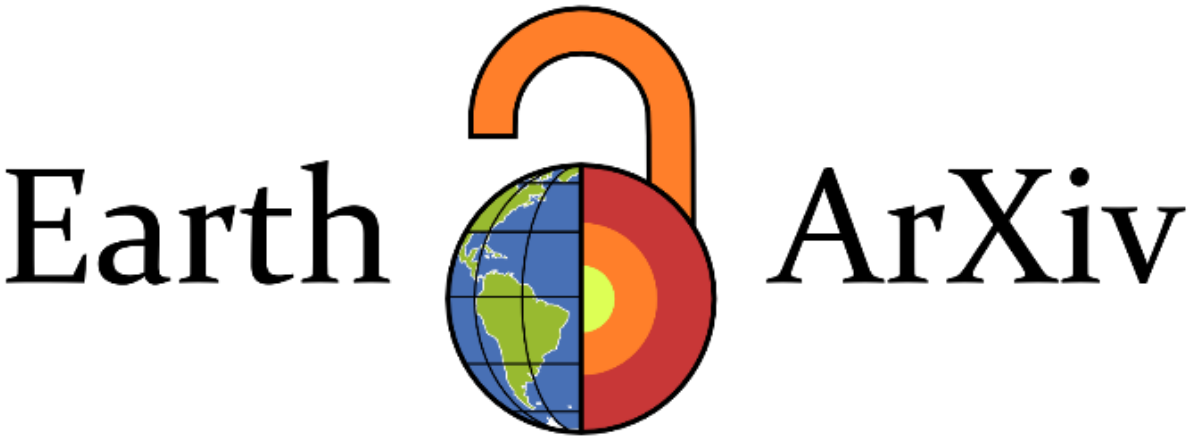

Climate as the Primary Moderator: Towards Context-Driven Design and Implementation of Vertical Greenery Systems for Stormwater Management

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Abstract

Urbanisation intensifies stormwater management challenges by expanding impervious surfaces, increasing flood risk and degrading water quality. Vertical Greenery Systems (VGS) are increasingly promoted as nature-based solutions for space-constrained cities, yet their performance remains highly variable and context-dependent. This systematic review, conducted in accordance with PRISMA guidelines and synthesising evidence from 34 peer-reviewed studies, demonstrates that VGS hydrological efficacy is not a universal constant but is fundamentally moderated by local climatic conditions. Climate acts as the primary filter, shaping system function across tropical, temperate, Mediterranean, arid, and cold zones, each presenting distinct opportunities and constraints. Beyond climate, performance is refined by system typology (green façades versus living walls), plant functional traits (notably root architecture), and substrate composition, which together determine trade-offs between runoff delay, retention, and water quality improvement. The review further reveals a stark divergence in adoption barriers: in the Global North, high costs, regulatory complexity, and data gaps create institutional inertia, whereas in the Global South, limited awareness, misaligned priorities, and weak policy frameworks relegate stormwater management to a low priority. To address these challenges, we propose a five-pillar implementation framework centred on climate-responsive design protocols, advanced economic valuation of co-benefits, adaptive governance, long-term monitoring, and context-sensitive community engagement. This review provides actionable, evidence-based guidance for integrating VGS as resilient, equitable, and multifunctional components of sustainable urban water management, tailored not to global templates, but to local environmental and socio-institutional realities.

Keywords: Green Walls, Vertical greenery systems (VGS), Building Envelope, Stormwater management, Green Infrastructure

1. Introduction

Urban areas worldwide are experiencing unprecedented growth, with over 55% of the global population residing in cities and projections indicating this figure will reach 68% by 2050 [1]. This rapid urbanisation has dramatically transformed natural landscapes into densely built environments characterized by expansive impervious surfaces, including

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buildings, roads, and parking lots [2, 3]. These impermeable surfaces fundamentally alter the natural water cycle by preventing water infiltration, significantly increasing the volume and velocity of stormwater runoff, and reducing groundwater recharge [4, 5, 6]. This disruption exacerbates global environmental challenges, including habitat fragmentation, urban heat island (UHI) effects, and carbon emissions, which collectively undermine progress toward the United Nations Sustainable Development Goals (SDGs) and climate resilience targets.

The consequences of this disruption are manifold: increased flood risks, deteriorated water quality in receiving water bodies, erosion of urban streams, and heightened pressure on ageing drainage infrastructure [7, 8, 9]. Traditional stormwater management systems, primarily comprising grey infrastructure such as pipes, culverts, and centralized treatment facilities, often prove inadequate in addressing these challenges, particularly as climate change intensifies precipitation patterns and extreme weather events leading to increased pressure on urban drainage systems [10, 11, 12]. The economic impacts of urban flooding alone are staggering, with annual damages estimated to exceed tens of billions of dollars globally, highlighting the urgent need for innovative and sustainable solutions [13, 14].

To address these challenges, Nature-Based Solutions (NBS) have emerged globally as a transformative approach to urban water management. Recognised by international bodies such as the European Commission and the United Nations, NBS refer to actions inspired and supported by nature that simultaneously provide environmental, social, and economic benefits, aligning with global agendas such as the Paris Agreement and the Kunming-Montreal Global Biodiversity Framework[15, 16]. These solutions aim to enhance resilience and sustainability by working with natural processes rather than relying solely on conventional engineering methods [17, 18]. Within this framework, Green Infrastructure (GI), a term often used interchangeably with NBS but more specifically referring to the network of natural and semi-natural systems designed into urban environments, plays a pivotal role. GI includes a diverse range of interventions such as bioswales, permeable pavements, green roofs, rain gardens, and increasingly VGS [19, 20]. These approaches are gaining momentum in policy frameworks worldwide, with many major cities implementing comprehensive GI strategies to enhance urban resilience, biodiversity, and water quality [21, 22, 23]. VGS, in particular, exemplify a multifunctional NBS that addresses interconnected crises of urbanisation, climate change, and biodiversity loss by merging hydrological performance with ecological restoration [24, 25].

Vertical Greenery Systems (VGS), also termed vertical gardens, green walls, or living walls, are vegetated structures installed on building facades that transform vertical surfaces into multifunctional ecosystems [26]. VGS can be broadly classified into two primary categories, as illustrated in Figure 1, green façades (ground-based systems with climbing plants) and living walls (wall-based systems with substrates) [31]. Green façades utilize climbing plants rooted in the ground or planters that grow along supportive structures such as cables, meshes, or trellises [27, 28]. In contrast, living walls incorporate growing media directly into the vertical structure, supporting a more diverse range of plant species through various modular systems, including panel systems, felt systems, and container systems [29]. This structural distinction is crucial for understanding their stormwater management potential, as substrate volume, composition, and placement directly influence water retention capacity and evapotranspiration rates [30], while their vertical orientation maximizes space efficiency in dense cities—a critical advantage for achieving SDG 11 (Sustainable Cities and Communities).

