Report On

Innovative Construction Technologies for Green and Climate-Resilient Housing: The Potential of Moss Concrete

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Executive Summary

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Submitted to

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by

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Introduction

Modern urban infrastructure is reliant on concrete, yet this reliance comes at a steep environmental cost. Cement production alone accounts for approximately 8% of global CO2 emissions, while concrete's high thermal mass exacerbates the Urban Heat Island (UHI) effect, raising city temperatures and increasing energy demands for cooling. While conventional greening solutions like living walls exist, they are often resource-intensive, operationally complex, and require soil, irrigation, and deep-rooting structures.

This research project explores moss concrete as a practical, low-cost, and passive alternative. Moss concrete is a "bioreceptive" material, specifically engineered to foster the growth of mosses (bryophytes) that do not penetrate or crack substrates, while directly growing on its surface. This "living skin" is a self-sustaining system that eliminates the need for soil or irrigation. This study provides a comprehensive review of this technology, synthesizes its environmental benefits, and presents a clear, evidence-based pathway for its adoption within the Indian housing sector to create more climate-resilient and nature-inclusive urban environments.

1. Objective

The primary objective of this research was to evaluate moss concrete as a multifunctional, bioreceptive material that can support moss growth without soil, irrigation, or fertilizers, presenting it as an innovative and viable pathway for climate resilient housing in India.

To achieve this, the study pursued several core objectives:

- To establish the scientific basis for engineering this material by modifying key properties, including porosity, surface texture, and alkalinity.
- To systematically review and compare various preparation methodologies, such as intact colony transfer, slurry application, and two-layer composite systems, to identify the most scalable and effective approaches.
- To consolidate the evidence on its multiple environmental benefits, specifically its contributions to urban cooling, noise absorption, air purification, and stormwater regulation.
- To propose a practical framework for species selection and outline key research gaps to guide future implementation.
- To propose a novel, one-of-a-kind research direction for the Indian context: the evaluation of Panchagavya as a nutrient-carrying bio-adhesive for moss application.

2. Methodology

The methodology for this project was a comprehensive literature synthesis designed to build a practical, evidence-based overview of moss concrete technology. It involved a systematic review of scientific papers, patent filings, and applied case studies. The first step was a fundamental analysis of the material science, comparing the composition (e.g., pH, porosity, aggregates, and use of Supplementary Cementitious Materials) of conventional concrete versus bioreceptive concrete to establish the core principles of its design. Following this, the research critically assessed five distinct application methodologies: intact colony transfer, slurry application, pre vegetated panels, passive colonization, and two-layer composite systems. These methods were evaluated for their establishment speed, coverage, durability, and scalability. To ground this analysis in real world application, the study distilled practical, reproducible protocols from six international case studies, including an important field study from Visakhapatnam, India. This synthesis of theoretical and practical data was then used to quantify key performance metrics (such as cooling potential in degrees Celsius and acoustic absorption coefficients) and to develop a functional species selection framework based on a building's specific microclimate and exposure.

3. Outcomes

The research concludes that moss concrete is a "viable and distinct pathway" (Section 10) for green building, offering significant, quantifiable benefits. The study confirms its ability to create a self-sustaining "living skin" that functions "without soil, irrigation networks or secondary frames," offering a key advantage over traditional green walls. The evidence demonstrates clear environmental performance: moss covered surfaces remain 2–5°C cooler than bare concrete (Section 7.1), directly mitigating the UHI effect; thick moss cushions achieve significant sound absorption of ~0.55 (Section 5.1); and the moss canopy is highly effective at intercepting and retaining particulate matter (PM2.5/PM10) (Section 7.3).

Furthermore, the study identifies practical application protocols suitable for the Indian context. The "two-layer composite system" (Section 4.5) is presented as an advanced solution for new builds, while the low cost " slurry method," successfully tested in Visakhapatnam (Section 5.5), is ideal for community led retrofitting and affordable housing projects. By eliminating complex support systems, the technology "significantly lowers construction and maintenance costs" (Section 7.6), reducing both initial capital (CAPEX) and long term operational (OPEX) expenditure.

4. Specific Recommendations & Action Plan for NHB

Based on the research findings and the critical "Research Gaps" (Section 8) and "Future Work" (Section 11) identified in the paper; the following recommendations are proposed for consideration by the National Housing Bank (NHB):

A. Policy Interventions

Based on the research findings, particularly the "Lack of Standardization" identified as a major weakness (Table 4), we recommend key policy interventions. A primary action would be for NHB to facilitate the creation of an Indian Standard (IS) Code for bioreceptive concrete. This standard should define test protocols, material descriptors, and biological acceptance criteria, as called for in Section 8. Concurrently, NHB should champion the integration of moss concrete into national green building frameworks like GRIHA, offering specific credits for its demonstrated benefits in passive cooling and stormwater management. To overcome initial adoption hurdles, a dedicated financing scheme or interest subvention for affordable housing projects utilizing this low cost, passive cooling technology is also recommended.

B. Programmatic/Scheme-Based Actions

On the programmatic front, the research explicitly identifies critical research gaps that NHB can lead in addressing. We recommend establishing a targeted R&D fund to conduct "long horizon adhesion and coverage" studies under diverse Indian conditions (dust, heat, monsoon) as called for in Section 8. This fund should also be used to develop an "India specific species and ecotype baseline" and sponsor the proposed future research into a Panchagavya based bio adhesive (Section 11). Launching a multi city pilot program, building on the successful case studies (Section 5), would validate performance and durability in India's different climatic zones. Finally, sponsoring capacity building workshops for architects, engineers, and contractors would be essential to move this technology "from prototypes to programmes" (Section 10) and ensure its standardized, reproducible application.

Conclusion

This research confirms that moss concrete has evolved from a novel concept into a mature, deployable technology with clear, evidence-based protocols. The findings present an unambiguous answer to India's urgent, interconnected challenges of affordable housing, urban heat, and climate resilience. This low-cost, passive, and scalable solution directly advances our most critical Sustainable Development Goals (SDGs), namely SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action).

The potential of this technology is immense and, as of now, almost entirely untapped. The action plan proposed here, spanning standardization, targeted R&D, and pilot programs provides the definitive roadmap to bridge the gap from research to implementation. This is a strategic moment for the National Housing Bank. With decisive leadership, NHB can do more than just fund housing; it can seed an entire green-tech ecosystem. This is India's opportunity to pioneer a technology that is both environmentally sustainable and economically profitable, setting a new global standard and showcasing to the international community how to build a new generation of truly climate-resilient cities from the ground up.

Innovative Construction Technologies for Green and Climate-Resilient Housing: The Potential of Moss Concrete

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Abstract

Concrete is central to modern infrastructure but is also a major driver of carbon emissions, heat accumulation in cities, and ecological loss. Conventional eco concrete approaches have attempted to reduce these impacts, yet most remain resource intensive or complex to implement. The present study explores moss concrete as a bioreceptive and multifunctional material that allows the growth of mosses on its surface while maintaining structural performance. Designed with increased porosity, surface texture, and moderated alkalinity, moss concrete enables the establishment of moss communities without soil, irrigation, or fertilizers. Different preparation methods including intact colony transfer, slurry application, pre vegetated panels, passive colonization, and two-layer composite systems are reviewed in detail. Evidence shows that moss concrete contributes to cooling, noise absorption, air purification, stormwater regulation, and biodiversity support in urban environments. A species selection framework linked to local microclimates is outlined, with emphasis on applications in Indian cities where pollution, heat stress, and rapid urban growth demand resilient and low maintenance solutions. Research gaps include standardization of test protocols, durability in diverse climates, and economic evaluation. The study further proposes the use of Panchagavya as a nutrient carrying adhesive to enhance moss establishment. Overall, moss concrete is presented as a practical and innovative pathway for climate resilient and nature inclusive housing.

Keywords: Moss concrete, Bioreceptivity, Urban cooling, Air quality, Green housing, Sustainable construction

List of abbreviations used

- **ASTM** — American Society for Testing and Materials
- **CAPEX** — Capital Expenditure
- **CEM III/B** — Blast-furnace slag cement (EN 197 designation)
- **CNC** — Computer Numerical Control (as in CNC-milled moulds)
- **CO_2** — Carbon dioxide
- **ETICS** — External Thermal Insulation Composite System
- **Fv/Fm** — Maximum quantum yield of photosystem II (chlorophyll fluorescence metric)
- **ISO** — International Organization for Standardization
- **kHz** — kilohertz (frequency unit)
- **MPC** — Magnesium Phosphate Cement
- **NO_x** — Nitrogen oxides
- **OPEX** — Operating Expenditure
- **PAM (as in MINI-PAM II)** — Pulse-Amplitude Modulation fluorometer
- **PAR** — Photosynthetically Active Radiation
- **pH** — Acidity/alkalinity measure
- **$PM_{2.5}$** — Fine particulate matter $\leq$2.5 µm
- **PM_{10}** — Particulate matter $\leq$10 µm
- **RC** — Reinforced Concrete
- **SCMs** — Supplementary Cementitious Materials
- **UHI** — Urban Heat Island
- **UHPC** — Ultra-High-Performance Concrete
- **W/C ratio** — Water to Cement ratio

1 Introduction

Concrete is the backbone of modern urban infrastructure used in buildings, roads, and utilities worldwide. However, this ubiquity comes at a steep environmental cost. Cement production alone accounts for approximately 8% of global CO_2 emissions, driven by the high energy demands of calcining limestone and the release of carbon during processing (Habert et al., 2020). Beyond emissions, concrete's high thermal inertia exacerbates the urban heat island (UHI) effect, elevating ambient temperatures in cities and increasing energy demands for cooling (Zhou et al., 2014). Moreover, its impermeable surface restricts natural water infiltration, aggravating urban flooding and reducing groundwater recharge. Concrete also displaces green infrastructure, leading to biodiversity loss, habitat fragmentation, and ecological homogenization (Forman, 2014). Despite advances in eco-concretes and carbon capture techniques, most solutions remain resource-intensive or operationally complex. There remains a critical need for multifunctional materials that not only reduce concrete's environmental impact but also actively contribute to urban ecological performance.

