- [23] Khire MV, Benson CH, Bosscher PJ. Water balance modeling of earthen final covers. *Journal of geotechnical and geoenvironmental engineering* 1997; 123(8): 744-54. [https://doi.org/10.1061/\(ASCE\)1090-0241\(1997\)123:8\(744\)](https://doi.org/10.1061/(ASCE)1090-0241(1997)123:8(744))
- [24] Miyazaki T. Water flow in unsaturated soil in layered slopes. *Journal of Hydrology* 1988; 102(1-4): 201-14. [https://doi.org/10.1016/0022-1694\(88\)90098-4](https://doi.org/10.1016/0022-1694(88)90098-4)
- [25] Chen Y, Gao Y, Ng CW. A new capillary barrier system for retaining wall backfilled with fine-grained soil. *Computers and Geotechnics* 2020; 118: 103324. <https://doi.org/10.1016/j.compgeo.2019.103324>
- [26] Li X, Li X, Wu Y, Gao L. A novel unsaturated drainage layer in capillary barrier cover for slope protection. *Bulletin of Engineering Geology and the Environment* 2023; 82(4): 108. <https://doi.org/10.1007/s10064-023-03093-8>
- [27] Thuo J, Yang K, Huang C. Infiltration into unsaturated reinforced slopes with nonwoven geotextile drains sandwiched in sand layers. *Geosynthetics International* 2015; 22(6): 457-74. <https://doi.org/10.1680/jgein.15.00026>
- [28] Chinkulkijniwat A, Horpibulsuk S, Bui Van D, Udomchai A, Goodary R, Arulrajah A. Influential factors affecting drainage design considerations for mechanical stabilised earth walls using geocomposites. *Geosynth Int* 2017; 24(3): 224-41. <https://doi.org/10.1680/jgein.16.00027>
- [29] Rahardjo H, Satyanaga A, Leong EC, Wang JY. Unsaturated properties of recycled concrete aggregate and reclaimed asphalt pavement. *Engineering Geology* 2013; 161: 44-54. <https://doi.org/10.1016/j.enggeo.2013.04.008>
- [30] Lin C, Zhang X, Galinmoghdam J, Guo Y. Working mechanism of a new wicking geotextile in roadway applications: A numerical study. *Geotextiles and Geomembranes* 2022; 50(2): 323-36. <https://doi.org/10.1016/j.geotexmem.2021.11.009>
- [31] Mitchell J, Zornberg J. Reinforced soil structures with poorly draining backfills part ii: case histories and applications. *Geosynthetics International* 1995; 2(1): 265-307. <https://doi.org/10.1680/jgein.2.0011>
- [32] Berg RR, Christopher BR, Samtani NC. *Design of mechanically stabilized earth walls and reinforced soil slopes-volume ii*. 2009.
- [33] Samtani N, Nowatzki E. Mechanically stabilized earth (mse) wall fills a framework for use of local available sustainable resources (lasr). 2021.
- [34] Rahardjo H, Santoso VA, Leong EC, Ng YS, Tam C, Satyanaga A. Use of recycled crushed concrete and secudrain in capillary barriers for slope stabilization. *Canadian Geotechnical Journal* 2013; 50(6): 662-73. <https://doi.org/10.1139/cgj-2012-0035>
- [35] Portelinha F, Zornberg J. Effect of infiltration on the performance of an unsaturated geotextile-reinforced soil wall. *Geotextiles and Geomembranes* 2017; 45(3): 211-26. <https://doi.org/10.1016/j.geotexmem.2017.02.002>
- [36] Jayanandan M, Viswanadham B. Geogrid reinforced soil walls with marginal backfills subjected to rainfall: numerical study. *Indian Geotechnical Journal* 2020; 50(2): 238-51. <https://doi.org/10.1007/s40098-019-00396-0>
- [37] Vibha S, Divya P. Performance of geosynthetic reinforced steep soil slopes at the onset of rainfall infiltration. In: *Proceedings of the Indian Geotechnical Conference 2019: IGC-2019 Volume V*. Springer; 2021, p. 167-76. [https://doi.org/10.1007/978-981-33-6466-0\\_15](https://doi.org/10.1007/978-981-33-6466-0_15)