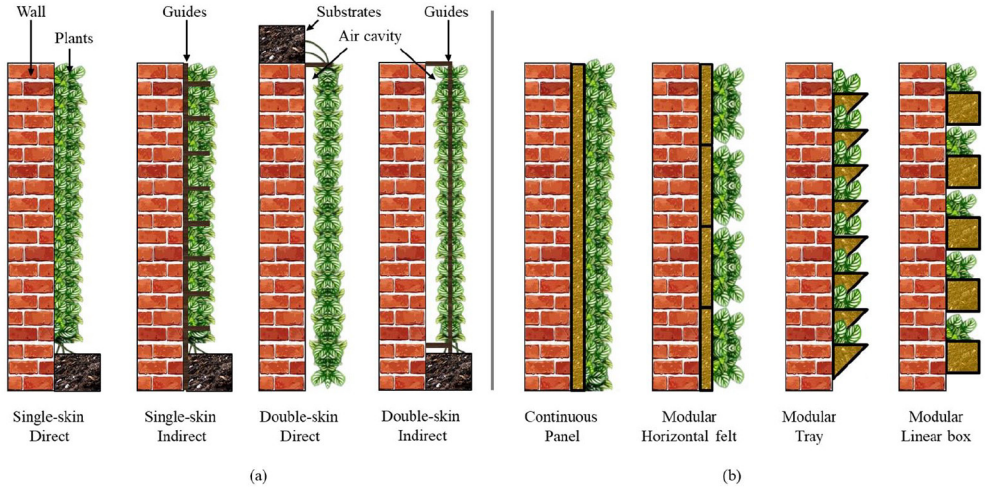

Figure 1: Schematic diagram illustrating the two primary types of VGS: (a) green façades, which utilize climbing plants rooted at ground level or in planters, and (b) living walls, which integrate growing media directly into the vertical structure to support a diverse range of plant species. [31]

Beyond stormwater management, VGS contribute to broader planetary health goals [32, 33, 34, 35]. During rainfall events, vegetation intercepts precipitation, reducing the kinetic energy of raindrops and delaying runoff [36]. The substrate and growing medium then retain a significant portion of this rainfall, with storage capacities varying based on substrate depth, composition, and antecedent moisture conditions [37, 38]. Water retained in the substrate is subsequently released through evapotransipration, completing the cycle and restoring capacity for future rainfall events [39]. Field studies have demonstrated considerable retention efficiencies, with living walls capable of retaining a significant amount of rainfall, depending on climate conditions and design specifications [30, 36, 40]. By mitigating flood risks VGS directly support climate adaptation efforts outlined in the IPCC's Sixth Assessment Report [41]. Beyond volume reduction, VGS also improve water quality by filtering sediments, absorbing pollutants, and supporting microbial communities that break down contaminants [42]. This multifunctional performance addresses both quantity and quality aspects of stormwater management while advancing SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action) [43, 44, 45, 46]

Despite their recognised potential, VGS remain underutilised in mainstream urban planning. While various studies have documented VGS benefits in isolated contexts, the lack of comprehensive evaluations that synthesize both quantitative and qualitative evidence limits our understanding of the factors influencing their performance and adoption [47] . This review addresses these knowledge gaps by critically evaluating existing literature through a climate-stratified lens to identify how contextual and design-specific factors shape VGS performance and adoption, moving beyond universal claims toward actionable, place-based guidance. By contextualising VGS within global sustainability frameworks, this synthesis aims to bridge the gap between niche green technologies and scalable strategies for resilient, equitable cities in the face of climate change.

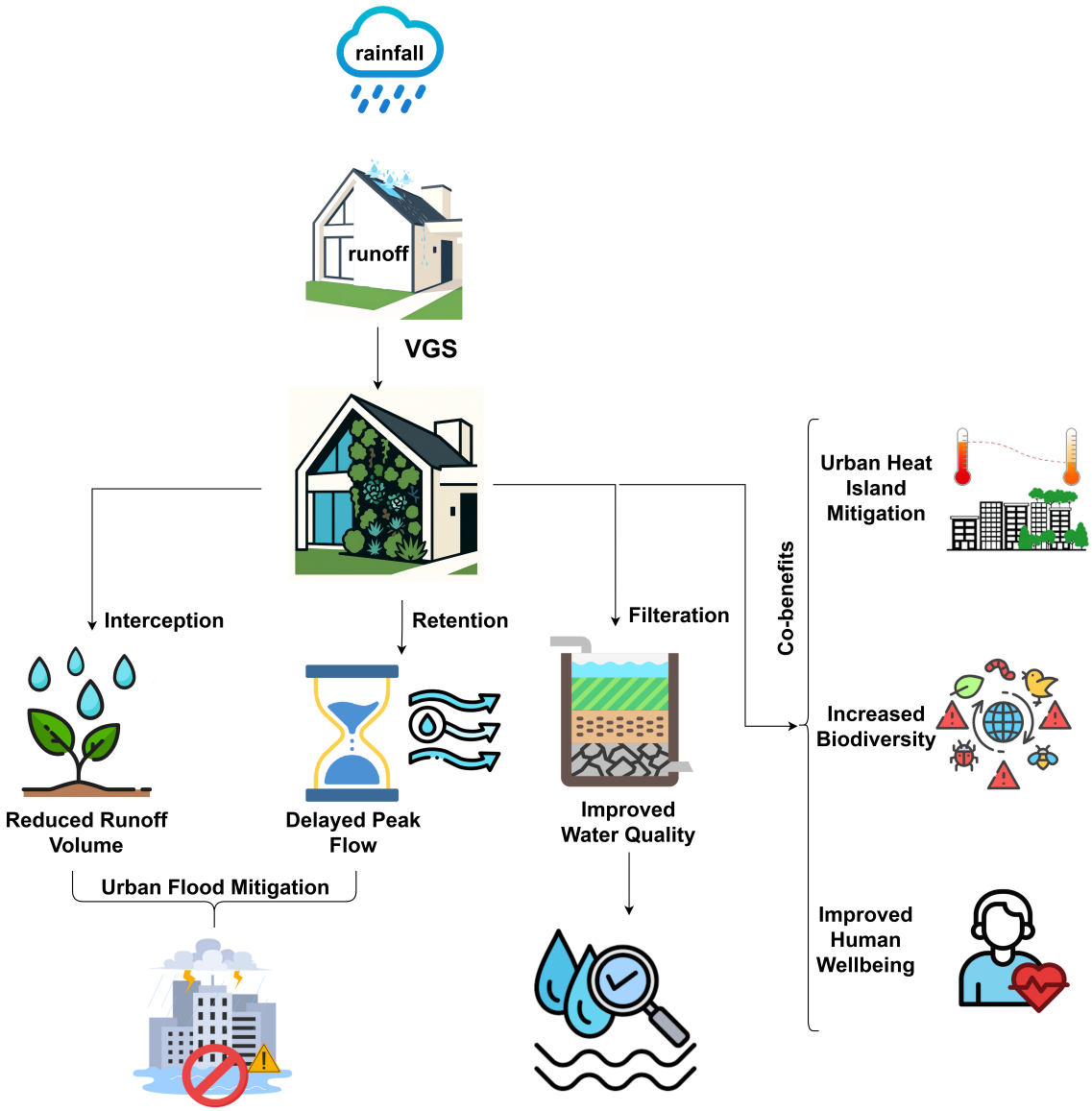

Figure 2: Schematic diagram illustrating the stormwater management process and multifunctional benefits of VGS, including rainfall interception, retention, evapotranspiration, pollutant filtration, and co-benefits such as urban cooling and biodiversity enhancement.

2. Methodology

2.1. Review Design and Objectives

This systematic review was meticulously designed to investigate the role of VGS in urban stormwater management, focusing on their effectiveness, including runoff reduction and pollutant removal, and the factors influencing their performance and practical adoption. The review adheres to established systematic review protocols, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure a transparent, reproducible, and methodologically rigorous process [48]. The overarching research question guiding the review is: How effective are VGS in managing stormwater runoff in urban environments, and what factors influence their performance and adoption? This question served as the foundation for selecting studies, extracting data, and synthesising findings, aiming to provide a comprehensive and interdisciplinary understanding of the topic. Additionally, the review aims to identify pathways for scaling

and optimising green wall technologies as part of broader urban climate adaptation strategies.

