

Design for Maintainability (DFM) of Living Building Envelopes: A Prisma-Informed Qualitative Literature Review of Green Façades in High-Humidity Coastal Environments

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Abstract

The integration of vegetation into building envelopes through green façades and living walls offers established thermal, environmental, and economic benefits, yet these benefits depend on maintenance performance that is rarely addressed at the design stage, particularly in high-humidity coastal environments where salt-laden air, wind-driven rain, and cyclical wetting accelerate corrosion, biofouling, and substrate degradation. This study adopts a PRISMA-informed qualitative literature review guided by PRISMA 2020 reporting protocols to examine how Design for Maintainability (DfM) principles have been applied to living building envelopes, drawing on evidence identified through Google Scholar and synthesised through thematic analysis. From an initial pool of 2,761 records identified across five search strings, 35 studies met the eligibility criteria and were included in the final synthesis. The findings show that DfM has been most systematically developed within a Singapore-based body of research establishing design-stage maintainability frameworks for vertical greenery systems, but this evidence has not been tested specifically against coastal stressors. Irrigation design emerges as the most consequential and climate-sensitive maintainability variable, with direct effects on vegetation health, biological colonisation, and fire risk, while structural corrosion evidence, though consistent, is drawn largely from general materials-testing literature rather than façade-specific coastal studies. The review concludes that DfM principles for green façades remain underdeveloped for high-humidity coastal contexts specifically, and recommends corrosion-resistant hardware specification, climate-responsive irrigation redundancy, and field-based coastal monitoring as priorities for both practice and future research.

Keywords: Design for Maintainability, Green Façade, High-Humidity Coastal Environment, Living Building Envelope, Vertical Greenery System.

Introduction

Buildings account for a substantial share of global energy use, emissions, and resource depletion, pushing architectural practice toward regenerative, climate-responsive design that contributes to ecosystem services rather than merely reducing harm (Manso & Castro-Gomes, 2015). Living Building Envelopes (LBEs), meaning green façades and living walls that make vegetation a functional part of the building skin rather than a decorative addition, are among the most visible expressions of this shift. Through shading,

evapotranspiration, and biological filtration, they measurably reduce surface and air temperatures and cut cooling demand, echoing the broader urban-scale finding that green and blue infrastructure mitigates urban heat island intensity (Gunawardena, Wells, & Kershaw, 2017), and improve urban air quality and biodiversity (Aung, Liana, Htet, & Bhaumik, 2023), while life-cycle analyses suggest their higher installation cost can be offset by long-term operational savings, provided maintenance is properly budgeted (Huang, Lu, Wong, & Poh, 2019; Ottel  , Perini, Fraaij, Haas, & Raiteri, 2011).

These benefits are conditional, not automatic. A living envelope layers a biological system onto a technical one: vegetation needs irrigation, pruning, and periodic replacement, while the supporting cables, anchors, drainage, and substrate are exposed to weathering, corrosion, and biological colonisation. Mohanta et al. (2022) show that maintainability performance is set largely at the design stage, not corrected afterward, yet most green fa ade research still treats maintenance as a post-occupancy facilities-management issue rather than a design parameter. This gap is most consequential in high-humidity coastal environments, where elevated humidity, salt-laden air, wind-driven rain, and cyclical wetting accelerate corrosion, substrate degradation, and algal or fungal growth well beyond what temperate-climate DfM guidance anticipates.

Statement of the Problem

Design for Maintainability has been established as a credible design philosophy for vertical greenery systems, most notably through a concentrated body of Singapore-based research that catalogues recurring defects and formalises design-stage interventions (Chew & Conejos, 2016; Chew, Conejos, & Bin Azril, 2018). However, this evidence base was developed within a broadly tropical climate and has not been systematically tested against the specific compounding stressors of high-humidity coastal environments, namely salt-laden air, wind-driven rain, and cyclical wetting and drying, all of which accelerate corrosion, biofouling, and substrate degradation beyond typical tropical or temperate baselines.

At the same time, evidence on individual coastal deterioration mechanisms exists but remains fragmented across adjacent literatures such as materials science, general building envelope research, and microbiology, rather than being integrated into fa ade-specific, maintainability-oriented guidance. This leaves practitioners designing green fa ades for coastal cities without a consolidated, climate-specific evidence base to inform decisions on irrigation redundancy, corrosion-resistant hardware, and inspection intervals. Without such consolidation, green fa ades risk premature failure, elevated lifecycle cost, and disinvestment once visible defects appear, undermining the sustainability case that motivates their adoption in the first place. This study addresses that gap through a PRISMA-informed qualitative literature review on Design for Maintainability as applied to living building envelopes in high-humidity coastal environments.

Aim of the Study

The aim of this study is to critically evaluate how Design for Maintainability (DfM) principles have been incorporated into the design and long-term performance of green façade systems in high-humidity coastal environments, through a PRISMA-informed qualitative literature review.

Objectives of the Study

To achieve the stated aim, the following specific objectives have been formulated to:

- i. examine the concept of DfM and its application to living building envelopes, including the typology and performance characteristics of green façades in high-humidity coastal environments;
- ii. identify the major maintenance challenges affecting green façades in these environments and evaluate existing DfM strategies developed to address them; and
- iii. develop a thematic framework of best-practice DfM strategies and future research directions for maintainable green façade design.

Research Questions

- i. What Design for Maintainability principles have been applied to living building envelopes and green façade systems?
- ii. What maintenance challenges affect green façades in high-humidity coastal environments?
- iii. Which design strategies improve the long-term maintainability and lifecycle performance of green façade systems?