To address these challenges, researchers are developing bioreceptive concrete, engineered to support biological colonization without compromising structural performance. Among these innovations, moss concrete stands out as a passive, low-maintenance solution that turns building surfaces into living ecological systems. Unlike traditional green facades that require soil, irrigation, and deep rooting structures, moss concrete fosters the growth of bryophytes, a class of non-vascular plants that adhere to surfaces via rhizoids. These structures do not penetrate or crack substrates, making them ideal for vertical or retrofit applications (Lăcătușu et al., 2023). Mosses offer photosynthetic air purification, absorbing CO_2, NO_x, and $PM_{2.5}$. A pilot prototype using sphagnum moss in a biofiltration system demonstrated substantial reductions in air pollution while operating in dense, impermeable urban zones (Инелова et al., 2022). Moreover, moss-covered concrete contributes to urban cooling via evapotranspiration. The moisture retained and slowly released by the moss layer reduces surface and ambient temperatures, helping offset the thermal mass effect of conventional concrete structures (Mahmoud, 2022). Importantly, moss systems create microhabitats for insects, fungi, and bacteria, thus restoring localized urban biodiversity. These ecosystems also enhance nutrient cycling and ecological resilience in cityscapes where vegetative life is otherwise limited (Fragnière, 2024).

The bioreceptive concrete mix is engineered with properties like increased porosity and surface roughness, which retain ambient moisture and nutrients, enabling moss growth without soil or external inputs. Once exposed to appropriate microclimatic conditions, mosses establish spontaneously, forming a self-sustaining vegetative layer (He et al., 2020). Field demonstrations, such as those by the Dutch start-up Respyre have shown that optimized moss-concrete composites can grow and persist without irrigation, anchoring systems, or fertilizers, especially in shaded, humid urban microclimates. These systems significantly reduce installation and operational costs, compared to conventional living walls, making them scalable in both retrofitting and new builds.

2 Comparative framework: conventional concrete versus bioreceptive moss concrete

This section contrasts conventional structural concrete with a bioreceptive moss-concrete skin. The aim is to highlight design levers that increase near-surface water storage and micro-texture while keeping structural performance in a core layer through a two-layered approach. Key differences between ordinary cement and Moss concrete can be understood from **Table 1**.

Table 1. Fundamental and structural differences between the ordinary cement and Moss concrete (Bioreceptive cement)[1]

[1]*Aspect*	*Conventional Concrete*	*Moss Concrete (Bioreceptive)*
Cement content	100% OPC (high alkaline content)	OPC reduced; partial replacement with fly ash, slag or MPC cement to lower alkalinity. pH modifiers (citric acid, silica fume) included. (Pozzolanic Waste Material)
Aggregates	Dense aggregates (gravel, sand) for maximum strength, low porosity.	Porous/light aggregates (expanded clay, perlite) to increase voids. Adjusted grading for microporosity. Surface intentionally rough/textured.
Water content	Optimized for strength (low W/C ratio ~0.4–0.5).	Slightly higher water content for workability and pore formation. Possibly use of foaming agents for extra pores (in some experiments). Water-to-cement ratio adjusted to balance structural needs with moss needs.
Additives	Plasticizers, etc. for strength/workability as needed.	Moisture retaining additives (hydrogel, SAP). Slow-release fertilizer (N, P, K) mixed in. Possibly fibres to hold water and aid cracking resistance.
Expected pH	Highly alkaline initially (pH ~12.5) – hostile to bryophytes.	Moderated pH (target slightly acidic to neutral) via cement reduction and additives. Moss prefers ~pH 5.0–6.5, so design strives to approach that.
Strength target	High compressive strength (depending on grade e.g. M30, M40).	Sufficient strength for intended use (often non-structural panels). Accepts moderate strength (e.g. M20) as long as it supports itself and any loads. Emphasis on durability & bonding of moss rather than very high PSI.
Density	~2200–2400 kg/m³ for normal concrete.	Lower density (due to porous aggregates and air voids). More akin to lightweight concrete, improving thermal insulation too.

[1] Key sources: (Cruz and Beckett, 2016; Manso et al., 2014; Mohanty et al., 2025; Mustafa et al., 2021; Susanto, 2018.; M. Veeger et al., 2021; Veeger et al., 2025b, 2025a)

While the concept of vegetation concrete was introduced in the 1990s, primarily in slope stabilization and erosion control applications, recent advancements have refocused on urban facades and aesthetic integration with architecture. For example, vegetation concrete used on highway embankments has shown success in blending structural reinforcement with ecological restoration (Faiz et al., 2022). Unlike those older systems that often require embedded seeds, irrigation, or soil amendments, modern moss concrete targets thin moss layers, functioning as living biofilms that contribute to air filtration, surface cooling, and microhabitat creation, all while occupying minimal space and adding minimal weight.

India, home to 17 of the world's 30 most polluted cities, faces severe air quality degradation alongside intensifying heatwaves and rapid urbanization. Cities like Delhi, Ghaziabad, and Kanpur frequently record $PM_{2.5}$ levels far exceeding WHO guidelines, contributing to respiratory illnesses, reduced productivity, and rising urban mortality (IQAir, 2024). Simultaneously, urban heat island effects intensify during the subcontinent's scorching summers, exacerbating energy demands for cooling and stressing already overburdened infrastructure (Islam et al., 2024). In this setting, moss concrete emerges as a low-energy, nature-based strategy that synergizes well with India's need for passive cooling, air purification, and affordable green infrastructure. Its self-sustaining design eliminates the need for irrigation or soil-based systems, reducing both upfront costs and long-term maintenance factors especially crucial in resource-constrained urban environments.

This paper aims to deliver a practical, step-by-step overview of moss concrete formulation and application, with emphasis on adaptability to Indian climatic conditions. It will detail how to engineer bioreceptive concrete mixes, how to encourage moss colonization, and how to evaluate performance in terms of ecological and structural benefits. Additionally, we will contrast moss concrete with other greening technologies such as green roofs and vertical planters based on cost, maintenance, thermal regulation, and scalability. With India committing to net-zero by 2070 and expanding its smart cities program, such bio-integrated innovations are poised to play a vital role in shaping resilient, breathable, and thermally comfortable cities.

3 Bioreceptivity of Concrete

The term bioreceptivity was first introduced by Guillitte, (1995) who defined it as *"the aptitude of a material to be colonized by living organisms without necessarily implying deterioration"*. In the case of concrete, this refers to its capacity to support colonization by mosses, lichens, algae, and other organisms. Bioreceptivity is governed by intrinsic material factors including porosity, surface roughness, water retention, and chemical composition, as well as extrinsic environmental factors such as humidity, light, and air pollution. Studies demonstrate that increasing porosity and surface roughness, using slag-based binders, and avoiding hydrophobic coatings can enhance moss establishment, while smoother, sealed concretes are less conducive to colonization (Mustafa et al., 2021). Furthermore, the geometry of concrete panels can be engineered to optimize water retention, thereby promoting ordered and sustainable colonization (Manso et al., 2015). These insights underscore how bioreceptive concrete can be purposefully designed to merge infrastructure with ecological function. Various measure to improve the bioreceptivity can be seen from **Table 2.**

Table 2. Measures to increase the bioreceptivity of cementitious substrates for moss concrete[2]

Intervention (material/finish)	*Targeted parameter(s)*	*Implementation examples*	*Effect on bioreceptivity*	*Observations*
Increase near-surface water storage	Capillary water availability; retention time at the surface	Incorporate porous/expanded aggregates (e.g., crushed expanded clay, vermiculite) in the near-surface zone; design non-optimal aggregate packing to raise void ratio	Both crushed expanded clay and vermiculite improved moss colonisation on concrete surfaces; non-optimal packing increased overall porosity and bioreceptivity.	Improves establishment especially during dry intervals; monitor mechanical performance and ravel resistance for highly open skins.
Add superabsorbent polymers (SAPs)	Transient water storage; re-wetting capacity	Low-dosage SAPs in the surface mortar/skin	SAPs increased water retention and supported establishment on bioreceptive concrete.	Excessive SAPs may weaken surface; optimise dosage and confinement to the cover zone.
Engineer surface roughness (micro-texture)	Microhabitats; boundary-layer moisture; initial attachment	Surface retarder/brush-off finish; rough formliners	Rougher surfaces raised water absorption and provided protected niches, improving establishment and survival.	Roughness from binder reduction alone showed no clear effect in some studies; pair roughness with hydrologically open microstructure.
Apply micro-patterning / shallow relief	Water flow guidance; local retention	Shallow grooves/concavities; hybrid panels with bioreceptive "islands"	Surface patterning directed flow and improved bioreceptivity; biological growth localised to bioreceptive regions in hybrid UHPC–bioreceptive panels.	Use to concentrate moss where desired (logos/bands); verify cleanability in service.