2.2. Search Strategy and Eligibility Criteria

A systematic literature search was conducted across two major multidisciplinary databases, Scopus and Web of Science. The search strategy combined green wall terminology (VGS, green walls, living walls, green façades) with stormwater management terms (runoff reduction, infiltration, urban drainage, water quality improvement). Boolean operators and phrase searching were applied to refine the search string:

("Vertical greenery systems" OR "Green walls" OR "Living walls" OR "Vertical gardens" OR "Vegetated walls" OR "Vertical vegetation" OR "Green facades" OR "Bio walls" OR "Vertical landscaping" OR "Plant walls" OR "Plant clad walls" OR "Vertical vegetation systems" OR "Vertical greening" OR "Climbing plants on walls" OR "Wall-mounted greenery" OR "Living architecture") AND ("Stormwater" OR "Rainwater" OR "Runoff" OR "Retention" OR "Stormwater runoff control" OR "Stormwater management" OR "Stormwater mitigation" OR "Water infiltration" OR "Stormwater quality" OR "Water quality improvement" OR "Stormwater treatment" OR "Urban hydrology" OR "Urban drainage" OR "Sustainable urban drainage" OR "Urban water management" OR "Hydrological performance" OR "Green Stormwater Infrastructure" OR "Best management practices" OR "Rainwater management" OR "Rainwater control" OR "Rainwater harvesting" OR "Sustainable drainage systems (SuDS)" OR "Flood mitigation").

To ensure the relevance and quality of the evidence base, pre-defined eligibility criteria were applied. Studies were included if they: (i) empirically investigated VGS integrated into built environments; (ii) quantitatively or qualitatively reported on stormwater-related outcomes (e.g., runoff reduction, peak flow attenuation, pollutant removal); and (iii) discussed influencing factors related to system design, vegetation, or implementation context. The review was limited to peer-reviewed journal articles published in English. Editorials, conference proceedings, and theoretical studies without empirical data were excluded.

2.3. Study Selection Process

The study selection process adhered to PRISMA guidelines, involving identification, screening, eligibility assessment, and inclusion phases. The PRISMA flow diagram Figure 3, illustrates the study selection process, from initial database searches to final inclusion of 34 articles. Initially, 257 articles were retrieved from Scopus and Web of Science, which were reduced to 176 after applying inclusion filters. Duplicate removal further refined the dataset to 118 unique articles. These articles underwent a rigorous title and abstract screening to evaluate their relevance, excluding 38 studies that did not focus on VGS, lacked a stormwater emphasis, or failed to provide empirical data. Full-text reviews were conducted for the remaining 80 articles, resulting in the exclusion of 46 studies that did not meet the inclusion criteria. Ultimately, a final dataset of 34 articles was selected, forming the evidence base for the review.

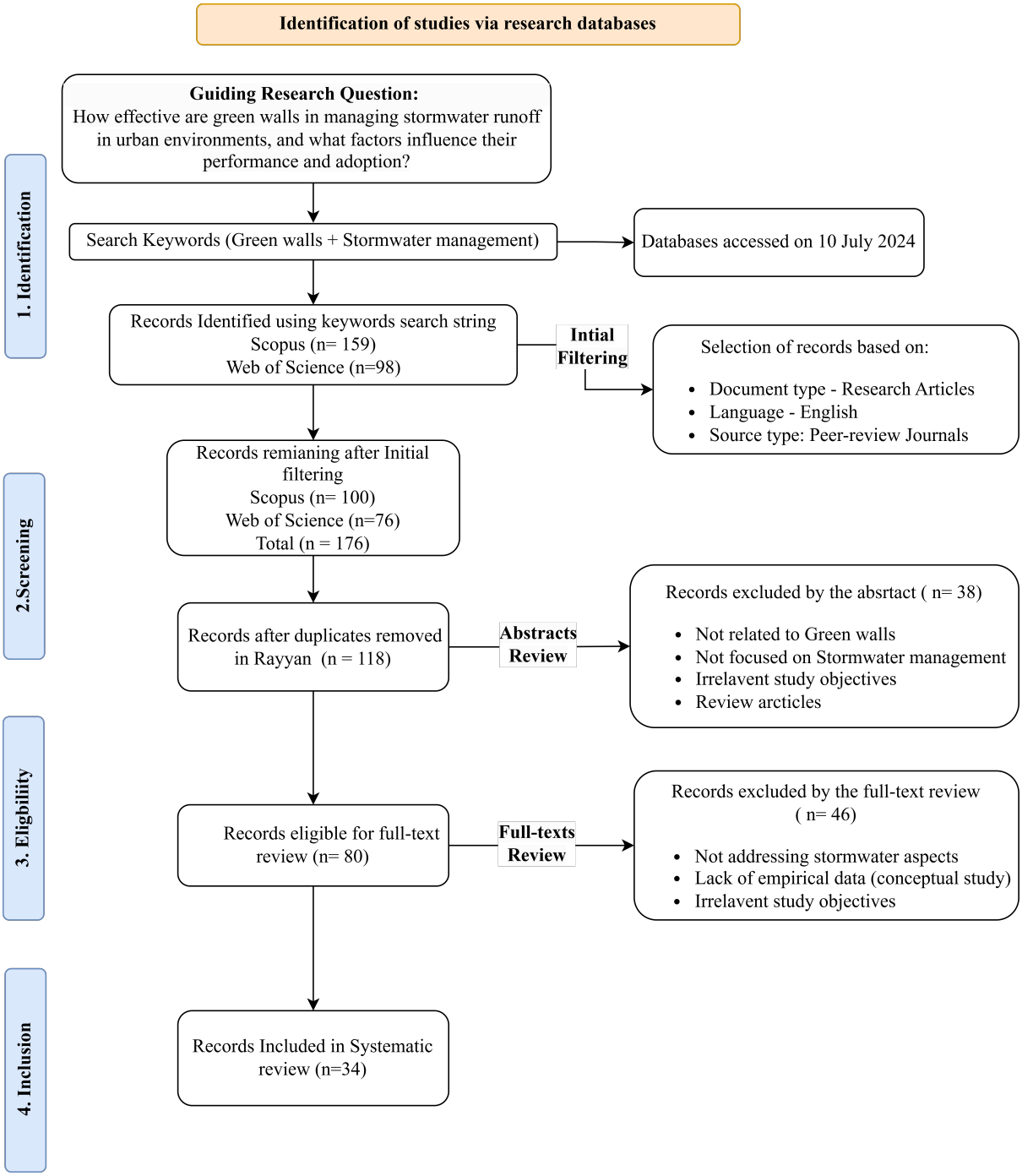

Figure 3: PRISMA flow diagram illustrating the systematic study selection process. The search identified 257 records from Scopus and Web of Science. After initial filtering for peer-reviewed English articles, 176 records remained. Following duplicate removal, 118 unique records were screened by abstract, resulting in 80 eligible for full-text review. A final 34 studies were included in the systematic review after applying eligibility criteria focused on empirical data related to VGS and stormwater management.

2.4. Data Extraction and Synthesis

To enable the stratified synthesis presented in the results, data from the 34 included studies were extracted into a standardised framework designed to capture the key moderators of performance. The extraction protocol was organised around the following domains, which were pre-identified as potential sources of variation:

- Climate and Geographic Context: Location, Köppen-Geiger climate classification,

and hemisphere, as detailed in Figure 4.

- System Design and Typology: VGS type (Green Façade vs. Living Wall), specific wall design, substrate/media type and depth, and irrigation source (e.g., rainwater, greywater).
- Biological and Material Components: Plant species and their documented functional traits (e.g., root architecture, evapotranspiration rate, drought resilience).
- Performance Metrics: Quantitative and qualitative data on stormwater runoff reduction, water retention capacity, peak flow mitigation, and pollutant removal efficiencies.
- Implementation Context: Reported economic costs, maintenance requirements, policy gaps, and social or regulatory barriers.