Scope of the Study

This study is thematically focused on the application of Design for Maintainability principles to living building envelopes, with particular emphasis on green façades and living wall systems operating in high-humidity coastal contexts. Rather than being bound to a single country or city, the review draws on evidence from tropical and coastal urban settings globally, including Singapore, Hong Kong, Sri Lanka, Australia, and coastal Europe, reflecting the geographic distribution of the available literature. The review is temporally bounded primarily to publications spanning 2016 to 2025. Four exceptions are retained and explicitly treated as justified exceptions: three foundational studies published in 2011, 2013, and 2015 (Ottel , Perini, Fraaij, Haas, & Raiteri, 2011; Perini & Rosasco, 2013; Perini, Ottel , Haas, & Raiteri, 2013; Tam si & Dobszay, 2015) are retained because they establish typological, lifecycle, cost, or design constructs still used in the review, while one 2026 study (Hassan, Elsady, & Haggag, 2026) is retained because of its direct relevance to project-lifecycle risk assessment. These exceptions are therefore deliberate rather than inadvertent departures from the principal date range. The study draws on a PRISMA-informed

qualitative literature review methodology guided by PRISMA 2020 reporting protocols, synthesising evidence identified through Google Scholar using five structured search strings covering system typology, durability, maintainability, and coastal or tropical climate terms.

Limitations of the Study

This study acknowledges several limitations that should be considered when interpreting its findings. First, the search was conducted using Google Scholar rather than institutional databases such as Scopus, Web of Science, or ScienceDirect, reflecting accessibility constraints; while Google Scholar offers broad coverage, its relevance ranking and result counts are approximate rather than exact. Second, in line with established guidance on the diminishing relevance of results deep into a Google Scholar search (Haddaway, Collins, Coughlin, & Kirk, 2015), a practical screening cap was applied rather than an exhaustive review of all 2,761 records identified, meaning some relevant studies may not have been captured. Third, the final synthesis draws on 35 studies for which full-text content was retrieved and verified within the timeframe of this review; a further 110 records that passed title and format screening remain eligible but were not reviewed in full text, and are noted here as a concrete direction for follow-up work rather than as an oversight. Fourth, the review is restricted to English-language publications, which may exclude relevant research published in other languages. Finally, a small number of included sources have author details that could not be independently verified against the original publication and are flagged accordingly in the reference list. Notwithstanding these limitations, the study provides a transparent and reproducible synthesis of available evidence that meaningfully advances understanding of DfM application to green façades in high-humidity coastal environments.

Literature Review

Conceptual Review

Living Building Envelopes: Concept and Typology

Living Building Envelopes marks a shift in the building envelope's role, from a passive protective barrier to an active interface that responds to its microclimate. Manso and Castro-Gomes (2015) distinguish two principal typologies: green façades, where climbing plants grow directly on the wall surface (direct systems) or on an independent supporting structure such as cables or mesh (indirect systems); and living wall systems, which use modular panels, felt, or hydroponic trays to support a denser, more varied planting palette independent of ground-level soil. Perini, Ottelé, Haas, and Raiteri (2013) formalise these variants into a process tree linking system choice to installation, irrigation, and end-of-life pathways. Indirect and modular systems generally improve air circulation and maintenance access at the cost of higher installation complexity, while living walls carry a substantially

heavier maintenance burden, since irrigation, substrate, and structural supports all require continuous monitoring. Table 1 presents a comparative typology of these systems.

Feature	Direct Green Façade	Indirect Green Façade	Living Wall System
Support structure	None; plants attach directly to wall	Cables, mesh, or trellis, offset from wall	Modular panels, felt, or hydroponic trays
Air circulation behind foliage	Poor; moisture trapped against surface	Good; offset gap improves airflow	Good to moderate, depends on panel design
Irrigation demand	Low to moderate (often soil-rooted)	Moderate	High; continuous, engineered system required
Maintenance intensity	Low installation, higher long-term wall risk	Moderate	High; irrigation, substrate, structure all need monitoring
Relative installed cost	Lowest	Moderate	Highest
Typical failure mode	Adhesive/root damage to wall finish	Support corrosion, growth control	Irrigation blockage, panel/substrate degradation

Table 8: Typology comparison of living building envelope systems.

Sources: Manso & Castro-Gomes (2015); Perini, Ottel  , Haas, & Raiteri (2013)

Green Façade Performance

Thermal and environmental performance is the most studied dimension of green faades. Vegetation lowers faade surface and ambient temperatures via shading and evapotranspiration, improving indoor thermal comfort and reducing cooling load (Thomsit-Ireland et al., 2020), consistent with broader evidence that green infrastructure mitigates urban heat island intensity at the city scale (Gunawardena, Wells, & Kershaw, 2017), with the magnitude depending on plant species, foliage density, orientation, and climate (Cuce et al., 2021). Economically, life-cycle analyses indicate that higher installation costs can be recovered through energy savings and extended envelope life (Ottel   et al., 2011; Huang et al., 2019), but a systematic review of 15 economic studies found this recovery is highly system-dependent: living walls carry maintenance costs many times higher than green faades, driven chiefly by irrigation, substrate replacement, and plant turnover (Madushika, Ramachandra, & Geekiyanage, 2022). These costs feed directly into adoption decisions: barrier studies identify maintenance-cost uncertainty, rather than installation cost alone, as a primary obstacle to broader uptake, particularly as green faades are increasingly specified on high-rise urban buildings (Knifka, Karutz, & Zozmann, 2023; Yahya et al., 2024).