- [38] Lal BRR, Padade A, Mandal J. Numerical simulation of eps geofoam as compressible inclusions in fly ash backfill retaining walls. In: *Ground improvement and geosynthetics*. Publication: Ground Improvement and Geosynthetics; 2014, p. 526-35. <https://doi.org/10.1061/9780784413401.052>
- [39] Parmar K, Ranjan R, Patel JB, Tandel Y, Vashi J. Numerical investigation of rainfall-induced instability of reinforced soil walls with select and marginal backfills. *Transportation Infrastructure Geotechnology* 2025; 12(5): 151. <https://doi.org/10.1007/s40515-025-00608-6>
- [40] Mills-Beale J, You Z. The mechanical properties of asphalt mixtures with recycled concrete aggregates. *Construction and Building Materials* 2010; 24(3): 230-5. <https://doi.org/10.1016/j.conbuildmat.2009.08.046>
- [41] Mariyappan R, Palammal JS, Balu S. Sustainable use of reclaimed asphalt pavement (rap) in pavement applications-a review. *Environmental Science and Pollution Research* 2023; 30(16): 45587-606. <https://doi.org/10.1007/s11356-023-25847-3>
- [42] Harnas F, Rahardjo H, Leong E, Wang J. Experimental study on dual capillary barrier using recycled asphalt pavement materials. *Canadian Geotechnical Journal* 2014; 51(10): 1165-77. <https://doi.org/10.1139/cgj-2013-0432>
- [43] Bhardwaj S, Aggrawal S, Gupta V, Pandey M. Use of recycled concrete aggregate in construction. *Int J Emerg Technol Eng Res IJETER* 2016; 4(10): 81-7.
- [44] Tam VW, Soomro M, Evangelista ACJ, Haddad A. Deformation and permeability of recycled aggregate concrete-a comprehensive review. *Journal of Building Engineering* 2021; 44: 103393. <https://doi.org/10.1016/j.jobbe.2021.103393>
- [45] Rahardjo H, Harnas F, Satyanaga A, Leong E, Wang C, Wong J. Numerical simulation of Geobarrier System under rainfall infiltration. *Landslides and Engineered Slopes Experience, Theory and Practice* 2019; 5(1): 1699-706. <https://doi.org/10.1201/9781315375007-200>

- [46] Vieira CS, Pereira PM. Use of recycled construction and demolition materials in geotechnical applications: A review. *Resources, Conservation and Recycling* 2015; 103: 192-204. <https://doi.org/10.1016/j.resconrec.2015.07.023>
- [47] Park T. Application of construction and building debris as base and subbase materials in rigid pavement. *Journal of Transportation Engineering* 2003; 129(5): 558-63. [https://doi.org/10.1061/\(ASCE\)0733-947X\(2003\)129:5\(558\)](https://doi.org/10.1061/(ASCE)0733-947X(2003)129:5(558))
- [48] Arulrajah A, Piratheepan J, Disfani MM, Bo MW. Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. *Journal of Materials in Civil Engineering* 2013; 25(8): 1077-88. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000652](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000652)
- [49] Poon CS, Chan D. Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. *Construction and Building Materials* 2006; 20(8): 578-85. <https://doi.org/10.1016/j.conbuildmat.2005.01.045>
- [50] Koerner RM. *Designing with geosynthetics-Vol. 1; vol. 1*. Xlibris Corporation; 2012.
- [51] Jarjour J, Meguid M, Bhat S. Drainage performance of wicking geotextiles under rainfall and capillary rise conditions. *Geosynthetics International* 2026; 33(1): 109-24. <https://doi.org/10.1680/jgein.25.00030>
- [52] Azevedo M, Zornberg J. Capillary barrier dissipation by new wicking geotextile. In: *Panamerican conference on unsaturated soils*. 2013, p. 20-2. <https://doi.org/10.1201/b14393-88>
- [53] Pickles C, Zornberg J. Hydraulic classification of unsaturated nonwoven geotextiles for use in capillary barriers. In: *Proceedings of GeoAmericas 2012, the second Pan-American Geosynthetics Conference*. 2012, p. 1-4.