Tune paste/porosity strategy	Permeability vs. sorptivity balance at skin	Adjust w/c or binder:aggregate ratio; air-void control	Raising w/c (0.5→0.6) did not significantly increase bioreceptivity in one study, whereas more porous mortars (via binder–aggregate proportion/type/size) performed better in another.	Prioritise near-surface porosity and connectivity over bulk paste porosity; confirm by sorptivity tests.
Nutrient micro-dosing in matrix	Local P/Ca availability; early metabolism	Trace bone ash or similar benign nutrient sources	Measures that add nutrients are among those repeatedly found to improve bioreceptivity; bone ash is used in successful bioreceptive mixes.	Keep doses low to avoid leaching/biofouling; pair with hydrological measures.
SCM blending / alternative binders (comparative evidence)	Moderate pore-solution alkalinity; refine microstructure	FA, SF, BFS; CAC/SAC/LSAC systems	OPC pore solution is highly alkaline (pH≈12–13); SCMs and alternative cements reduce alkalinity; e.g., 5% SF reduced pH to 9.8 (28 d) and 9.0 (90 d) in vegetation concrete; FA/SF combinations lowered pH and improved plant compatibility.	For moss, the role of pH alone is mixed/unclear across studies, hydrology and roughness are first-order controls but SCMs remain desirable for sustainability and compatibility.
Acid-wash / carbonation (comparative)	Surface pH reduction; $Ca(OH)_2$ depletion	Mild organic acids (e.g., oxalic acid spray/soak)	Documented to reduce pH in vegetation concrete; considered as post-treatment lever on alkalinity.	Use judiciously; ensure no adverse salt formation or durability penalties; confirm with phenolphthalein/pH profiling.

Recycled fine aggregates in skin	Hygroscopic fines; capillarity; sustainability	0–4 mm recycled concrete fines in surface mortar/tiles	Recycled fines used in validated bioreceptive mixes for moss testing; recycled aggregates can meet ecological performance targets in vegetation concretes when properly processed.	Check variability; pre-treat (e.g., acid-wash) if needed; verify salts/alkali release.
Two-layer design (bioreceptive skin on structural core)	Decouple structural and bioreceptive functions	Thin bioreceptive overlay on UHPC/RC core	Biological growth confined to bioreceptive layer in hybrid panels, enabling targeted colonisation without compromising the core.	Enables maintenance/renewal of only the outer skin; consider differential shrinkage/bond.[2]

[2] *Sources:* (Guillitte, 1995; Manso et al., 2015, 2014; Mohanty et al., 2025; Perini et al., 2011; Perini and Rosasco, 2013; Max Veeger et al., 2021; M. Veeger et al., 2021; Veeger et al., 2025a, 2025b)

4 Moss Concrete Preparation Methodologies

The preparation of moss concrete is a multidisciplinary process that combines principles of material science, bryology, and architectural design to create substrates capable of sustaining moss growth. It represents a convergence of green material innovation and urban ecological design, aiming to produce substrates that not only perform structurally but also act as living habitats. Unlike conventional concrete, which is dense, alkaline, and poorly suited to colonization, moss concrete is engineered with optimized porosity, water retention, and surface roughness to support bryophyte attachment and growth. Various moss concrete preparation methodologies have been discussed elaborately hereunder.

4.1 Intact-Colony Transfer (Adhesive-Assisted)

The intact-colony transfer technique is among the most straightforward methods for moss concrete preparation, as it relies on transplanting living moss cushions directly onto pre-prepared bioreceptive concrete. Substrates are typically cast using supplementary cementitious materials (SCMs) such as slag or fly ash and lightweight aggregates that reduce alkalinity and increase water-holding capacity, which are critical for bryophyte survival (Mustafa et al., 2021). After a standard 28-day curing period, the panels are surface-treated (via brushing, retarders, or acid etching) to generate mm-scale roughness, improving sorptivity and micro-habitat provision (Bone et al., 2022). Moss colonies are carefully harvested from donor habitats and cleaned to remove soil particles, ensuring minimal contamination from higher plants. A thin adhesive layer, most commonly methylcellulose, validated as a non-toxic moss adhesive is applied on the pre-wetted surface (Lei et al., 2020). Cushions of 5–15 mm thickness are pressed onto the surface, arranged in staggered patterns to reduce self-shading. Laboratory conditioning under misting and moderate irradiance (~130 μmol m^{-2} s^{-1} PAR) for three weeks allows attachment before panels are moved outdoors. Studies show this method achieves rapid and reliable establishment, making it ideal for façade greening applications in controlled projects (Fragnière, 2024). The schematic of the procedure can be understood from **Figure 1**.

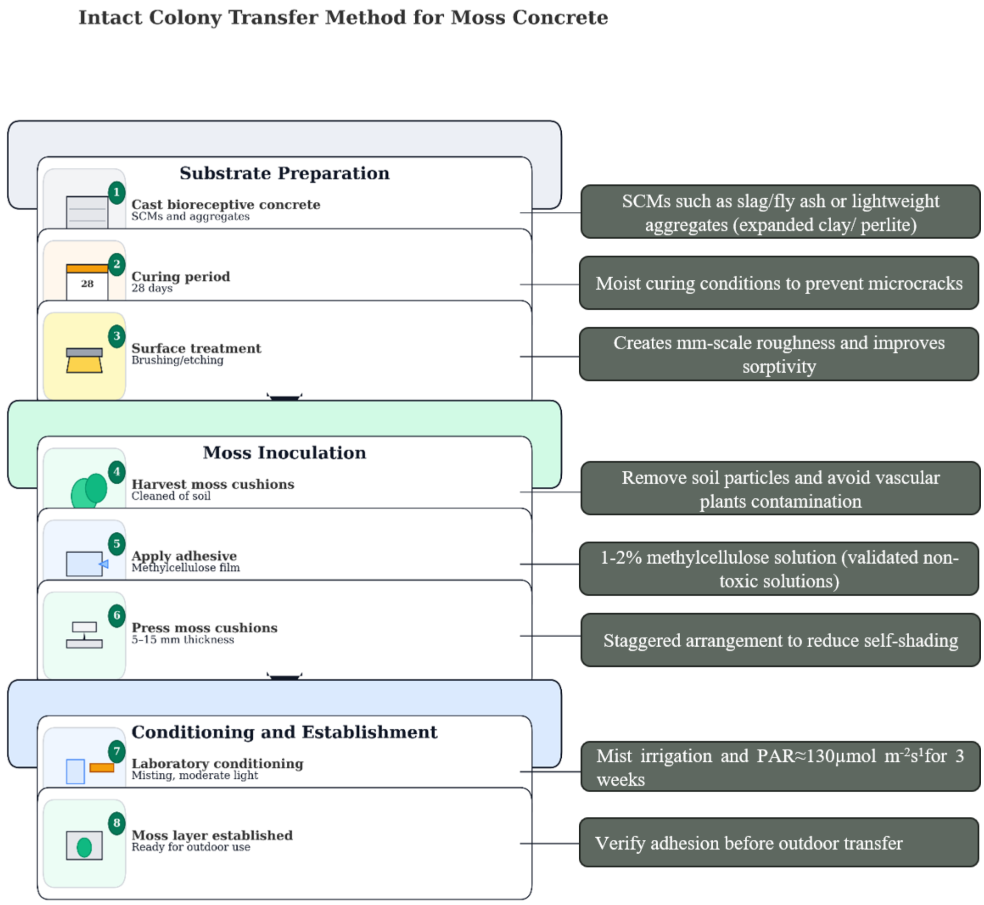

Figure 1 *Workflow of the Intact Colony Transfer Method for moss concrete.* The process comprises substrate preparation, moss inoculation, and conditioning, with annotations highlighting key parameters such as curing time, adhesive concentration, cushion thickness, and light intensity for reproducible establishment.

4.2 Slurry Method (Fragment Suspension)

The slurry method establishes moss on concrete surfaces by fragmenting moss cushions into small pieces, usually 1–5 mm in size, and suspending them in a viscous carrier for application. This technique aims to achieve rapid and uniform coverage across large or vertical areas. The scientific literature on façade-scale slurry inoculation is still limited; however, a number of Chinese patents have documented the use of slurry-based moss inoculation for ecological restoration and concrete greening. For example, researchers describe a moss-turf ecological restoration technique in which moss fragments are mixed with additives to form a slurry that is sprayed onto disturbed or concrete surfaces for rapid colonization (Qingfang. W., et al., 2006). Similarly, Changjie et al., (2020) detail an ecological reconstruction method for concrete spray layers, where drought-tolerant moss fragments are suspended in a carrier and applied to sprayed concrete slopes to initiate colonization (Changjie et al., 2020). To improve adhesion and survival, Lei et al. (2022) proposed a special adhesive for moss based on methylcellulose, chitosan, and attapulgite clay, which provides a non-toxic carrier medium that enhances water retention and fragment stability (Lei et al., 2022).