Indicator	Green Façade	Living Wall	Source
Façade surface temperature reduction	Moderate	Moderate to high (denser foliage)	Thomsit-Ireland et al. (2020); Gunawardena et al. (2017)
Cooling-load reduction	Variable; orientation, density, climate	Variable, generally higher (coverage density)	Cuce et al. (2021)
Life-cycle cost recovery	More favourable; lower O&M cost base	Less favourable unless energy savings are substantial	Huang et al. (2019); Ottelé et al. (2011)
Relative maintenance cost	Baseline (1x)	Several times higher than green façades	Madushika, Ramachandra, & Geekiyanage (2022)

Table 9: Reported performance benefits by system type.

Sources: Thomsit-Ireland et al. (2020); Gunawardena et al. (2017); Cuce et al. (2021); Huang et al. (2019); Ottelé et al. (2011); Madushika, Ramachandra, & Geekiyanage (2022)

The literature is disproportionately weighted toward these operational performance indicators. Comparatively few studies treat maintenance as a design variable rather than a post-installation management task.

Design for Maintainability: Concept and Application to Living Building Envelopes

Design for Maintainability reframes maintenance as a design-stage responsibility rather than a reactive, post-construction activity, embedding accessibility, inspectability, durability, replaceability, and modularity into components from the outset. Within general building envelope research, DfM is supported by predictive, condition-based maintenance models (Ferreira, Silva, de Brito, & Flores-Colen, 2023) and by service-life literature synthesising 107 publications on envelope component durability (Silva & de Brito, 2021). Studies from the Nigerian construction sector show that overlooking maintainability at the planning stage drives up facilities-management costs and shortens asset life (Frank & Brisibe, 2019). Applied specifically to vertical greenery, a concentrated body of Singapore-based research develops this into a green maintainability framework (Chew & Conejos, 2016; Chew, 2016), which is examined further in the theoretical and empirical reviews below.

Theoretical Review

Design for Maintainability as a Theoretical Lens

As a theoretical construct, Design for Maintainability treats maintainability not as an emergent property of a completed building but as a design variable that can be specified, scored, and optimised before construction. This theoretical positioning is significant

because it relocates responsibility for long-term performance from facilities managers, who inherit a building's defects, to designers, who determine whether those defects are foreseeable and preventable. Applied to living building envelopes, this lens directs analytical attention toward design decisions, such as material selection, access provision, and irrigation zoning, as the primary explanatory variables for long-term maintenance outcomes, rather than treating maintenance burden as an inherent and unavoidable property of vegetated systems.

Service Life Planning

Service Life Planning, formalised in the ISO 15686 series (ISO, 2011), provides a complementary theoretical basis by treating every building component's service life as predictable and shaped by material choice, exposure conditions, and maintenance access. Applied to green façades, Service Life Planning implies that the service life of both the vegetative and structural components should be estimated at the design stage, with inspection and replacement pathways planned in advance rather than reactively determined once defects appear.

Life Cycle Thinking

Life Cycle Thinking extends this reasoning by evaluating a building's environmental, economic, and social impact across its full life, from material extraction through construction, operation, and eventual replacement or demolition. Within this review, Life Cycle Thinking supports the central premise that a green façade's sustainability cannot be judged on thermal or ecological performance alone: if excessive maintenance demand or premature failure erodes those gains over time, the system has not delivered genuine lifecycle sustainability regardless of its performance when newly installed. Together, Design for Maintainability, Service Life Planning, and Life Cycle Thinking form the theoretical basis for the conceptual framework presented in section 2.4.

Empirical Review

Applied Evidence on Design for Maintainability in Vertical Greenery Systems

Empirically, the Singapore-based DfM literature catalogues recurring vertical greenery system defects, including leaky irrigation, excessive algae growth, and restricted maintenance access, against specific design interventions such as accessible service walkways, corrosion-resistant fixings, and redundant irrigation zoning (Chew, Conejos, & Bin Azril, 2018). This work is formalised into a weighted DfM assessment scoresheet intended to help designers compare vertical greenery system options before construction rather than diagnosing failures afterward (Conejos, Chew, & Bin Azril, 2019; Conejos & Chew, 2020). This maintainability-first orientation echoes broader building envelope research outside the vegetated-façade niche: predictive maintainability frameworks for conventional envelope elements similarly argue that most in-service defects originate in

decisions made during design and materials selection (Ferreira et al., 2023), while a parallel framework specific to green building envelopes in warm-humid regions catalogues design-related defects through literature synthesis, field study, and practitioner survey (Mohanta et al., 2022).

Maintenance Challenges in High-Humidity Coastal Environments

Coastal climates compound nearly every failure mode already known to affect green façades. Vegetation management demand rises sharply with humidity and rainfall exposure (Perera, Jayasinghe, Halwatura, et al., 2021). Irrigation infrastructure design directly determines maintenance frequency and vegetation survival in warm climates (Kaltsidi, Fernández-Cañero, Franco-Salas, & Pérez-Urrestarazu, 2020; Pérez-Urrestarazu, 2021). Moisture and biological colonisation represent the defining coastal risk: algal biofilms measurably lower substrate pH and increase water absorptivity (Nowicka-Krawczyk et al., 2025), active fungal and bacterial communities live within the systems themselves (Fleck et al., 2020), and, counter-intuitively, irrigation lapses raise fire risk by drying vegetation (Dahanayake & Chow, 2018). Structural durability is equally exposed: marine-exposure testing shows galvanised steel protective coatings can fail within six months in high-chloride coastal conditions (Daniel, Wang, Li, Dong, Udoh, Zhang, Zhong, & Zhong, 2023). Accessibility and occupant engagement matter too, since visible decline in a poorly accessible installation can trigger disinvestment even when the underlying defect is minor (Gunawardena & Steemers, 2020). Collectively, these are not independent problems but an interacting system, in which a corroded bracket, for instance, may only be discovered once resulting vegetation dieback makes it visible. Figure 1 illustrates this compounding pathway, showing how humidity and salt exposure drive the three mechanisms above to accelerate one another before converging on a visible defect and, ultimately, a maintenance response.