- [54] Krisdani H, Rahardjo H, Leong E. Experimental study of 1-d capillary barrier model using geosynthetic material as the coarse-grained layer. In: *Unsaturated Soils 2006*. 2006, p. 1683-94. [https://doi.org/10.1061/40802\(189\)141](https://doi.org/10.1061/40802(189)141)
- [55] Henry KS, Holtz RD. Geocomposite capillary barriers to reduce frost heave in soils. *Canadian Geotechnical Journal* 2001; 38(4): 678-94. <https://doi.org/10.1139/t01-010>
- [56] Lee H, Calvin K, Dasgupta D, Krinner G, Mukherji A, Thorne P, et al. *ipcc, 2023: Climate change 2023: Synthesis report, summary for policymakers. contribution of working groups i, ii and iii to the sixth assessment report of the intergovernmental panel on climate change [core writing team, h. lee and j. romero (eds.)]. ipcc, geneva, switzerland. Tech. Rep.; Intergovernmental Panel on Climate Change (IPCC); 2023.*
- [57] Tami D, Rahardjo H, Leong EC, Fredlund DG. Design and laboratory verification of a physical model of sloping capillary barrier. *Canadian Geotechnical Journal* 2004; 41(5): 814-30. <https://doi.org/10.1139/t04-036>
- [58] Garcia E. *Function of permeable geosynthetics on artificial unsaturated embankments subjected to rainfall infiltration*. Master's thesis; 2005.
- [59] Hamdany AH, Shen Y, Satyanaga A, Rahardjo H, Lee TTD, Nong X. Field instrumentation for real-time measurement of soil-water characteristic curve. *International Soil and Water Conservation Research* 2022; 10(4): 586-96. <https://doi.org/10.1016/j.iswcr.2022.01.007>
- [60] Yang KH, Wu HM, Tseng TL, Yoo C. Model tests of geosynthetic-reinforced soil walls with marginal backfill subjected to rainfall. *Geotextiles and Geomembranes* 2023; 51(2): 342-59. <https://doi.org/10.1016/j.geotexmem.2022.12.002>
- [61] You Z, Xu J, Liu H, Peng Y, Zhang Z. Laboratory evaluation of water absorption and drainage performance of a new wicking geotextile in loess-sand mixtures. *Geotextiles and Geomembranes* 2025; 53(6): 1558-76. <https://doi.org/10.1016/j.geotexmem.2025.08.003>
- [62] Balakrishnan S, Viswanadham B. Performance evaluation of geogrid reinforced soil walls with marginal backfills through centrifuge model tests. *Geotextiles and Geomembranes* 2016; 44(1): 95-108. <https://doi.org/10.1016/j.geotexmem.2015.06.002>
- [63] Guilhot D, Hoyo TMD, Bartoli A, Ramakrishnan P, Leemans G, Houtepen M, et al. Internet-of-things-based geotechnical monitoring boosted by satellite insar data. *Remote Sensing* 2021; 13(14): 2757. <https://doi.org/10.3390/rs13142757>
- [64] Mohammed SA, Zornberg JG. Assessing the influence zone and drainage efficiency of geotextiles with enhanced lateral drainage abilities in unsaturated soil systems. *Geosciences* 2026; 16(1): 22. <https://doi.org/10.3390/geosciences16010022>
- [65] Li Gy, Zhan Lt, Chen Ym, Feng S, Zhang Zh, Du Xi. Effects of flow rate and pore size variability on capillary barrier effects: A microfluidic investigation. *Canadian Geotechnical Journal* 2022; 60(6): 902-16. <https://doi.org/10.1139/cgj-2022-0298>
- [66] da Hora Lôbo BR, Machado SL, Filho EPM. Assessment of cover layers using an instrumented 2d channel with control for climate conditions. *International Journal of Civil Engineering* 2023; 21(9): 1433-45. <https://doi.org/10.1007/s40999-023-00839-z>
- [67] Ajdari M, Vahedifard F, Amiratifi A. Physics-informed data-driven modeling of unsaturated soils under thermo-hydro-mechanical loading conditions. *Journal of Geotechnical and Geoenvironmental Engineering* 2025; 151(10): 04025108. <https://doi.org/10.1061/JGGEFK.GTENG-13239>

<https://doi.org/10.65904/3083-3590.2026.02.05>

© 2026 Guzmán-Martínez *et al.*

This is an open access article licensed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>) which permits unrestricted use, distribution and reproduction in any medium, provided the work is properly cited.