In addition to cellulose- and polymer-based carriers, several non-scientific horticultural practices have promoted the use of dairy-based slurries (buttermilk, yogurt, or beer mixtures) as carriers for moss inoculation as described in **Figure 2**. The procedure generally involves fragmenting fresh moss cushions into small pieces and blending them with dairy products to produce a viscous mixture, which is then painted or sprayed onto concrete or stone substrates. The rationale is that dairy components act as organic adhesion agents while simultaneously providing initial nutrients for moss establishment. However, while such methods are widely circulated in gardening and ecological art contexts, they are not supported by peer-reviewed façade engineering research.

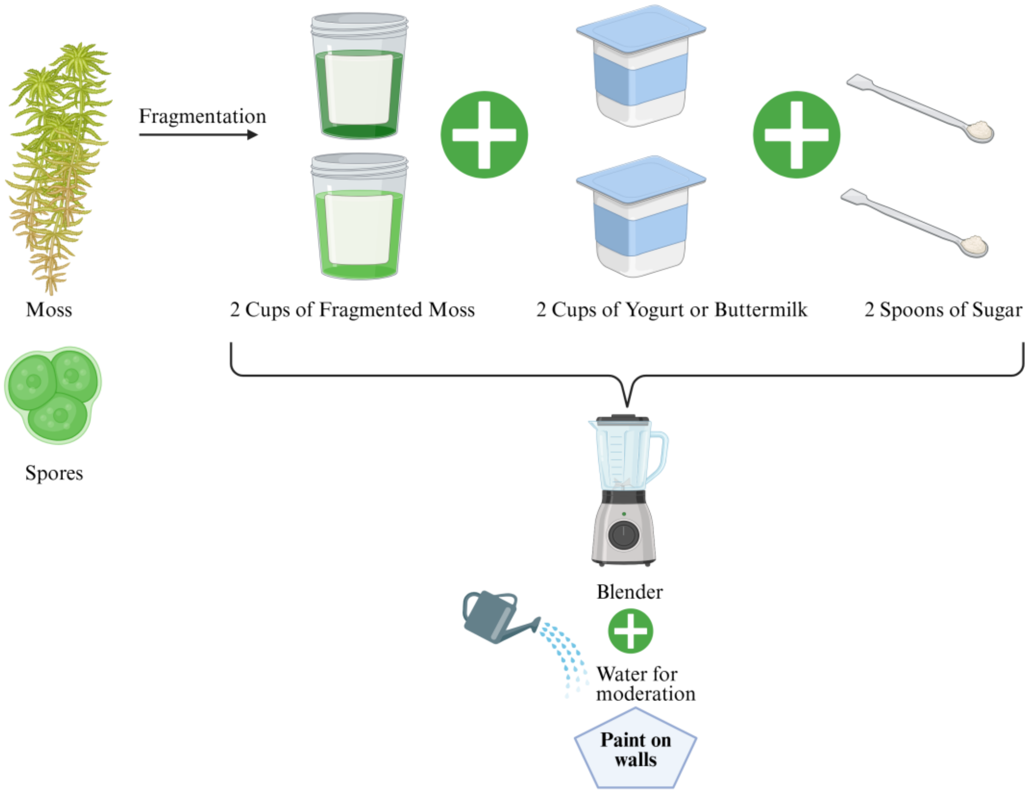

Figure 2 Slurry method of preparation of moss concrete

Reports from horticultural extension guides emphasize that dairy slurries often produce inconsistent establishment, requiring constant moisture and shaded microclimates to prevent desiccation (UNH Extension, 2011). Furthermore, the inclusion of organic dairy products introduces risks of bacterial contamination, foul odor, and unwanted microbial growth, making them unsuitable for controlled architectural or ecological applications (McCoy, 2022).

4.3 Pre-Vegetated Bioreceptive Panels

The pre-vegetated panel approach mitigates early establishment risks by cultivating moss on panels under controlled conditions prior to site installation. Panels are fabricated with bioreceptive concrete formulations and inoculated via intact-colony or slurry techniques. They are maintained in growth chambers or factory greenhouses under controlled humidity, irrigation, and light (~80% relative humidity, 15–25 °C, and ~130 μmol m^{-2} s^{-1} PAR). Over 3–4 weeks, moss regenerates protonema and forms firm attachments, which are verified by dry-down stress tests before deployment (Zechmeister et al., 2023). Pre-grown panels are transported in breathable coverings and installed with minimal acclimation misting. This method ensures predictable establishment and reduces the risk of desiccation or sloughing in harsh urban climates. Field experiments with layered living concrete (LLC) panels have confirmed the viability of this strategy, showing sustained moss colonization for multiple years under outdoor exposure (Jakubovskis et al., 2023).

4.4 Material-Side Enabling (Passive Colonization)

Instead of relying on active seeding, the material-side enabling method focuses on engineering the concrete itself to favor spontaneous moss colonization from airborne spores and propagules. This is achieved by adjusting both the mix composition and surface morphology to enhance water retention and reduce chemical barriers to growth. Recent work on alkali-activated fly ash–slag concretes has demonstrated that incorporating up to 80% fly ash with slag binders not only reduces embodied carbon but also improves pore structure, sorptivity, and compatibility with biotic colonizers compared to Portland cement matrices (Yuan et al., 2025). Similarly, studies show that supplementary cementitious materials (SCMs) such as silica fume, copper slag, and ceramic waste aggregates lower surface alkalinity and increase micro-scale porosity, thereby enhancing the primary bioreceptivity of cementitious substrates (Villagrán-Zaccardi et al., 2021). Surface structuring techniques such as brushing, imprinting, or retarder washing further create microtopographies and water-holding niches that capture spores and propagules, accelerating natural colonization processes (D'Orazio et al., 2014; Hayek et al., 2023).

Once installed outdoors, such bioreceptive panels are left to colonize passively across seasonal wetting and drying cycles, a process that can take 1–2 years depending on the local climate. While slower than active seeding, this approach has the advantage of minimal labor, zero inoculation costs, and long-term resilience, since the moss community is self-selected from the local spore rain. In coastal environments, pervious concrete designs with engineered porosity have been shown to support spontaneous colonization of mosses, lichens, and algae, confirming that substrate permeability is a key driver of ecological integration (Garty, 1988). In practice, passive colonization is often hybridized with selective patch seeding to accelerate uniformity, but its ecological minimalism makes it a promising strategy for large-scale, low-maintenance applications.

4.5 Two-Layer Composite Panels

The most advanced greening strategy involves the use of two-layer composite systems, where a structural concrete core (e.g., UHPC or reinforced concrete) is combined with a bioreceptive outer skin specifically engineered for ecological colonization. The structural core ensures mechanical stability and durability, while the lightweight, porous overlay is optimized for water retention, reduced alkalinity, and micro-roughness that enhance moss adhesion. Inoculation can be achieved via intact-colony transfer, slurry spraying, or passive recruitment through spore rain (**Figure 3**). Crucially, recent studies have demonstrated that colonization is confined to the outer layer, leaving the load-bearing structural core unaffected by biological activity. For example, Frantová et al. (2024) showed that magnesium phosphate cement overlays applied onto conventional OPC concrete tiles supported microbial and moss colonization due to their optimized pH and porosity, while preserving the structural integrity of the substrate underneath (Frantová et al., 2024).

Similarly, Jakubovskis (2024) highlighted the potential of biophilic facades through field-tested bioreceptive composites, showing that controlled and aesthetically managed colonization is possible when greening is confined to an engineered skin rather than the bulk structural element (Jakubovskis, 2024). This modular concept allows the bioreceptive skin to be replaced or renewed without compromising the core, offering a scalable pathway for vertical façade applications. Complementary advances in bio-concretes also support this trend, as reviews emphasize the integration of biologically active materials and microbial processes into outer concrete layers to enhance both ecological value and self-healing potential, linking durability with ecological functionality (Ojha et al., 2025).