Figure 1. Compounding Deterioration Pathway in High-Humidity Coastal Green Façades

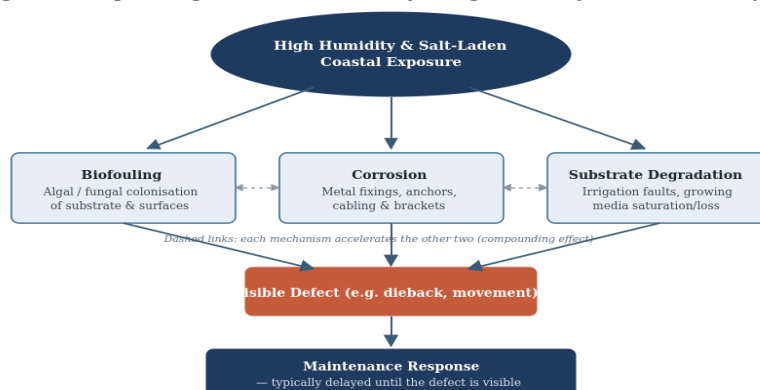


Figure 1: Compounding deterioration pathway in high-humidity coastal green façades.

Source: Author (2026)

Conceptual Framework

The conceptual framework for this study is grounded in the Design for Maintainability, Service Life Planning, and Life Cycle Thinking constructs reviewed above. It treats high-humidity coastal exposure, comprising humidity, salt-laden air, wind-driven rain, and cyclical wetting, as the environmental context in which green façades operate. This context acts on a mediating design construct, namely Design for Maintainability principles such as accessibility, durability, inspectability, replaceability, modularity, and corrosion resistance. These principles in turn shape maintenance performance, which determines whether a system's environmental and economic benefits are sustained across its lifecycle. This chain of relationships, from environmental context through the mediating DfM construct to maintenance performance and lifecycle outcomes, is illustrated as a flowchart in Figure 2 below. The eight thematic synthesis categories primarily map as follows: living building envelope technologies and green façade performance relate to system characteristics and lifecycle outcomes; Design for Maintainability principles map to the mediating DfM construct; maintenance challenges and coastal environmental influences map to environmental exposure and maintenance performance; lifecycle performance maps to lifecycle sustainability outcomes; emerging digital maintenance technologies maps to monitoring and inspectability; and research gaps and future directions cut across all framework elements by identifying where evidence remains weak.

Figure 2. Conceptual Framework: DfM as the Mediating Construct



Figure 2: Conceptual framework linking coastal exposure, DfM principles, maintenance performance, and lifecycle sustainability.

Source: Author (2026)

Identified Gaps in the Literature

Three gaps recur across the literature reviewed in this study. First, there is a geographic concentration of empirical DfM-for-VGS case studies in a small number of tropical Asian cities, and the transferability of resulting design guidance to other high-humidity coastal contexts with different salinity, storm exposure, or construction practice is rarely tested. A review of vertical greenery system design practice across multiple countries confirms this pattern, finding that most projects also lack a defined pre-design goal-setting phase and,

critically, lack any post-installation monitoring phase, prompting a proposed integrated design approach that treats maintenance monitoring as a formal design deliverable (Farrokhirad, Rigillo, Köhler, & Perini, 2024). Second, most existing maintainability frameworks were developed for conventional, non-biological building systems and do not explicitly address the horticultural, ecological, and seasonal variables specific to living envelopes. Third, maintainability is typically evaluated in isolation from other sustainability metrics, such as energy performance, biodiversity, and cost, rather than as an integrated design objective. Collectively, these gaps motivate the qualitative, theme-based synthesis undertaken in this review, which aims to consolidate a fragmented, multi-disciplinary evidence base into design-actionable themes specific to high-humidity coastal green façades.

Methodology

Research Design

This study adopts a PRISMA-informed qualitative literature review to synthesise evidence on the application of Design for Maintainability to living building envelopes, with emphasis on green façades in high-humidity coastal environments. A qualitative rather than statistical synthesis was chosen because the goal is to identify recurring themes, methodological approaches, and research gaps, not to pool effect sizes (Snyder, 2019). The review follows the PRISMA 2020 guidelines for transparent, reproducible identification, screening, and inclusion of literature. As the study relies exclusively on published, publicly accessible secondary data, no human participants or confidential information were involved, and formal ethical approval was not required; all sources are nonetheless cited in accordance with standard academic integrity practice.

Review Protocol and Search Strategy

The review protocol, developed prior to the literature search, specified the research questions (section 1.5), search strategy, eligibility criteria, screening procedure, and synthesis method in advance, in line with PRISMA 2020 reporting guidance for transparent and reproducible reviews. Because access to additional subscription databases was unavailable, the search was conducted on Google Scholar across five search strings (Table 3), restricted to 2016 to 2025. The resulting review is therefore framed as PRISMA-informed rather than as an exhaustive multi-database systematic review. Google Scholar was selected as the primary search tool given accessibility constraints. Per established guidance on using Google Scholar for evidence synthesis, screening was limited to relevance-ranked results rather than exhaustive review of all hits, since relevance declines sharply beyond the first 200 to 300 results for a given query (Haddaway, Collins, Coughlin, & Kirk, 2015). In practice, a further reduced cap of approximately 75 results per string was applied given the resource constraints of a single-researcher review.

Search String (Google Scholar)	Hits (2016 to 2025)
"green facade" OR "living wall" "design for maintainability"	32
"vertical greenery system" durability "coastal" OR "tropical"	678
"building envelope" "maintainability"	1,010
"green wall" OR "green facade" corrosion OR biofouling OR biodeterioration	664
"vertical greenery system" OR "green facade" irrigation maintenance failure	377
Total (raw, pre-deduplication)	2,761

Table 3: Search strings and combined Google Scholar hit counts (2016 to 2025).