Given the significant heterogeneity in methodologies, scales, and reporting formats among the studies, a quantitative meta-analysis was not feasible. Instead, we employed a thematic synthesis following the approach of Thomas and Harden [49], complemented by population-adjustment techniques for aggregate data as described by Remiro-Azócar et al. [50]. This involved stratifying the studies into comparative groups based on the primary moderators: first by climate zone, and then within those groups by system design and component selection, e.g., substrate depth, vegetation type, drainage configuration. This analytical approach allowed the identification of patterns and explanations for disparate findings, forming the basis for the hierarchical framework of influencing factors developed and discussed using principles of thematic synthesis and contextual moderation.

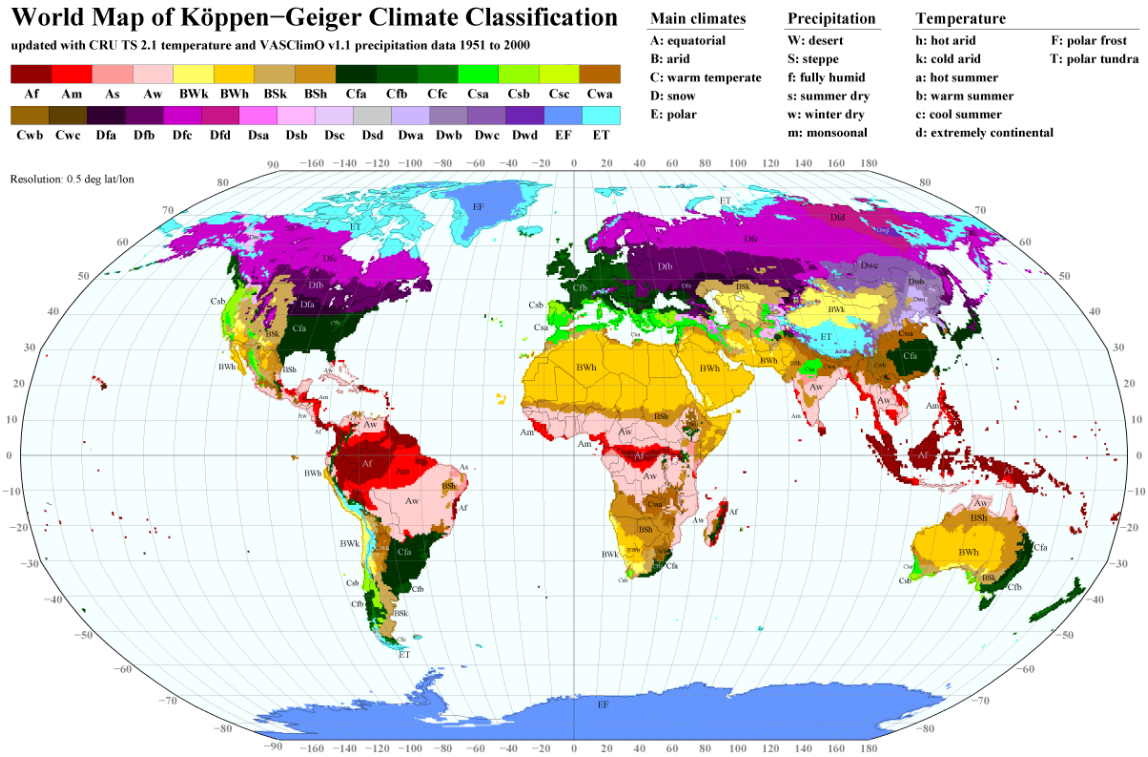

Figure 4: World Map of Köppen-Geiger Climate Classification [51]. This system categorizes climate based on temperature, precipitation, and seasonal patterns, providing a standardized framework for analysing environmental data.

3. Results

This systematic review synthesises data from 34 studies on VGS to move beyond generalised performance claims. The geographic distribution of these studies spans diverse global contexts, with notable concentrations in Europe, East Asia, Australia, and North America, while revealing limited representation from Africa and South America as shown in Figure 5. This distribution underscores both the global interest in VGS and specific regional research gaps. Our analysis reveals that the effectiveness of VGS in stormwater management is not a universal constant but is predominantly moderated by a hierarchy of contextual and design factors. The following sections present a stratified synthesis, beginning with the overriding influence of climate, to disentangle these complex relationships and identify the primary drivers of system performance.

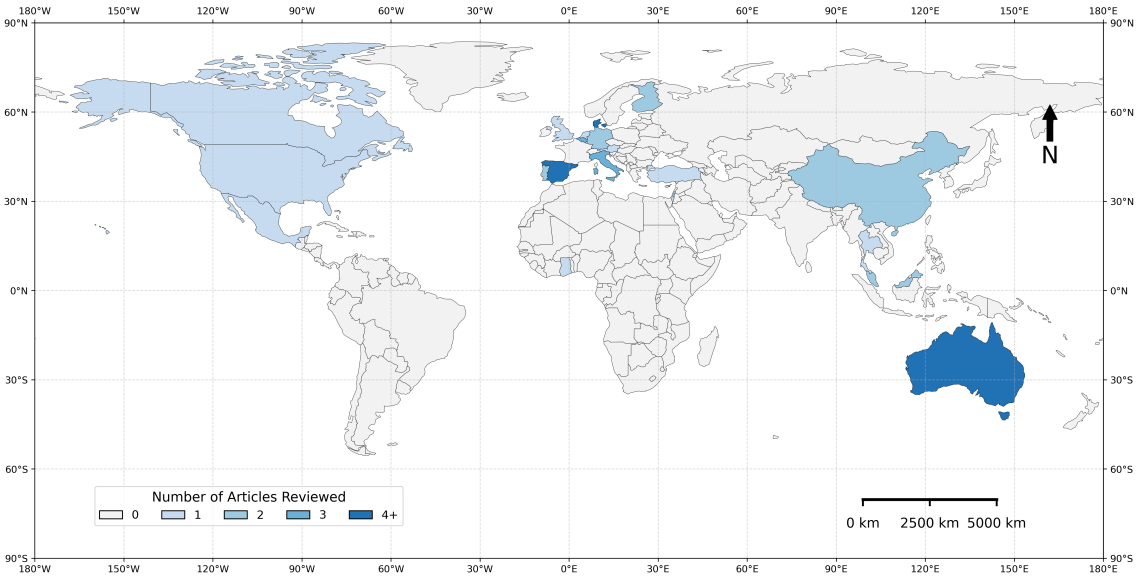

Figure 5: Geographic Distribution of Studies on VGS and Stormwater Management included in this systematic review. The map highlights strong research representation in Europe, East Asia, Australia, and North America, with notable gaps in Africa, South America, and large parts of Asia.

3.1. A Meta-Framework for VGS Performance: The Primacy of Climate

The Köppen-Geiger climate classification, as illustrated in Figure 4, provides a critical lens through which to analyze the disparate performance metrics reported in the literature [52]. Grouping the studies into major climate zones reveals distinct patterns, challenges, and optimal design strategies, effectively controlling for the significant confounding variable of geographic location.

In temperate regions, which constitute a significant portion of the studied systems, e.g., [53, 54, 55, 56, 57], VGS performance is characterised by its strong seasonality and reliance on evapotranspiration. The synthesis indicates that well-designed systems can effectively manage frequent, low-to-moderate intensity rainfall. For instance, a fully-foliated green façade in the UK demonstrated a substantial precipitation interception capacity of 54–94%, effectively delaying runoff by 30 minutes or more [55]. However, performance is highly contingent on solar exposure.