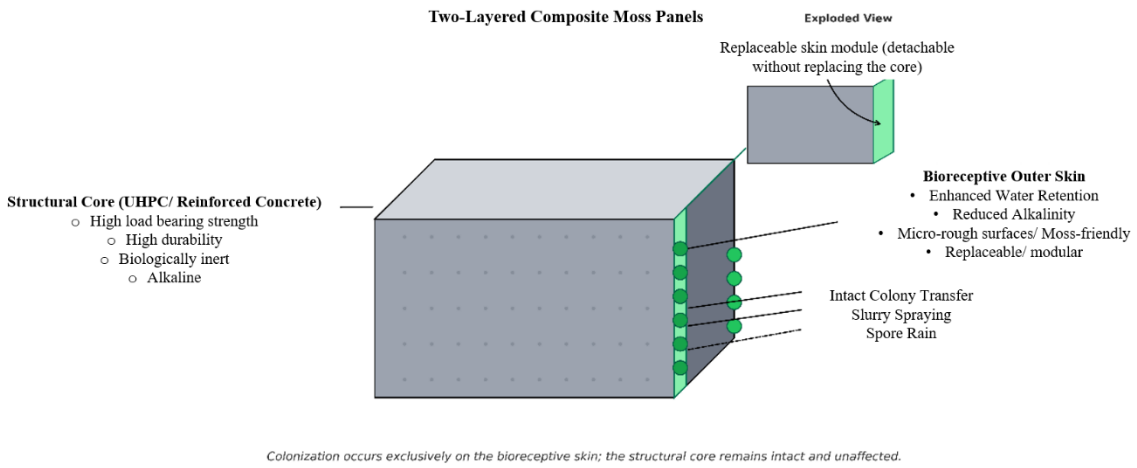

Figure 3 Two-layer composite moss panels. The structural core ensures stability, while the bioreceptive outer skin supports moss colonization through intact-colony transfer, slurry spraying, or spore rain. Colonization remains confined to the outer skin, which is modular and replaceable without affecting the core.

Together, these findings align with biocentric architectural design principles, where building envelopes are conceived not merely as barriers but as ecological interfaces balancing infrastructure performance with biodiversity support and long-term sustainability. **Figure 4** gives a comparative analysis of the discussed methods in terms of establishment speed, coverage percentage and durability.

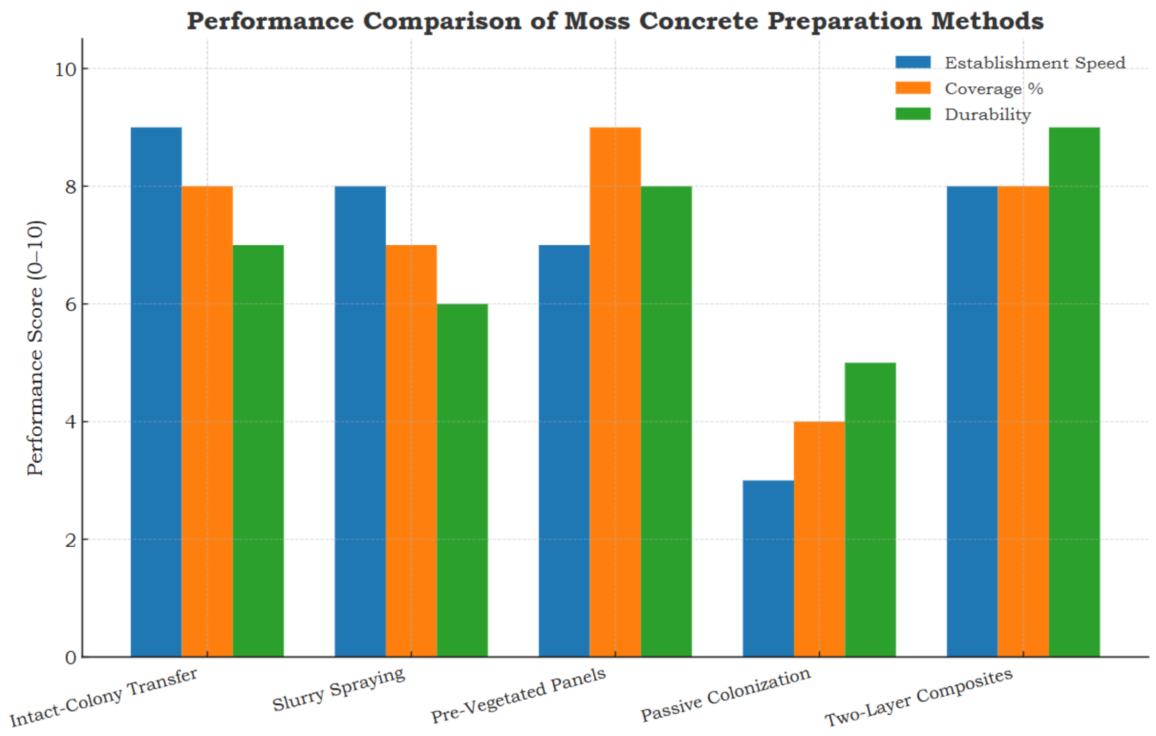

Figure 4 Conceptual performance comparison of moss concrete preparation methods. Establishment speed, coverage, and durability are scored on a relative scale (0–10) to highlight the strengths and limitations of each approach. Values are indicative and provided for illustrative purposes only.

5 Successful Case Studies on Moss Concrete

5.1 Case study A — The Netherlands

A laboratory study (Veeger et al., 2025a) prepared acoustics grade bioreceptive concrete discs sized to fit Brüel & Kjær impedance tubes, with diameters of 100 mm and 29 mm, using 0.5 mm ePLA FDM moulds in vase mode to ensure an airtight fit. The concrete employed a previously developed matrix comprising CEM III/B binder, 0 to 4 mm recycled concrete aggregate, and bone ash, and specimens were water cured for 28 days before moss application. Six epilithic urban pioneer species common on concrete, namely *Brachythecium rutabulum*, *Rhynchostegium confertum*, *Grimmia pulvinata*, *Orthotrichum diaphanum*, *Tortula muralis*, and *Ptychostomum capillare*, were harvested from existing concrete and transplanted with a non-toxic methylcellulose adhesive that did not interfere with acoustical response. After application, samples were conditioned for three weeks in a growth chamber under a ViparSpectra XS1000 light set to 130 μmol m^{-2} s^{-1} photosynthetically active radiation, with daily watering. Hydration states for measurement were defined explicitly as follows: saturated immediately after watering with capillaries water filled; hydrated after air drying to towel dry with capillaries empty and leaf porosity maximised; and dry when Fv/Fm was below 0.1, verified with a MINI PAM II after 20 minutes of dark adaptation.

Monitoring focused on frequency resolved normal incidence sound absorption according to ISO 10534 2 and ASTM E1050 across 50 to 6400 Hz, combining data from the two tubes with a 1200 to 1600 Hz crossover. Replication was n = 3 for 100 mm specimens and n = 5 for 29 mm specimens per species, and statistics used Kruskal and Wallis tests with Conover and Iman post hoc procedures and Benjamini and Hochberg correction. After three weeks of conditioning, thick cushion *Grimmia pulvinata* layers exceeding 15 mm achieved an average absorption coefficient of approximately 0.55 in the dry state with a high frequency peak near 0.88 at 6.4 kHz, whereas pleurocarps such as *Brachythecium rutabulum* and *Rhynchostegium confertum* showed lower averages; saturated states generally reduced absorption in the low to mid frequency bands. Methodologically, this protocol of harvested colonies affixed with methylcellulose, fixed PAR lighting, defined hydration states, and impedance tube conformant concrete geometry provides a rigorous transplant benchmark for post seeding on pre cured, slag rich, low alkalinity concrete.

5.2 Case study B — Indonesia

A tropical pre vegetation study (Susanto, 2018) evaluated three concrete matrices: TM I, Portland cement with fly ash; TM II, normal concrete; and TM III, crushed brick concrete. Three surface finishes were assessed, including ribbed and unfinished, and three bryophyte species were used, namely *Hyophila involuta*, *Bryum apiculatum*, and *Barbula indica*. The experimental set comprised nine facade panels and twenty-seven cubes, with nine additional non vegetated cube controls. Panels measured 50 cm in width and 8 cm in thickness, and cubes were 150 × 150 × 150 mm prepared to ASTM C109. Surfaces were preconditioned to support bryophyte establishment, after which moss was cultured and applied as a slurry prepared by blending locally collected epilithic colonies with yogurt and water, then painted onto panels and cubes. The environmental set up targeted a surface pH from 5 to 5.5, approximately 60 percent surface moisture, and daily watering, and the test site within the Universitas Indonesia campus was selected for a stable moist microclimate. Growth was recorded on days 1, 7, 14, 21, and 28. At 28 days the ribbed finish improved water holding and moss cover relative to smooth surfaces, and *Hyophila involuta* on the TM III crushed brick matrix produced the most persistent cover among treatments. Compressive strength of pre vegetated cubes was lower than that of the non-vegetated controls at day 28, indicating an early age strength penalty associated with pre seeding. Overall, the protocol of pre vegetating panels with a dairy based moss slurry under daily misting, while factoring surface texture and eco mix, represents a complete pre seeding route tested at panel scale in a humid tropical setting with explicit controls.

5.3 Case study C —United Kingdom

Architectural scale prototypes used magnesium phosphate cement and magnesium phosphate cement sandstone composites engineered to a near neutral surface pH of about 7 to 8 to favour bryophyte colonisation, with aggregate grading and water content tuned to increase capillarity and surface roughness for improved bioreceptivity (Cruz and Beckett, 2016). Three-dimensional façade geometries with fissures, striations and shallow depressions were fabricated in CNC milled moulds to route incident rainfall into designated growth niches and to create shaded refugia that moderate drying. Seeding was delivered by robotic deposition of an aqueous suspension of algae cells and moss spores, allowing precise placement on predefined growth areas without added organic adhesives or nutrient carriers. Panels were oriented preferentially to the north west and placed outdoors for a full year of environmental monitoring, relying on ambient rainfall rather than fixed irrigation.