Source: Author (2026).

Inclusion and Exclusion Criteria

To ensure consistency and relevance, explicit inclusion and exclusion criteria were established before study selection, presented in Table 4.

Inclusion Criteria	Exclusion Criteria
Published in peer-reviewed journals	Focused exclusively on landscape architecture with no building envelope application
Focused on green façades, living walls, vertical greenery systems, or living building envelopes	Investigated horizontal green roofs only
Investigated maintainability, durability, lifecycle performance, inspection, maintenance, or DfM	Conference abstracts, editorials, dissertations, patents, or non-peer-reviewed publications
Addressed sustainable building envelopes or façade systems	Lacked sufficient methodological detail
Written in English; published 2016 to 2025	Duplicate publications

Table 4: Inclusion and exclusion criteria.

Source: Author (2026).

Study Selection Process

Selection followed the four PRISMA 2020 stages. At identification, the five search strings returned 2,761 combined records. At screening, 235 records were retained after title-level review, applying the relevance-ranking cap described in section 3.2; 3 duplicates were removed, leaving 232 unique records. At eligibility, records were assessed against the criteria in Table 4: 61 were excluded as off-topic on closer review, 2 as non-peer-reviewed trade or commercial content, and 24 as non-journal or conference formats such as books, theses, or unpublished documents, leaving 145 records sought for full-text retrieval. Each eligible record was appraised using a structured, predefined qualitative appraisal protocol developed for this review. Because no named instrument such as CASP or JBI was used, the appraisal criteria were explicitly defined as: clarity of research objectives; methodological appropriateness; transparency of data collection; validity and transparency of analytical

procedures; relevance to Design for Maintainability; and contribution to living building envelope research. The same criteria were applied consistently to all 35 studies for which full-text content was retrieved and verified, and the identified methodological limitations are reported in Table 5. No numerical quality score was assigned because the review sought thematic synthesis rather than quantitative quality aggregation. Within the resource constraints of this study, full-text content was retrieved and verified for 35 studies, which form the final qualitative synthesis; the remaining 110 eligible records were not reviewed in full text within the review timeframe, as noted in section 1.7.

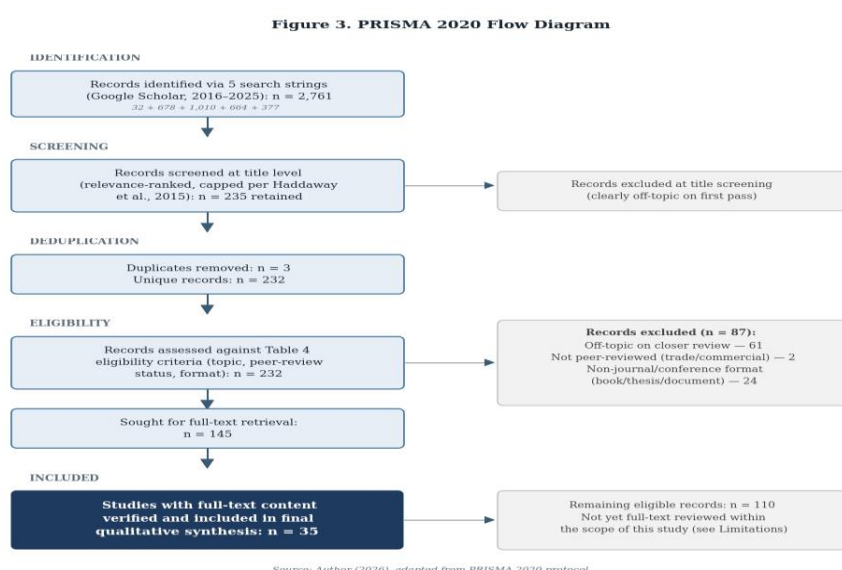


Figure 3: PRISMA 2020 flow diagram.

Source: Author (2026).

Data Extraction and Synthesis

Data were extracted into a structured matrix capturing author or authors, year, country, key finding, and identified limitation for each of the 35 included studies. Given the diversity of study designs, climatic contexts, and performance indicators across the included literature, thematic analysis was used in place of quantitative meta-analysis (Braun & Clarke, 2006; Thomas & Harden, 2008), combining deductive coding against the review's core constructs (typology, performance, DfM principles, maintenance challenges, structural durability) with inductive coding to allow context-specific sub-themes to emerge from the literature. Evidence was grouped into eight recurring themes: living building envelope technologies; green façade performance; Design for Maintainability principles; maintenance challenges; lifecycle performance; coastal environmental influences; emerging digital maintenance technologies; and research gaps and future directions. Trustworthiness of the synthesis was supported by the explicit eligibility criteria, the predefined qualitative appraisal protocol applied to all 35 included studies, systematic screening and extraction procedures,

transparent reporting of the search-to-inclusion funnel in Figure 3, and adherence to PRISMA 2020 reporting standards throughout.

Results and Discussion

Overview of Included Studies

The 35 included studies span 2011 to 2025, drawn predominantly from Europe (11 studies) and Singapore and Southeast Asia (9 studies), with smaller contributions from Australia, Hong Kong, Sri Lanka, Nigeria, Hungary, and Poland. A clear disciplinary pattern is evident across the corpus: studies published before 2020 predominantly adopt typology and performance framing, while more recent publications increasingly foreground maintainability, durability, and design-process concerns. This distribution confirms one of the gaps identified in section 2.5: DfM-specific empirical work on vertical greenery remains concentrated in a small number of tropical Asian and European contexts, with high-humidity coastal settings outside these regions represented only indirectly, through climate-adjacent findings such as the Sri Lankan and Hong Kong studies, rather than through direct coastal case studies.