A study in the northeastern USA (Northern Hemisphere) found that southeast-facing walls retained approximately 18% more water than northwest-facing orientations due to greater solar exposure and higher evapotranspiration rates [30]. This orientation effect is

hemisphere-dependent, in the Southern Hemisphere, north-facing walls receive equivalent insolation and are expected to outperform south-facing orientations. This underscores a critical design consideration for the Northern Hemisphere that is often overlooked in generic guidelines. The primary challenge in these climates is maintaining functionality during cold periods. Studies noted reduced infiltration rates at 2°C [53] and the necessity for winter drainage to prevent freezing damage [30, 58], highlighting a seasonal performance limitation that must be accounted for in annual hydrological models.

In water-stressed Mediterranean and semi-arid climates, the function of VGS shifts from managing excess water to optimising retention and reuse. The analysis shows that systems here must balance high evapotranspiration demand with limited water availability. Research in Italy demonstrated that modular living walls with lightweight, water-retentive substrates like a mixture of Irish peat and perlite could retain 21–24% of stormwater volume and reduce peak flows by up to 79% [59, 40]. Similarly, a study in Mexico highlighted the effectiveness of hybrid wetland prototypes using Eichhornia crassipes for both water retention and contaminant removal, pointing to the value of multi-functional design in resource-scarce environments [60]. A key insight from this climate group is the strategic opportunity for greywater integration. Studies in Australia and across Southern Europe [61, 62, 63] consistently found that using greywater to supplement irrigation bridges the soil moisture deficit during extended dry periods, turning VGS from a seasonal stormwater solution into a year-round water treatment and recycling asset.

The defining challenge for VGS in tropical regions is the high intensity and volume of rainfall. The synthesised evidence suggests that while VGS can be effective for frequent, low-intensity storms, they face a performance ceiling during extreme monsoon events. A SWMM simulation for a system in Malaysia indicated a 55% runoff reduction for a 1-year average recurrence interval (ARI) storm, with observed data showing 52–87% reduction depending on intensity and duration [37]. However, the study also noted that performance declined sharply with higher rainfall intensity and longer duration, indicating that VGS alone may be insufficient for peak flood mitigation in these contexts. This finding strongly supports their integration as a component within a larger, hybrid grey-green infrastructure network designed to manage first-flush volume and delay peak flows[64].

The limited number of studies from cold climates points to unique barriers and adaptations. Research in Finland and Canada emphasised the critical role of substrate composition, with non-organic, free-draining materials like sandy loam being essential to prevent nutrient leaching and system damage from freeze-thaw cycles [64, 65, 66]. The application of Plant Growth-Promoting Microbes (PGPMs) was shown to enhance stormwater retention and improve plant water-use efficiency in these conditions, offering a promising biological strategy to bolster performance [66]. These findings highlight that in cold climates, the resilience of the material and biological components is as important as their hydraulic performance.

3.2. Moderator Analysis: Unpacking the Influence of System Design and Configuration

Within the overarching context of climate, the specific design and configuration of the VGS emerge as critical moderators of its hydrological function. Our analysis distinguishes between two primary system typologies: Green Façades, the climbing plants rooted at the base or in intermediate boxes and Living Walls, the modular panels or planter boxes with continuous substrate, as demonstrated in Figure 1. The synthesised data suggests a trade-off between hydrological functionality and complexity. Green façades, such as the trellis systems studied in the UK [55], excel in rainfall interception and evapotranspiration,

Table 1: Overview of Climate Zones and Key VGS Performance Considerations

Climate Zone	Key Performance Characteristics	Primary Design Focus	Studies
Tropical	High retention (52–87%) for frequent, low-intensity storms; challenges with monsoon-scale hydraulic overload.	Free-draining substrates; modularity; rapid drainage.	[37, 67]
Temperate	High seasonal variability (18–58%); orientation and plant selection are critical drivers.	High root biomass plants; SE orientation (NH); managing dormancy.	[61, 30, 55, 68]
Mediterranean	Moderate retention (21–58%); balancing dry-season irrigation with wet-season drainage.	Lightweight, porous substrates (e.g., peat-perlite); drought-tolerant species.	[59, 69, 40]
Arid	Shift from retention to water recycling and aquifer recharge; high irrigation dependency.	Closed-loop greywater / rainwater systems; xerophytic species.	[60]
Cold	Hydrological inactivity in winter, performance confined to growing season.	Frost-resistant engineering; system draining; durable materials.	[64, 65, 66]

effectively delaying and reducing runoff volume with generally lower maintenance and cost requirements. However, their stormwater retention capacity is limited to the soil volume at their base. In contrast, Living Walls, with their integrated substrate layers, offer direct stormwater retention, treatment, and greater design flexibility. For example, modular living walls were consistently reported to retain significant water volumes, ranging from 21–24% in Italy [59] to substantial first-flush capture in the USA [30]. The "Total Value Wall" in Belgium, a complex living wall system, demonstrated a water retention capacity of 15.72% [70]. The moderator analysis thus reveals that the choice between a façade and a living wall should be driven by the primary project goal: runoff delay and volume reduction (façades) versus active retention, treatment, and reuse (living walls).

A subtle yet significant finding from the analysis is the effect of orientation, which is intrinsically linked to hemispheric location, a detail often absent from high-level guidelines. As noted previously, the study in USA (Northern Hemisphere), found southeast-facing walls outperformed northwest-facing ones due to greater solar exposure [30]. This finding implies that the optimal orientation would be north-facing in the Southern Hemisphere to achieve the same solar gain. The failure of individual studies to contextualise their orientation findings highlights a critical gap in the literature and a necessary consideration for global design manuals.

3.3. Optimising Biological and Material Components

3.3.1. Plant Functional Traits: Beyond Aesthetics to Hydrological Function

The analysis moves beyond simply listing effective plant species to identifying the functional traits that underpin their performance. A consistent finding across multiple climates is the paramount importance of root system architecture. Species with high root biomass and dense root structures, such as Carex appressa, are repeatedly correlated with superior hydrological performance. In temperate China, C. appressa was associated

with infiltration rates as high as 315 mm/h, directly linking root growth to improved soil structure and hydraulic conductivity [53]. Similarly, Australian studies highlighted C. appressa and Canna × generalis as effective at reducing contaminants in green wall systems [63, 56], suggesting that root traits may play a key role in both water quantity and quality management. Furthermore, the analysis underscores a strategic distinction between plants selected for their evapotranspiration capacity and those chosen for drought resilience. In temperate Denmark, for instance, Knautia arvensis and Geranium sanguineum were identified as optimal for balancing high evapotranspiration under well-watered conditions with an ability to survive drought periods, a key trait for managing stormwater variability [71]. Conversely, in semi-arid and Mediterranean climates, the use of xerophytic species and succulents (e.g., Sedum spp.) is prevalent, prioritising water conservation and system survival during extended dry periods [60, 62]. This evidences a clear trade-off: designing for maximum ET-driven retention may compromise system resilience in water-scarce regions, and vice versa.

3.3.2. Substrate Composition: The Engine of Hydraulic and Treatment Performance

The substrate is revealed not as a passive growing medium, but as the central engine governing the hydraulic and treatment functionality of living walls. The analysis identifies a recurring tension between hydraulic performance and pollutant removal efficacy, often dictated by substrate composition. Lightweight, inorganic media such as perlite, expanded clay, and lava rock are consistently associated with high infiltration rates and reduced clogging potential, making them ideal for managing peak flows [72, 70]. However, these "Fast Media" typically offer lower pollutant removal due to shorter retention times and limited capacity for microbial colonisation or chemical adsorption. In contrast, organic and fine-textured media like coco coir and peat exhibit high water retention and superior treatment capabilities. For example, a coco coir and perlite mix (3:1 ratio) was shown to optimise chemical oxygen demand (COD), and total suspended solids (TSS) removal in a Malaysian system [73]. This points to the necessity of media blending to achieve multi-functional performance.