Earlier brick scale materials work in the same programme established the materials envelope and inoculum logic. A composite of magnesium phosphate cement with sandstone was selected to match mineral composition and achieve a near neutral pH, and target pioneer mosses included *Atrichum undulatum* and *Hedwigia ciliata* which are cushion forming acrocarps adapted to rough mineral substrates. Process parameters for that calibration phase are reported, including 3D printing on a ZCorp 510 platform with 0.25-millimetre layers using an organic binder, followed by drying at 30 °C for two hours before depowdering, with aggregate size and water content systematically varied to control surface porosity, capillary action and roughness. The programme also recommends characterising the façade material at multiple scales, for example porosity and pH at the surface and in the near surface zone using porosimetry and x ray tomography, and using environmental simulation tools to coordinate orientation and rainfall capture.

Taken together, the technical sequence of near neutral magnesium phosphate cement, digitally fabricated water routing geometry and adhesive free robotic spore deposition followed by yearlong field exposure defines a reproducible post seeding protocol that yields fine spatial control of colonisation on cementitious façades while maintaining a clear reporting framework for pH, porosity and environmental drivers.

5.4 Case study D —The Netherlands

A facade panel series was produced with CEM III/B containing about seventy five percent slag, with 0 to 4 mm sand and 5 to 8 mm gravel at a water cement ratio of 0.60. Panels were evaluated for biocolonisation in a greenhouse maintained at 20 to 24 °C and 75 to 85 percent relative humidity for approximately four months (Mustafa et al., 2021). Inoculation began with moss spores and, after pilot observations, panels were recoated with a moss slurry. To manage surface wetness, orientation was adjusted over time, with six weeks placed horizontally to retain water films, then vertically to assess adherence and drainage, and later returned to horizontal to restore wetting. Irrigation used rainwater sprays two to three times per day for about thirty seconds per event. Periodic overheating to around 32 °C accelerated drying and reduced coverage, so the panels were relocated within the greenhouse to re-establish the 20-to-24-degree operating range. Monitoring combined qualitative colonisation mapping with micro climate logging, including changes in panel mass, relative humidity measured at ridges and in alcoves, and surface temperature. Water pathing was also assessed visually during spray events. The geometry with deeper recessed macro features, referred to as Panel 2 in the design set, sustained higher water retention and showed the earliest and most persistent green colonisation when compared with flat controls. Methodologically, this is a geometry led spore or slurry route with explicit wetness management through panel orientation and frequent misting, and it is suitable for screening macro and micro groove patterns on slag rich concrete in controlled environments.

5.5 Case study E —Visakhapatnam, India

An undergraduate investigation (Saikumar et al., 2024) at Dr Lankapalli Bullayya College of Engineering, Visakhapatnam, prepared standard concrete cubes by batching, vibration during casting for five to ten minutes, demoulding after twenty-four hours, and water curing at seven, fourteen, and twenty-eight days in accordance with Indian Standards. The inoculum was a dairy based slurry prepared with locally collected Pine Hill Moss and Springy Turf Moss. The formulation blended two to three cups of fresh moss with two to three cups of a wet dairy medium such as yogurt, condensed milk, or buttermilk, plus one to two tablespoons of sugar, and water to a brushable consistency. The mixture was rested at room temperature for about two days before use, then applied to cleaned cube faces with a thick brush and immediately misted with filtered or rain water. Surfaces were kept damp but not soaked; the report warns that overwatering can wash off spores and notes that early surface mold from the dairy carrier typically subsides within the first six weeks. Visible moss development was expected in about four to six weeks under regular sprinkling. Growth was monitored by repeated thickness readings with vernier calipers at multiple points on each 150 mm cube; across three replicates, thickness increased from about 1.20 to 1.68 mm over five weeks, giving week five averages of 1.406, 1.396, and 1.468 mm. The team also recorded paired surface temperatures that showed cooler moss-covered cubes relative to plain concrete: indoors, means of 27.0 °C versus 28.0 °C, and outdoors, 28.6 °C versus 30.5 °C. Twenty-eight-day compressive strengths for moss concrete specimens reached about 24.44 MPa for M20 and 28.99 MPa for M25 under the reported curing schedule. Overall, the protocol demonstrates a field practical post seeding route suited to Indian logistics, combining accessible materials, simple application and moisture control, and low-cost monitoring of coverage, thickness, and surface temperature.

5.6 Comparative Analysis of Moss Concrete Case Studies

Table 3 summarizes key insights from different research and practice-based experiments on moss-concrete systems. Each case study explores unique methods of moss application, performance observations, and challenges. Together, they highlight the interdisciplinary nature of moss-concrete design, blending ecology, material science, and architecture and key differences between them can be seen from **Table 3.**

Table 3 Comparative analysis of the case studies

Case Study	*Key Lessons Learned*	*Future Study Requirements*
A. Controlled Laboratory Study	- **Acoustic Function:** Thick moss layers, especially *Grimmia pulvinata*, greatly enhance sound absorption at higher frequencies. However, when moss is saturated with water, its absorption ability decreases. - **Application Method:** Applying moss spores after concrete has cured, using an adhesive, is suitable for acoustic testing. - **Moisture Conditions:** Consistent hydration states must be defined, as	- **Aging Effects:** Investigate how acoustic performance changes as moss matures, decays, or regenerates. - **Biodiversity Testing:** Examine the acoustic properties of a wider range of moss species under different growth conditions. - **Environmental Response:** Assess how varying light, humidity, and temperature cycles affect both moss survival and acoustic efficiency.

	moisture levels strongly influence sound performance.	
B. Tropical Field Experiment	- **Surface Finish:** Ribbed (textured) surfaces capture more water and support denser moss cover than smooth ones. - **Concrete Mix:** Mixtures containing crushed brick (TM III) provided the best moss persistence in tropical climates. - **Structural Trade-off:** Pre-seeding at early curing stages reduces concrete's compressive strength.	- **Durability Studies:** Evaluate long-term effects of moss colonization on structural strength and weathering resistance. - **Species Suitability:** Test a wider variety of moss and bryophyte species adapted to tropical environments. - **Surface Preparation:** Develop optimized pre-conditioning methods that promote moss growth without compromising concrete integrity.
C. Robotic Seeding Method	- **Chemical and Geometric Factors:** Moss colonization succeeds best on near-neutral pH surfaces (7–8) with designed 3D geometries that guide water flow and create shading. - **Seeding Technique:** Robotic spore deposition enables precise placement without adhesives or growth media, offering high design control. - **Environmental Integration:** Natural rainfall alone can sustain growth, reducing the need for artificial irrigation.	- **Scalability:** Test whether robotic seeding can be economically and practically applied to large-scale construction projects. - **Long-Term Monitoring:** Track moss community development over several years to assess ecological stability and facade performance. - **Material Innovation:** Explore neutral pH construction alternatives (e.g., different aggregates or low-alkali binders).

D. Geometry-Led Slurry Application	- **Structural Features:** Deeply recessed grooves in concrete retain water effectively, making them ideal for moss colonization. - **Moisture Management:** Regular misting and strategic panel orientation are key to maintaining surface wetness for moss establishment. - **Controlled Environment:** Consistent temperature and humidity in greenhouse settings significantly improve early moss growth.	- **Pattern Optimization:** Experiment with diverse geometric patterns to identify forms that maximize moss coverage and water retention. - **Inoculation Comparison:** Compare long-term success of spore-based vs. slurry-based inoculation across different geometries. - **Practicality and Cost:** Weigh the costs and energy demands of greenhouse cultivation against real-world outdoor applications.
E. Community-Sourced Slurry Method	- **Accessibility:** Simple, locally available materials (e.g., yogurt, sugar, and wild moss) can be used to prepare an effective moss slurry. - **Watering Needs:** Gentle, consistent misting supports growth, whereas heavy watering may wash away moss spores. - **Thermal Regulation:** Moss-covered surfaces can reduce surface temperature, offering passive cooling benefits. - **Concrete Curing:** Standard curing practices do not appear to hinder moss establishment.	- **Protocol Development:** Create standardized, replicable community methods for slurry preparation and application. - **Durability Testing:** Study how dairy-based slurry and subsequent moss growth affect long-term concrete strength. - **Species and Formula Variation:** Test different moss species and slurry recipes to identify the best combinations for varying climates and concrete compositions.

6 Species selection framework for moss concrete: evidence-based guidance from published case studies

Species choice should follow the microclimate engineered at the concrete skin. Across laboratory discs, greenhouse panels and outdoor pilots, establishment and persistence have been governed first by near surface water availability and micro texture, with surface chemistry a supporting lever rather than the primary control (Manso et al., 2014; Veeger et al., 2021; Mustafa et al., 2021; Veeger et al., 2025b). This mechanistic view is consistent with a survey of 137 urban concrete communities which found a strong exposure signal: cushion forming acrocarps dominated exposed, sunlit and wind affected situations, whereas mat forming pleurocarps dominated shaded and protected locations (Veeger et al., 2025c). The practical implication is that species choice must be coupled to orientation, shading, wind, and the time a surface remains moist after wetting, and to the way the concrete skin has been designed to store and route water.