Comprehensive Evidence Matrix

Table 5 presents the full data-extraction matrix of all 35 reviewed studies, organised with country or context, key findings, and identified limitations for each.

S/N	Author(s) & Year	Country / Context	Key Finding	Limitation
1	Manso & Castro-Gomes (2015)	Portugal / Europe	Typology review distinguishing green façade and living wall systems	Conceptual review; no primary field data
2	Perini, Ottel�, Haas, & Raiteri (2013)	Europe	Formalises a “process tree” linking system typology to installation and end-of-life pathways	Framework paper, not empirically validated
3	Ottel�, Perini, Fraaij, Haas, & Raiteri (2011)	Europe	Comparative LCA: living walls carry higher embodied environmental burden than fa�ades	LCA only; no cross-climate field validation
4	Perini & Rosasco (2013)	Europe	Cost–benefit analysis: green fa�ades more cost-effective than living walls over lifecycle	European cost data; limited transferability

S/N	Author(s) & Year	Country / Context	Key Finding	Limitation
5	Madushika, Ramachandra, & Geekiyanage (2022)	Multi-country (review)	Systematic review of 15 studies: living wall maintenance cost several times higher than façades	Aggregated review; source studies vary in rigor
6	Gunawardena, Wells, & Kershaw (2017)	UK	Green and blue urban infrastructure measurably mitigates urban heat island intensity at city scale; cited here as broader context for building-scale vegetated cooling	Studies urban-scale green/bluespace generally, not green façades specifically
7	Cuce et al. (2021)	Review (multi-region)	Cooling-load reduction highly dependent on density, orientation, and climate	Review; no new field data
8	Huang, Lu, Wong, & Poh (2019)	Singapore (tropical)	Life-cycle cost analysis: maintenance is the dominant long-run cost driver for VGS	Singapore-specific cost structure
9	Thomsit-Ireland et al. (2020)	UK	Green façades reduce model-building temperature and alter relative humidity	Model-building scale, not full-scale field study
10	Yahya et al. (2024)	Malaysia	Green façade adoption on high-rise buildings driven by architectural intent; maintainability secondary	Regional scope
11	Knifka, Karutz, & Zozmann (2023)	Germany	Maintenance-cost uncertainty is a primary adoption barrier	Single-city case study (Leipzig)
12	Aung, Liana, Htet, & Bhaumik (2023)	Review	Green façades support Net-Zero Energy Building goals	Conceptual, limited empirical grounding
13	Chew & Conejos (2016)	Singapore	Establishes "green maintainability"	Singapore case-based

S/N	Author(s) & Year	Country / Context	Key Finding	Limitation
			linking design, sustainability, and FM from concept stage	
14	Chew, Conejos, & Bin Azril (2018)	Singapore	Catalogues VGS defects (irrigation leaks, algae, access) against design interventions	Expert-interview based; Singapore only
15	Conejos, Chew, & Bin Azril (2019)	Singapore	Develops weighted DfM assessment scoresheet for pre-construction VGS comparison	Validated only against Singapore case studies
16	Conejos & Chew (2020)	Singapore	Refines scoresheet with lessons from further case studies	Conference/working paper
17	Chew (2016), book	Singapore / general	Consolidates green maintainability and FM principles	Practitioner text, not a primary empirical study
18	Mohanta et al. (2022)	Warm-humid region (general)	Maintainability attribute checklist for wall, fenestration, and roof components	General envelope focus, not VGS-specific
19	Ferreira, Silva, de Brito, & Flores-Colen (2023)	Europe	Predictive, condition-based maintenance model for envelope components	Conventional envelopes; not vegetated
20	Silva & de Brito (2021)	Europe	Synthesises 107 studies on envelope component service life and durability	General envelope; limited VGS coverage
21	Frank & Brisibe (2019)	Nigeria	Overlooking maintainability at planning stage raises FM cost, shortens asset life	General construction sector, not VGS-specific
22	Perera, Jayasinghe, Halwatura, et al. (2021)	Sri Lanka (tropical)	Irrigation demand and growth vigour rise sharply with humidity and rainfall exposure	Simulation-based
23	Kaltsidi, Fernández-Cañero, Franco-	Spain	Felt-based living wall water-retention	Single system type tested

S/N	Author(s) & Year	Country / Context	Key Finding	Limitation
	Salas, & Pérez-Urrestarazu (2020)		design directly determines maintenance frequency	
24	Pérez-Urrestarazu (2021)	Spain (warm climate)	Irrigation demand varies more than threefold across similar installations	Warm climate; not specifically coastal
25	Nowicka-Krawczyk et al. (2025)	Poland (temperate)	Algal biofilms measurably lower substrate pH and increase water absorptivity	Temperate climate; lab/field study
26	Fleck et al. (2020)	Australia	Active fungal/bacterial communities within green walls require dedicated inspection regimes	Indoor active-wall system, not exterior façade
27	Dahanayake & Chow (2018)	Hong Kong	Irrigation lapses raise fire risk by drying vegetation in VGS	Fire-risk focus; not full maintainability scope
28	Daniel, Wang, Li, Dong, Udoh, Zhang, Zhong, & Zhong (2023)	Hainan, China (tropical marine)	Galvanised steel bolt coatings can fail within 6 months in high-chloride coastal conditions	Materials-testing scope; not building-envelope specific
29	Gunawardena & Steemers (2020)	Europe (10 installations)	Visible decline in a poorly accessible installation can trigger disinvestment	European installations only
30	Farrokhirad, Rigillo, Köhler, & Perini (2024)	Multi-country	Most VGS projects lack a pre-design goal-setting phase and post-installation monitoring	Design-process review, not performance data
31	Xiang & Tao (2023)	Hong Kong	Wind-driven rain can serve as a natural irrigation source, reducing engineered irrigation demand	Simulation-based; Hong Kong-specific