The most significant insight regarding substrates is the move towards engineered and recycled materials to enhance sustainability and functionality. The expanded cork agglomerate, a by-product of the cork industry, was demonstrated to retain up to 20 kg/m^3 of water while maintaining good drainage, presenting a cost-effective and eco-friendly alternative [69]. Similarly, the incorporation of superabsorbent polymers, including recycled variants from diapers, significantly enhanced the water retention capacity of cementitious materials, enabling the creation of bio-receptive surfaces that can sustain microbial life in dry climates [74]. These innovations highlight a promising frontier where the substrate itself becomes an active, multi-functional component of the urban water cycle.

Table 2: Key biological and material components influencing VGS performance.

Component	Functional Trait	Performance Benefits	Examples
Plants	High Root Biomass & Density	Improved soil structure & infiltration; Enhanced nutrient uptake[53, 63, 56].	*Carex appressa, Phragmites australis*
	High Evapotranspiration Capacity	Increased stormwater retention via water loss to atmosphere [30, 71].	*Canna x generalis, Knautia arvensis*
	Drought Resilience	System survival during dry periods; lower maintenance needs [60, 71].	*Sedum* spp., *Geranium sanguineum*
Substrate	"Fast Media" (High Hydraulic Conductivity)	High infiltration rates; reduced clogging risk; effective for peak flow reduction [72, 75].	Perlite, Expanded Clay, Lava Rock
	"Slow Media" (High Water Retention)	Superior pollutant removal; supports microbial communities; sustains plants [72, 73].	Coco Coir, Rockwool, Irish Peat
	Engineered & Recycled Materials	Enhanced sustainability; cost-effectiveness; unique water retention properties [74, 69].	Expanded Cork, Recycled Superabsorbent Polymers (SAPs)

3.4. Synthesized Key Performance Indicators (KPIs) for VGS in Stormwater Management

The reviewed studies employ a range of Key Performance KPIs to assess the stormwater management capacity of VGS, broadly falling into three interrelated categories: hydrological performance, water quality improvement, and system durability. Hydrological KPIs are the most commonly reported and include metrics such as runoff reduction, retention volume, peak flow attenuation, and time-to-peak delay, each reflecting the system's ability to intercept, store, and gradually release rainfall [30, 37, 55, 59, 68]. Water quality indicators are also frequently documented, with a focus on the removal or reduction of total suspended solids, organic pollutants, and nutrients such as nitrogen and phosphorus; some studies also examine the treatment of more complex contaminants using specialised media[42, 56, 63, 72]. A smaller but growing body of work incorporates operational and durability-related KPIs, including plant survival rates, substrate stability over time, maintenance frequency, and resistance to clogging or structural degradation [55, 70, 57]. Notably, while hydrological and water quality metrics are often derived from controlled or pilot-scale experiments, long-term field-based assessments of durability and maintenance requirements remain limited. The consistent use of these KPIs, particularly when reported alongside contextual variables such as climate zone, system type, and design specifications, enable more meaningful cross-study comparisons and supports the development of performance benchmarks tailored to local conditions.

3.5. Context-Driven Barriers to Adoption

The implementation of VGS is hindered not by a universal set of obstacles, but by a geographically and institutionally stratified landscape of barriers that vary significantly between the Global North and Global South. Our synthesis reveals that these constraints

are deeply intertwined with local economic conditions, regulatory maturity, technical capacity, and socio-cultural priorities. Recognising this heterogeneity is essential for designing targeted, equitable strategies that move beyond one-size-fits-all promotion.

In industrialised regions (Global North), adoption is primarily constrained by a nexus of economic, regulatory, and technical challenges. High upfront costs for installation and ongoing operational costs for maintenance, are the most frequently cited barriers.[54, 70, 76]. A cost-benefit analysis in Berlin concluded that the high costs of extensive façade greening reduced its cost-effectiveness compared to other SUDS measures, particularly when co-benefits like urban cooling or biodiversity were not monetised [54], highlighting a significant hurdle for public and private investment. This economic challenge is compounded by stringent regulatory frameworks and a lack of clear policy integration. For instance, in Flanders, Belgium, the reuse of treated greywater from a VGS had to comply with strict Legionella control thresholds [70] [28], creating a technical and monitoring burden. Similarly, an expert analysis across several European countries identified "conflicting legal frameworks" and "bureaucratic burden" as major institutional obstacles [57]. Compounding these issues is a lack of long-term performance data and shortage of skilled personnel, which together foster risk aversion among engineers and planners [57, 59, 66, 70]. Without robust evidence of durability under local climatic stresses, VGS are often excluded from critical stormwater infrastructure planning.

In contrast, the barriers in the Global South are rooted in institutional underdevelopment, misaligned stakeholder priorities, and limited technical capacity. Critically, only two of the 34 studies in this review originate from the Global South, one from Accra, Ghana [77] and one from Guadalupe, Mexico [60], highlighting a severe evidence gap. The Ghanaian case study is particularly revealing: when residents and developers were asked to rank drivers for VGS adoption, stormwater management and runoff quality ranked 12th and 13th out of 14 options, far behind aesthetics, health/well-being, and property value [77] This suggests a fundamental disconnect between the hydrological potential of VGS and public perception, a gap that cannot be bridged by technical specifications alone. Furthermore, unlike the over-regulated contexts of the North, the Global South often suffers from weak or absent policy frameworks specifically supporting VGS [78]. The Accra study explicitly noted “limited GRGW (green roofs green walls)-specific policies” and a lack of financial incentives such as tax breaks or density bonuses[77]. Operational sustainability is also at risk due to poor maintenance culture; without reliable stewardship, systems degrade rapidly, losing both function and visual appeal, a concern echoed even in UK studies where neglected façades saw interception capacity drop by over 50% [55].

Together, these findings underscore that successful VGS adoption requires context-sensitive framing, in the Global North, through economic de-risking, regulatory streamlining, and pilot monitoring programs; in the Global South, through co-benefit communication (linking VGS to cooling, health, and jobs), community co-design, and capacity-building initiatives that address maintenance and technical literacy. Ignoring these divergent realities risks entrenching inequitable innovation pathways where green infrastructure serves aesthetic or elite interests rather than functional, inclusive urban resilience.

4. Discussion

4.1. Climate-Responsive Performance: A Hierarchical Framework for VGS Design

This systematic review demonstrates that the performance of Vertical Greenery Systems is not a fixed metric, but rather an emergent property that is shaped by a distinct hierarchy

Table 3: Context-driven barriers to the adoption of VGS.

Barrier Category	Global North Context	Global South Context
Economic	High installation & maintenance costs [54, 76, 70]; Negative cost-benefit without optimisation [70].	Lack of financial incentives and investment models; Perceived economic gains focus on property value, not hydrology [77].
Regulatory & Policy	Stringent regulations [70]; Bureaucratic burdens and conflicting legal frameworks [57].	Weak or non-existent specific policies for VGS [77]; Lack of integration into urban planning agendas [77, 57].
Technical & Knowledge	Lack of skilled staff [57]; Limited long-term performance data for investor confidence [59, 66, 70].	Low stakeholder awareness of hydrological benefits; Stormwater management is a low-priority driver [77].
Operational	Maintenance required for clogging, plant health, and system integrity [54, 55, 75].	Poor maintenance culture leading to system degradation and reduced performance [55, 77].

of factors. At the pinnacle of this hierarchy sits climate, which acts as the primary filter, fundamentally dictating the role and limitations of a VGS within a local water cycle.