A simple diagnostic helps operationalise this coupling. For each facade or element, document aspect, shading, local ventilation, and a short measurement of time to surface dry after a standard misting. In the published trials, panels that retained a visible moisture film for tens of minutes after wetting and skins with millimetre scale texture that shelters the boundary layer supported faster establishment than smooth skins that dried within minutes (Veeger et al., 2021; Mustafa et al., 2021b; Veeger et al., 2025b). For exposed sunny and wind affected surfaces, acrocarps that form compact cushions and tolerate episodic drying are preferred; recurrent pioneers on concrete include *Tortula muralis*, *Grimmia pulvinata*, *Ptychostomum (Bryum) capillare* and *Orthotrichum diaphanum*. These taxa established reliably as intact colonies under moderate light with daily misting and delivered strong functional performance in dry and hydrated states on bioreceptive concrete (Veeger et al., 2025c; Veeger et al., 2025d). For shaded or north and east facing surfaces, pleurocarps that creep and exploit protected moisture films are favoured, notably *Brachythecium rutabulum*, *Hypnum cupressiforme* and *Rhynchostegium confertum*; these species dominated shaded urban concrete in the field survey and persisted on ribbed or unfinished finishes in tropical panel trials, where *Hyophila involuta* was a dependable option on roughened surfaces (Chairunnisa and Susanto, 2018b; Veeger et al., 2025d).

The inoculation mode should match species structure and project logistics. Where local cushions can be harvested under permission, intact colony transfer with a neutral methylcellulose adhesive and a three-week conditioning phase under moderate light and daily misting produced adherent, test ready mats for both acrocarps and pleurocarps in acoustics grade experiments (Veeger et al., 2025e). Where intact material is scarce, spore or fine fragment seeding on a water positive, textured skin is effective. Greenhouse panels cast with slag rich concrete that was deliberately not cured to preserve near surface porosity, misted two to three times per day at 20 to 24 °C and 75 to 85 percent relative humidity, and managed by alternating horizontal and vertical orientations to control wetness, reached visible colonisation within eight to twelve weeks (Mustafa et al., 2021c). In community and low-cost contexts in India, dairy based slurries with locally collected material such as Pine Hill Moss and Springy Turf Moss achieved visible cover on 150-mm cubes in about four to six weeks when surfaces were kept damp but not soaked; for public pilots a neutral carrier is preferable to reduce competing microbes while maintaining the same moisture regimen (Saikumar et al., 2024).

Material side design should support the chosen organism by prioritising near surface hydrology and micro texture. Practical measures include porous or lightweight fines such as crushed expanded clay or recycled 0-to-4-mm fines in the cover zone, non-optimal packing to raise connected pores, surface retarder or brush finishes for millimetre scale roughness, and shallow grooves or pockets that route runoff into intended growth fields (Veeger et al., 2021; Mustafa et al., 2021; Veeger et al., 2025a). Chemistry is supportive rather than decisive: supplementary cementitious materials and, in design research, magnesium phosphate cement can moderate surface alkalinity and contribute to bioreceptivity, but across case studies water availability and texture consistently explained colonisation outcomes better than pH alone (Manso et al., 2014; Cruz and Beckett, 2016; Mohanty et al., 2025).

Acceptance criteria and deployment timing provide closure for the selection and inoculation steps. Early success should be confirmed by time to first visible cover, time to at least seventy percent adherent cover, and the absence of sloughing after a twenty-four hour dry down. Where a function is targeted, add a quantitative metric such as average normal incidence absorption across 50 to 6400 Hz for acoustic panels or a defined reduction in surface temperature under standardised irradiance and airflow; report replicate numbers, controls and measurement uncertainty in each case (Veeger et al., 2025a; Saikumar et al., 2024). For Indian deployments, schedule initial seeding in the immediate post monsoon month in hot dry cities to exploit higher ambient humidity and lower dust loads, provide temporary shade cloth for the first two weeks on west and south faces, and in coastal monsoon climates rely on frequent light rainfall while using shallow grooves and pockets to prevent wash off (Mustafa et al., 2021; Veeger et al., 2021). Finally, source only local ecotypes under permission from urban concrete or nearby epilithic habitats as they have the highest chances of adaptability and voucher at least a subset through microscopy. Introduction of non-native taxa for facade pilots should be avoided.

7 Environmental, functional, and economic benefits of moss concrete

Moss concrete delivers a bundle of co-benefits characteristic of direct green systems, while avoiding irrigation hardware, soil volumes, and secondary frames common to living walls and planters. At the scale of buildings and streetscapes, published surveys and reviews attribute to green, nature-inclusive structures improved thermal comfort, reductions in stormwater runoff, and reductions in air and noise pollution, with moss communities a practical pioneer for pristine concrete surfaces. These outcomes are pertinent to bioreceptive concrete because urban acrocarp and pleurocarp mosses readily establish on bare cementitious substrates and form persistent covers in the right microclimates identified in field data from 137 concrete sites.

7.1 Urban heat mitigation and microclimate regulation

Three physical pathways underpin the cooling benefit: (i) short-wave modification (shading and altered reflectance) (Park et al., 2018), (ii) latent heat flux from evaporation of stored water (Verhoeven et al., 2023), and (iii) added thermal resistance of the moss layer (Bakatovich and Gaspar, 2019). Controlled analyses report that moss layers possess low thermal mass yet high water storage (up to ~4.7 L m^{-2}), enabling sustained evaporative cooling after rain events and measurable insulation. In panel experiments, dry moss reduced surface temperatures by ~0–5 °C; when wet, both bare and mossed panels cooled by ~5–10 °C, with mossed panels remaining ~2–5 °C cooler for longer due to retained moisture. At small scale in India, paired measurements on 150 mm cubes showed lower surface temperatures on moss-covered concrete than on plain concrete: indoors, 27.0 °C versus 28.0 °C (mean); outdoors, 28.6 °C versus 30.5 °C (mean), illustrating the direction and magnitude of effect under warm conditions relevant to Indian facades (Saikumar et al., 2024).

7.2 Noise attenuation

Hydrated and desiccated moss can behave as a fibrous, porous absorber whose acoustic impedance varies with species and water content. A recent impedance-tube study prepared bioreceptive concrete discs, transplanted six urban pioneer moss species with a neutral adhesive, and quantified normal-incidence absorption from 50–6400 Hz under defined hydration states to assess whether moss-covered bioreceptive concrete is a viable alternative to other vertical green typologies for noise mitigation (Kim et al., 2022; Sleinus et al., 2023; Veeger et al., 2025a).

7.3 Air quality services

Mosses present very high leaf area per unit mass, minimal cuticle, and sorptive tissues, which together favour interception and retention of particulate matter (PM) and dissolved pollutants (Varela et al., 2023). Evidence from field and engineered systems shows higher PM loading on moss than on tree leaves (e.g., ~5.6–33 mg g^{-1} dry mass on roadside moss turfs versus ~2.15–10.24 mg g^{-1} on leaves) and 11–38% PM reductions across moss-based filter prototypes under forced airflow, indicating real potential for near-surface air quality improvement when deployed at facade scale (Chaudhuri and Roy, 2023; Haynes et al., 2019; Niinemets and Tobias, 2019).

7.4 Stormwater moderation and water positivity

By design, bioreceptive skins elevate near-surface porosity and capillarity; the moss layer then acts as a transient sponge that holds and later releases water to the air, dampening peak runoff from vertical and inclined cementitious elements. Green structure syntheses attribute reduced stormwater runoff to vegetated skins; the moss layer's large water storage and evaporative fluxes clarify the mechanism on concrete.

The moss canopy itself acts as a transient sponge. Species-resolved tests on mosses growing on bioreceptive concrete show water-holding capacities spanning ~3–12× dry mass (e.g., *Rhynchostegium confertum* 3.11×; *Bryum capillare* 3.54×; *Syntrichia ruralis* 7.88×; *Eurhynchium striatum* 11.73×), with *B. capillare* quantifying to ~4.7 L m^{-2} storage (theoretical mitigation of ~4.7 mm rainfall). Effectiveness depends on both absorption rate and evaporation rate which is species-dependent, which together govern how quickly storage is reset between events (Veeger et al., 2023).

7.5 Carbon and pollutant mass balance

At canopy scale, bryophyte-dominated cryptogamic covers (mosses, lichens, algae) contribute measurably to atmospheric carbon uptake; a global synthesis estimated ~3.9 Pg C yr^{-1} of net CO_2 fixation which is about 7% of terrestrial net primary production together with ~49 Tg N yr^{-1} of biological N fixation, indicating a non-trivial role in carbon and nitrogen cycling that is relevant wherever engineered surfaces support bryophyte cover. (Elbert et al., 2012) A process-based global model constrained by observations assigns 1–6% of terrestrial NPP to lichens and bryophytes, reinforcing the expectation that established moss layers can make small but real contributions to local carbon budgets on built substrates, modulated by hydration and light (Porada et al., 2013). Laboratory flux measurements on cultivated roofing moss also show net CO_2 uptake magnitudes and environmental dependences germane to façade applications: a synthesized *Racomitrium japonicum* cultivar achieved best annualized CO_2 sink of −1.94 ± 0.72 kg CO_2 m^{-2} yr^{-1} at ~25 °C under moderate–high PAR, with performance declining at 10 °C and 35 °C underscoring temperature and irradiance control on moss carbon balance (Seo et al., 2023).