S/N	Author(s) & Year	Country / Context	Key Finding	Limitation
32	Gocer, Ramezannia, & Allison (2025)	Australia	Hardware design (media shrinkage, root growth, moisture/airflow) is critical to durability across diverse climates	Australia-specific; qualitative
33	Tamási & Dobszay (2015)	Hungary	Panel material selection (aluminium/iron/steel) materially affects system durability	Case-study based; single country; predates the review's primary 2016 to 2025 window
34	Hassan, Elsady, & Haggag (2026)	Cairo, Egypt	Failure Modes and Effects Analysis identifies and prioritises risk across the project lifecycle; monitoring and controlling phase found most critical	Questionnaire-based; single-country stakeholder sample; falls just beyond the review's primary 2025 cutoff
35	Palermo, Viviani, Pirouz, Turco, & Piro (2023)	Italy	Irrigation/fertilisation regime affects nutrient leaching over time, linking irrigation to substrate maintenance	Single experimental system

Table 5: Comprehensive evidence matrix of all 35 reviewed studies.

Source: Author (2026), compiled from the 35 included studies.

Thematic Synthesis

Typology and Performance

Consistent with the typology established in section 2.1.1, the included studies confirm that green façades and living walls diverge sharply in maintenance burden rather than simply in construction method. Cost-benefit and life-cycle evidence (Perini & Rosasco, 2013; Ottelé et al., 2011; Madushika et al., 2022) converges on a consistent finding: living walls' higher engineering complexity, comprising automated irrigation, substrate systems, and denser planting, delivers stronger thermal and aesthetic performance but at a maintenance cost several times greater than façades. This cost differential, more than raw installation price, appears to be the more decisive factor in system selection where budgets are constrained,

which directly reinforces the case for embedding maintainability considerations at the typology-selection stage rather than after a system type has already been chosen.

Design for Maintainability: Applied Evidence

The Singapore-based DfM literature (Chew & Conejos, 2016; Chew et al., 2018; Conejos et al., 2019; Conejos & Chew, 2020) remains the most methodologically developed body of evidence for translating DfM principles into VGS-specific design guidance, with a consistent core defect list, namely irrigation faults, algae growth, and restricted access, recurring across all four studies despite different case-study sets. Outside this cluster, general building-envelope maintainability research (Ferreira et al., 2023; Silva & de Brito, 2021; Mohanta et al., 2022) confirms the same design-stage logic applies to conventional envelope elements, but none of these frameworks were developed with vegetated systems in mind, which confirms the gap identified in section 2.5 that conventional DfM tools do not natively account for horticultural or seasonal variables.

Maintenance Challenges: Vegetation, Irrigation, and Biological Colonisation. Irrigation emerges as the single most cross-cutting maintenance variable across the included studies. Felt-based living wall trials (Kaltsidi et al., 2020; Pérez-Urrestarazu, 2021) demonstrate that water-retention design choices directly determine both maintenance frequency and plant survival, with irrigation demand varying more than threefold across comparable installations. This variability compounds in humid, high-rainfall conditions (Perera et al., 2021), where growth vigour and hence pruning frequency rise sharply, though notably, wind-driven rain can also partially substitute for engineered irrigation under the right façade geometry, as shown in a Hong Kong case study (Xiang & Tao, 2023), suggesting irrigation design should be climate-responsive rather than uniform. Biological colonisation is not incidental to this picture but causally linked to it: algal biofilms measurably degrade substrate chemistry and increase water absorptivity (Nowicka-Krawczyk et al., 2025), while active microbial communities within living walls require their own inspection regime independent of plant health monitoring (Fleck et al., 2020). Counter-intuitively, irrigation failure compounds fire risk rather than only aesthetic risk, since under-watered vegetation dries and becomes more flammable (Dahanayake & Chow, 2018), a finding with direct design implications for irrigation redundancy in fire-sensitive jurisdictions. Palermo et al. (2023) further show that irrigation and fertilisation regimes affect nutrient leaching over time, linking water-management decisions to substrate condition and therefore extending irrigation maintainability beyond plant survival to longer-term substrate management.

Structural Durability and Occupant and Institutional Factors

Structural evidence is comparatively thin but consistent: marine-exposure testing confirms galvanised steel corrosion protection can fail within six months under high-chloride conditions (Daniel et al., 2023), a timeframe far shorter than typical inspection cycles assume, while a Hungarian case study confirms panel material selection materially affects

durability outcomes independent of climate (Tamási & Dobszay, 2015). This is the area of the review with the fewest directly coastal, VGS-specific studies: the corrosion evidence, while highly relevant, is drawn from general materials-testing literature rather than a green-façade-specific study, again pointing to the geographic and disciplinary gap identified earlier. Beyond hardware, occupant and institutional behaviour proves equally consequential: European living wall reviews (Gunawardena & Steemers, 2020) show that visible decline in a poorly accessible installation can trigger disinvestment even where the underlying defect is minor, while a formal risk-assessment study applying Failure Modes and Effects Analysis across the green wall project lifecycle confirms that failure risk is distributed across design, construction, and operational phases rather than concentrated in any single stage (Hassan, Elsady, & Haggag, 2026), which reinforces the case for whole-lifecycle DfM thinking rather than a design-only or maintenance-only intervention.