The performance patterns we observed across different climate zones can be seen as direct consequences of biophysical limits. For example, the finding that southeast-facing walls in the Northern Hemisphere outperform northwest-facing ones by 18% [30] is more than just a design tip; it is clear evidence that solar-driven evapotranspiration is the central engine for restoring a system's retention capacity. This elevates a building's orientation from a minor consideration to a major hydraulic design parameter. Conversely, the winter performance decline in colder climates highlights a thermodynamic boundary, shifting the priority from maximum water retention to ensuring freeze-thaw resilience.

This climatic influence forces a redefinition of what constitutes a successful VGS. In water-scarce Mediterranean and arid climates, the integration of greywater effectively changes the system's core purpose from a passive stormwater sink to an active participant in a circular urban water metabolism. Here, VGS can function as a vertical bioreactor, closing water loops and delivering year-round benefits beyond stormwater. A powerful illustration of this principle in a cooler temperate climate is the VGS at Pável Carpenter's Alley in Uppsala, Sweden (Figure 6). This installation demonstrates how an engineered rainwater capture and drip irrigation system can overcome rainfall dependency, supporting full vegetation establishment and sustained hydrological function over several years [58, 79] In contrast, the performance ceiling observed in tropical systems during heavy monsoon rains reveals a fundamental constraint of hydraulic overload. This positions them not as standalone flood defences, but as ideal components for managing initial runoff volume and pollution within a broader, hybrid drainage network.

Beneath the overarching climate filter, the choice of system typology and components fine-tunes performance. The distinction between Green Façades and Living Walls represents a core trade-off. Façades often serve as cost-effective 'interception blankets' for reducing runoff volume, whilst Living Walls act as more complex 'biofiltration columns'

for improving water quality and enabling reuse. This decision should be driven by the project's primary goal. Furthermore, the consistent success of plants with dense root systems (e.g., Carex appressa) and the careful balancing act between 'fast' and 'slow' substrates show that biological and material selection are the essential levers for optimising a system to fulfil its climate-defined function.

Figure 6: VGS at Påvel carpenter's alley, Uppsala, Sweden (Butong)[79]. The schematic diagram illustrates vegetation growth from installation to over two years, supported by an integrated rainwater capture and drip irrigation system. This exemplifies how engineered water management can sustain VGS performance and plant health in climates where rainfall alone is insufficient.

4.2. Toward Equitable and Scalable Implementation: A Five-Pillar Framework

Although the biophysical performance of VGS is a critical determinant of their effectiveness, their real-world impact remains limited without widespread adoption. Our analysis identifies a fundamental socio-technical divide in the adoption pathways, where barriers are deeply embedded in the institutional fabric and social priorities of a region, creating two distinct implementation landscapes.

In industrialised nations, the challenge is not a lack of resources or technical capability, but a systemic inertia born from complexity. Here, VGS confront a tightly regulated, risk-averse infrastructure paradigm. The frequently cited high costs are symptomatic of a deeper issue: a failure of integrated valuation. When conventional cost-benefit analyses, as seen in Berlin, overlook co-benefits like urban cooling or biodiversity [54], VGS are unfairly pitted against grey infrastructure on a skewed playing field. This economic disincentive is then compounded by a regulatory maze. The experience in Flanders, where greywater reuse was hampered by Legionella controls [70], is not an isolated incident but an example of how well-intentioned, siloed regulations can inadvertently stifle innovation. This creates a vicious cycle: a lack of long-term performance data fosters risk aversion among engineers and planners [57, 70], which in turn limits the deployment needed to generate that very evidence. The result is a 'paralysis of complexity', where VGS are perceived as a high-risk niche product rather than a legitimate component of public infrastructure.

Conversely, the implementation context in the Global South is defined by a stark disconnect between technical potential and public perception. The severe evidence gap, with only two of our 34 studies from these regions, is itself a critical barrier, reflecting a broader marginalisation in global sustainability research. This lack of local data makes it difficult to build a convincing case. More profoundly, the findings from Accra are illuminating: when stormwater management ranks 12th out of 14 adoption drivers [77], it reveals that promoting VGS primarily for hydrological function is a strategic misalignment. The technology is competing in a landscape where immediate concerns of aesthetics, health, and economic status hold greater sway. This is not a public failing but a failure of framing. Unlike the over-regulated North, the challenge here is often an absence of supportive policy and financial incentives [77], leaving VGS in a policy vacuum without clear pathways for integration. When combined with concerns over maintenance, this priority-perception chasm can relegate VGS to decorative installations for elite spaces, undermining their potential for broad, functional resilience.

To bridge the stark divide in adoption barriers, the findings of this review must be translated into a strategic and actionable framework. We therefore propose five targeted pillars of intervention (Figure 7), each designed to address the specific socio-technical pathologies identified in the Global North and South. The first pillar, Climate-Responsive Design Protocols, calls for a shift from bespoke engineering to pre-validated, zone-specific design packages. This entails certifying details for frost resilience in the North, while in the South, it requires disseminating robust, low-maintenance templates for monsoon drainage and drought tolerance to build a crucial local evidence base. The second pillar, Advanced Economic Valuation and Financing, aims to break the cost paradox by mandating lifecycle analyses that monetise co-benefits in the North to justify green bonds, while in the South, aligning financing with high-priority drivers through micro-finance or tax breaks for developers. Third, Adaptive Policy and Governance necessitates smarter governance: streamlining bureaucratic processes and creating cross-departmental teams in the North, while in the South, building new policy frameworks that integrate VGS into urban development agendas. The fourth pillar, Long-Term Monitoring and Knowledge Sharing,

Figure 7: Five-Pillar Implementation Framework for Scaling VGS in Urban Stormwater Management.

treats data as critical infrastructure, demanding funded monitoring programmes with a dedicated focus on generating open-access performance data from the under-represented Global South. Finally, Community Engagement and Capacity Building secures the social license for technical solutions by upskilling the existing workforce in the North, and in the South, by launching awareness campaigns framed around cooling and well-being, coupled with training local crews to ensure longevity and ownership.

This five-pillar framework provides an actionable roadmap to transition VGS from isolated demonstrations into scalable, equitable, and resilient urban infrastructure, recognising that their ultimate potential hinges not on technical performance alone, but on overcoming the deeply embedded institutional, economic, and social barriers that currently limit their adoption. Together, these insights redefine VGS not as static infrastructure, but as dynamic, context-responsive systems whose success hinges on aligning ecological function with socio-institutional reality.

5. Conclusion

This systematic review advances the understanding of VGS in urban stormwater management by moving beyond generalised performance metrics towards a hierarchical, context-driven framework. The central insight is unequivocal: VGS hydrological function is not an inherent property of the technology, but an emergent outcome shaped primarily by local climate, and subsequently refined by system typology, biological traits, and substrate engineering. This layered perspective resolves apparent contradictions in the

literature—such as divergent retention rates or orientation effects—by demonstrating that optimal design in one climatic zone cannot be transplanted to another without significant adaptation.

The review further reveals that barriers to adoption are not uniform but geographically stratified: in the Global North, they stem from economic, regulatory, and technical complexities, whereas in the Global South, they arise from misaligned priorities, institutional gaps, and limited awareness of hydrological co-benefits. This duality underscores that successful implementation requires more than technical optimisation, it demands context-sensitive strategies that account for local socio-institutional realities.

The primary contribution of this work is therefore twofold. For researchers, it offers a robust analytical framework for future studies and highlights critical knowledge gaps, most notably the scarcity of long-term, full-scale performance data, especially in underrepresented regions such as the Global South and cold climates. For practitioners and policymakers, it provides actionable guidance to move away from one-size-fits-all approaches. By aligning VGS design with local climatic conditions, economic constraints, and governance contexts, stakeholders can integrate these systems more effectively into sustainable urban drainage strategies.