Discussion

The synthesis reveals three overarching structural dynamics that collectively characterise the DfM challenge for green façades in high-humidity coastal environments. First, a maturity gap exists between typology and application: typological and thermal-performance knowledge is well developed and broadly transferable across climates, but design-stage maintainability guidance is concentrated in a small number of tropical Asian case studies and has not been systematically extended to coastal-specific stressors such as salt-laden air and cyclical wind-driven rain. Second, a mechanism-integration gap runs through the coastal deterioration evidence: biofouling, corrosion, and substrate degradation are each well documented individually, largely within adjacent literatures such as materials science and microbiology, but rarely studied together within a single façade-specific investigation, despite the included evidence showing these mechanisms interact and compound one another. Third, a governance gap sits alongside the technical ones: even where design-stage guidance and hardware solutions exist, occupant perception and institutional maintenance investment decisions, rather than technical feasibility, determine whether a defect is addressed before or after it becomes visible. Confidence in individual findings nevertheless varies across the evidence base: simulation-based studies provide useful predictive insight but are less direct than field-measured evidence, while laboratory and materials-testing studies illuminate specific deterioration mechanisms without reproducing complete façade operating conditions. These differences are reflected in the limitation column of Table 5 and mean that the most specific coastal design recommendations should be treated as evidence-informed priorities requiring field validation rather than as universally validated thresholds.

Mapped against the conceptual framework in section 2.4, the included evidence populates each stage of the model unevenly. The mediating construct, Design for Maintainability principles, is well evidenced for accessibility, inspectability, and, to a lesser extent, corrosion resistance, but modularity and replaceability remain comparatively under-

studied at the empirical level, appearing mainly in conceptual or scoresheet-based work (Conejos et al., 2019) rather than field-measured outcomes. The outcome chain from maintenance performance to lifecycle sustainability is well supported by cost and life-cycle assessment evidence (Perini & Rosasco, 2013; Ottelé et al., 2011; Huang et al., 2019), but the environmental context node, meaning high-humidity coastal exposure specifically as opposed to tropical or humid conditions generally, remains the framework's weakest-evidenced link, confirming this review's central motivating gap rather than resolving it.

Compared to the well-resourced Singapore case studies, where a dedicated research programme has produced repeated, cumulative design guidance over a decade, high-humidity coastal contexts more broadly lack any equivalent sustained research effort, leaving practitioners to extrapolate from typological, tropical, or temperate-climate evidence rather than drawing on coastal-specific guidance. Irrigation design, corrosion-resistant hardware specification, and accessible inspection provision emerge as the three most actionable near-term levers available to designers in the absence of that dedicated evidence base, since each is directly supported by consistent, if geographically scattered, empirical findings within the included studies.

This gap carries particular weight for West African coastal cities such as Lagos, which share the humidity, salinity, and rainfall intensity of the coastal contexts represented in this review but are entirely absent from its included evidence base. The Singapore framework's core design levers, namely accessible service walkways, corrosion-resistant fixings, and redundant irrigation zoning, were developed and validated in a high-rise, high-humidity tropical setting broadly comparable to Lagos, suggesting these principles are a plausible starting point for adaptation rather than requiring an entirely new framework. However, Lagos and comparable Sub-Saharan African coastal cities differ from Singapore in construction supply chains, regulatory capacity, and the availability of specialist maintenance labour, meaning direct transfer of the Singapore scoresheet without local validation risks specifying hardware or inspection regimes that are technically sound but practically unmaintainable in the local market. Bridging this gap, between a technically mature but geographically distant framework and an entirely unstudied but climatically comparable region, represents the most direct opportunity for future research to extend this review's findings into practical, regionally grounded design guidance for West African coastal developments.

Conclusion and Recommendations

This review set out to examine how Design for Maintainability principles have been applied to living building envelopes, with particular attention to green façades operating in high-humidity coastal environments. Drawing on 35 studies synthesised through thematic analysis, three conclusions follow.

First, DfM as a design philosophy is well established for vegetated envelopes, but its most developed applications, namely the Singapore-based green maintainability framework,

remain geographically concentrated and have not been systematically tested against coastal-specific stressors such as salt-laden air and cyclical wind-driven rain exposure. Second, the evidence bases for individual coastal deterioration mechanisms, comprising biofouling, corrosion, and substrate degradation, is real and consistent, but drawn largely from adjacent literatures such as materials science, general building envelope research, and temperate-climate biology, rather than from integrated, façade-specific coastal studies. Third, irrigation design is the single most consequential and most climate-sensitive DfM variable identified across the synthesis, with direct downstream effects on vegetation health, biological colonisation, and even fire risk, making it the most actionable near-term design lever for practitioners working in humid coastal contexts.

To address these challenges, a design-stage intervention framework is required. First, specify corrosion-resistant hardware and inspection cycles shorter than the six-month coating-failure timeframe identified for high-chloride environments. Second, design irrigation systems with redundancy and climate-responsive control, for example by accounting for wind-driven rain contribution, rather than fixed schedules. Third, incorporate accessibility and modularity as explicit, scored design criteria at the concept stage, following the Singapore scoresheet model, rather than as post-occupancy retrofits. This review's central and most actionable gap is the near-absence of DfM studies conducted specifically in high-humidity coastal, as opposed to generally tropical or humid, settings. Future empirical work should prioritise field-based, multi-year monitoring of VGS installations in coastal cities, explicitly tracking corrosion, biofouling, and irrigation performance together rather than as separate research strands. The 110 eligible but unreviewed records identified in this review's screening process, described in section 3.4, represent a concrete starting point for that follow-up work.

Finally, this review draws on a single open-access search tool rather than institutional databases, applied a practical screening cap rather than an exhaustive review of all identified records, and reports a final synthesis set of 35 studies out of 145 eligible records, with the remainder identified for future extension of this work.

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