Ultimately, VGS hold significant promise as multifunctional components of resilient, sponge-like cities. Realising this potential, however, depends on a paradigm shift, from viewing VGS as decorative add-ons to recognising them as adaptive, engineered ecosystems that must be intelligently tailored to their environmental and social setting. When designed with this nuance, VGS can meaningfully contribute to flood mitigation, water quality improvement, and broader urban climate resilience in the 21st century.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

The authors would like to acknowledge the INTERREG Öresund-Kattegat-Skagerrak and Østfold University College for funding and support towards this research, conducted as part of the Green Sponge Buildings in Scandinavia (GSB) project.

CRediT Roles

Abdul Ghafoor Nizamani: Conceptualization, Methodology, Data Curation, Formal Analysis, Investigation, Writing - Original draft preparation, Visualization, **Geir Torgersen**: Funding Acquisition, Project Administration, Resources, Supervision, Writing – Review & Editing.

Conflict of 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 document.

Ethics statement

This paper does not involve human subjects, human data, tissue, or animals. The topic of study raises no ethical concerns. All data were sourced from secondary sources and the literature.

Appendix

Table A1: Summary of Reviewed Literature

Citation	Study Title	Climate-Country	Application	Study Type
[53]	Advancing the Sponge City Agenda: Evaluation of 22 plant species across a broad range of life forms for stormwater management	Cfa – China	Plant selection for biofilters	Experimental Study
[64]	Application of the Green Factor to a Typical Calgary Residential Site	Dfb – Canada	Integrating multiple GI	Simulation Study
[54]	Are Neighborhood-level SUDS Worth it? An Assessment of the Economic Value of Sustainable Urban Drainage System Scenarios Using Cost-Benefit Analyses	Cfb – Germany	Economic feasibility of SUDS	Economic/Policy Analysis
[61]	Assessing water retention and correlation to climate conditions of five plant species in greywater treating green walls	Cfb – Australia	Greywater-irrigated green walls	Controlled Field Experiment
[30]	Can Greenwalls Contribute to Stormwater Management? A Study of Cistern Storage Greenwall First Flush Capture	Dfb – USA	Cistern-based green wall	Pilot-Scale Demonstration
[62]	Closing Water Cycles in the Built Environment through Nature-Based Solutions: The Contribution of Vertical Greening Systems and Green Roofs	Dfb, Csa – Denmark, Germany, Italy, Portugal, Turkey, Israel	VGS & green roofs in Europe	Simulation Study
[63]	Designing green walls for greywater treatment: The role of plants and operational factors on nutrient removal	Cfb – Australia	Modular greywater green walls	Laboratory Experiment
[80]	Designing living walls for greywater treatment	Cfb – Australia	Sand-based living walls	Controlled Environment Experiment

Table A1: Annex-A: Summary of Reviewed Literature (Continued)

Citation	Study Title	Climate-Country	Application	Study Type
[60]	Enhancing Urban Water Quality with Green Infrastructure – A Study in Guadalupe, Nuevo Leon, Mexico	BSh – Mexico	GI prototype in semi-arid climate	Pilot-Scale Demonstration
[40]	Experimental analysis to assess the hydrological efficiency and the nutrient leaching behavior of a new green wall system	Csa – Italy	Modular green wall system	Experimental Study
[59]	Experimental and numerical analysis to assess the substrate hydraulic properties and the retention capacity of a green wall module	Csa – Italy	Modular green wall substrates	Field Experiment + Simulation
[55]	Field evaluation of precipitation interception potential of green façades	Cfb – UK	Green façades	Full-Scale Field Study
[37]	Green wall for retention of stormwater (Malaysia)	Af – Malaysia	Modular green walls	Modeling/Simulation + Field Observation
[72]	Green walls for greywater reuse: Understanding the role of media on pollutant removal	Cfb – Australia	Coir/perlite media	Laboratory Experiment
[65]	Improving runoff quality in VGS: Substrate type outweighed the effect of plant growth promoting microbes	Dfb – Finland	Biochar substrates in VGS	Pilot-Scale Demonstration
[58]	Into the air: a freestanding VGS for evapotranspiration of roof runoff	Cfb – Denmark	Freestanding VGS	Full-Scale Field Study
[73]	Lake Water Treatment Using Green Wall System: Effects of Filter Media Ratio and Lake Water Flow Rate on Treatment Performance	Af – Malaysia	Green wall filtration for lake water	Laboratory Experiment
[76]	Methodological framework for impact evaluation of Building-Integrated Greenery (BIG-impact)	Csa – Spain	BIG systems globally	Framework Development
[67]	Performance evaluation of integrating Vertical Garden Constructed Wetlands (VGCWs) with diverse plant species and modified media for treating septic tank effluent	Aw – Thailand	Vertical garden constructed wetlands for wastewater	Laboratory Experiment

Table A1: Annex-A: Summary of Reviewed Literature (Continued)

Citation	Study Title	Climate-Country	Application	Study Type
[75]	Performance of a green wall (Total Value Wall™) at high greywater loading rates and Life Cycle Impact Assessment	Cfb – Belgium	Greywater treatment green wall	Pilot-Scale Demonstration
[66]	Plant growth-promoting microbes improve stormwater retention of a newly-built VGS	Dfb – Finland	PGPM-inoculated VGS	Pilot-Scale Demonstration
[68]	Precipitation collection and evapo(transpi)ration of living wall systems: A comparative study between a panel system and a planter box system	Cfb – Netherlands	Living walls	Full-Scale Field Study
[81]	Rainwater Use for VGS: Development of a Conceptual Model for a Better Understanding of Processes and Influencing Factors	Cfb – Austria	Rainwater-fed VGS	Framework Development
[82]	Root growth of perennials in vertical growing media for green walls	Cfb – Denmark	Media selection	Controlled Environment Experiment
[56]	Seasonal operation of dual-mode biofilters: The influence of plant species on stormwater and greywater treatment	Cfb – Australia	Dual-mode biofilters	Controlled Environment Experiment
[74]	The effect of (and the potential of recycled) superabsorbent polymers on the water retention capability and bio-receptivity of cementitious materials	Cfb, Csa – Belgium, Spain	Bio-receptive building materials	Laboratory Experiment
[83]	The effects of vegetation on runoff and soil loss: Multidimensional structure analysis and scale characteristics	Cwa – China	Vegetation-based stormwater mgmt	Multiscale Field Experiments
[70]	Total Value Wall: Full Scale Demonstration of a Green Wall for Grey Water Treatment and Recycling	Cfb – Belgium	Decentralized greywater reuse	Full-Scale Field Study
[77]	Understanding the drivers of green roofs and green walls adoption in Global South cities: Analysis of Accra, Ghana	Aw – Ghana	GI adoption in Global South	Mixed-Methods Research
[84]	Urban Regreeneration: Green Urban Infrastructure as a Response to Climate Change Mitigation and Adaptation	Cfb – Spain	Integrated GI in Spanish towns	Case Study

Table A1: Annex-A: Summary of Reviewed Literature (Continued)

Citation	Study Title	Climate-Country	Application	Study Type
[85]	Urbanites' perception of vegetation in landscape-based stormwater management elements (LSM)	Cfb – Denmark	Perception of LSM (including green walls)	Mixed-Methods Research
[69]	Water retention and drainage capability of expanded cork agglomerate boards intended for application in green vertical systems	Csa – Portugal	Sustainable substrate material	Laboratory Experiment
[71]	Water use and drought responses of eight native herbaceous perennials for living wall systems	Cfb – Denmark	Species selection for living walls	Controlled Environment Experiment
[57]	What does it take to renature cities? An expert-based analysis of barriers and strategies for the implementation of nature-based solutions	Csa, Cfb, Dfb – Spain, Austria, Netherlands, UK, Switzerland, Slovenia, Sweden	NBS/green walls integration in European cities	Qualitative

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