For pollutant mass balance, the dominant mechanism for particulates is interception and retention within the highly porous, cuticle-poor moss canopy; contemporary reviews of moss biomonitoring clarify that cation-exchange capacity alone does not explain pollutant retention, and emphasize physical trapping of airborne particles and surface sorption as the operative processes (Varela et al., 2023). Field comparisons consistently show higher particulate loads on moss than on common urban foliage: along an urban gradient in Australia, roadside moss turfs accumulated ~5.6–33.0 mg PM g^{-1} dry mass versus ~2.15–10.24 mg g^{-1} on tree leaves measured concurrently (Haynes et al., 2019). Controlled-environment studies now quantify removal efficiencies applicable to façade elements: in a closed-loop wind tunnel chamber, vertical barriers made from three bryophyte species removed on average 41% of $PM_{2.5}$ and 47% of PM_{10} across 18 tests, with species-level variation but consistent superiority over an evergreen leaf control (Karklina et al., 2025). At façade scale, an experimental moss greening system for building envelopes (*Barbula unguiculata, Grimmia pulvinata, Homalothecium*/*Hypnum taxa*) reported fine-dust collection capacity under urban exposure, framing a pathway to integrate measured deposition into building mass-balance models.

7.6 Economic performance and maintenance

Once established, moss communities on bioreceptive concrete do not require soil, supplemental irrigation, fertiliser inputs, or a secondary support frame. These absences translate directly to lower construction cost as no irrigation network or no growth substrate trays are needed and lower recurrent maintenance relative to conventional living walls. The ecological engineering analysis is explicit that established moss on bioreceptive structures do not require additional irrigation or nutrients, nor do they need a supporting structure, which in turn significantly lowers construction and maintenance costs. At program level, recent reviews call for formal cost-effectiveness analyses comparing vegetation eco-concrete with conventional concrete and other green infrastructure once metrics are standardised.

8 Research Gaps

A standardised test set needs to be established that links material descriptors (e.g., sorptivity, surface roughness, near-surface pH) to biological acceptance criteria such as time to first visible cover, time to ≥70% adherent cover, no sloughing after a 24-h dry-down, and it should be validated through multi-lab ring trials. Façade-scale hydrology remains under-modelled; we need transient wetting–drying models that couple rainfall statistics, capillary uptake, storage in the concrete skin and moss canopy, and species-dependent evaporation, then translate these into practical rules for water-routing geometries. India-specific species and ecotype baselines are missing and should be built through voucher-based urban surveys and controlled screens for dust, heat, and salinity tolerance, including guidance on seasonal seeding windows. Comparative evidence on inoculation carriers and adhesives is incomplete. Dose–response and viscosity windows for neutral gels must be defined, and Panchagavya should be evaluated as a nutrient-carrying adhesive under filtered/pasteurised arms to isolate nutrient effects from bioburden.

Durability in Indian environments is underreported. Long-horizon adhesion and coverage under hot-dry and monsoon regimes, dust loading, coastal salinity, and high-temperature cycles need quantification, alongside runoff-quality monitoring during establishment and standard procedures for cleaning and patch repair of the bioreceptive skin. The structural compatibility of two-layer skins requires mapping bond durability to the structural core, shrinkage compatibility, carbonation/chloride profiles at reduced paste density, and minimum skin thickness and curing that preserve both safety and bioreceptivity. In-situ performance remains sparse; instrumented façade panels should report acoustics, surface-temperature moderation, stormwater attenuation, and pollutant deposition under controlled boundary conditions with area-normalised metrics. Finally, proper economic evaluation is lacking: paired CAPEX/OPEX datasets and life-cycle assessments against conventional façades and living walls are needed, and procurement tools.

9 Future of Moss Concrete

SWOT analysis of Moss concrete has been pictorially depicted in **Figure 5** as it gives an AI generated assessment of the future of moss concrete based on the Case Studies covered in the present study. The findings of the SWOT analysis are given in **Table 4**.

Figure 5 SWOT analysis for the future of Moss Concrete

Table 4. SWOT Analysis of the Future of Moss Concrete

Aspect	*Key Points*	*Elaboration*
Strengths	**Acoustic and Thermal Benefits**	Proven ability to absorb urban noise and reduce surface temperatures, creating more comfortable, quieter, and cooler urban living conditions.
	Aesthetic and Biophilic Appeal	Enhances cityscapes by integrating natural greenery into built environments, improving psychological well-being, sense of connection to nature, and urban biodiversity.
	Versatile Applications	Suitable for diverse uses: decorative cubes for cooling, small-scale features for aesthetics, or large-scale panels for building facades, ensuring flexibility of deployment.
	Accessibility and Low Cost	Community-driven, DIY-friendly methods make the technology cost-effective and socially inclusive, fostering local participation and green infrastructure at a grassroots level.

	Reduced Maintenance	Some systems can self-sustain with ambient rainfall, reducing irrigation needs, maintenance costs, and water consumption.
Weaknesses	**Inconsistent Performance**	Moss establishment depends on climate, surface texture, material mix, and technique, leading to unreliable outcomes across projects and geographies.
	Early-Age Strength Penalty	Pre-seeding techniques may compromise the initial structural integrity of concrete, limiting its use in load-bearing structural elements.
	Vulnerability to Environmental Stress	Sensitive to heat, dryness, and inconsistent watering—high risk of moss decline or total loss in harsh conditions.
	Lack of Standardization	Absence of codified procedures or testing standards complicates reproducibility, industry adoption, and scalability.
	Slurry and Adhesive Issues	Dairy-based slurries risk mold contamination; chemical adhesives may alter properties or introduce environmental/health risks.
Opportunities	**Urban Green Infrastructure**	Can play a central role in urban greening strategies, helping combat the urban heat island effect, sequester carbon, and improve local air quality.
	Advanced Materials and Robotics	Integration of novel cement formulations, computational design, and robotic seeding can make moss concrete more reliable, scalable, and automated.
	Circular Economy	Incorporating industrial by-products (e.g., fly ash, recycled aggregates) situates moss concrete in a sustainable, closed-loop construction model.
	Commercialization	Opportunity to market pre-vegetated facade panels, modular building kits, or DIY-friendly products, bridging research and industry demand.
	Further Research	A growing research arena exists for species optimization, long-term durability studies, and universal protocols, encouraging academia–industry partnerships.
Threats	**Climate Change**	More extreme droughts, temperature spikes, and weather fluctuations could undermine moss viability and limit regional applications.
	Public Perception	Failed projects or visible mold/durability issues may reduce trust among developers, regulators, and the public, delaying adoption.
	Competing Technologies	Competes with conventional living walls and hydroponic systems that may appear more robust, engineered, and easily maintained.
	Regulatory Hurdles	Lack of standard testing methods or structural performance metrics may prevent regulatory approval or slow integration into building codes.
	Biological Variability	Moss is a living system subject to natural unpredictability (species competition, disease, growth patterns), creating risks relative to engineered alternatives.

9.1 Future of Moss Concrete in India and Abroad

Moss concrete represents a promising direction in sustainable construction, merging ecological function with architectural design. Its future trajectory differs across India and international contexts but converges around the themes of urban resilience, biophilic design, and climate adaptation**.**

9.2 In India

India's cities face challenges **of** heat stress, air pollution, stormwater management, and rapid urbanization**.** Moss concrete offers an accessible, low-cost solution by:

- Reducing urban heat island effects through evaporative cooling.
- Improving air quality by capturing particulate matter.
- Enhancing passive cooling in buildings, relevant for affordable housing and dense urban settlements.
- Offering community-friendly approaches (DIY slurry methods) that make it viable for local initiatives and small-scale projects.

However, its success in India hinges on species selection suited to hot–dry and monsoon climates, standardized community protocols, and long-term durability studies under dust, salinity, and temperature extremes. With targeted research and local adaptation, moss concrete could become a scalable component of green infrastructure in Indian cities.

9.3 Abroad

Globally, moss concrete aligns with trends in biophilic urbanism and circular economy practices**.** In Europe and East Asia, research has already demonstrated potential in prefabricated façade panels, robotic seeding, and advanced cement mixes**,** positioning moss concrete for commercialization. These regions are driven by strong climate policies and green building standards**,** making moss concrete a candidate for integration into urban greening strategies and carbon-neutral construction goals**.**

Yet, challenges remain—competition from other green wall systems, regulatory barriers due to lack of standardization, and uncertainties around biological variability. Addressing these through long-term monitoring, material innovation, and standardized performance metrics will be critical for large-scale adoption.

Thus, in both India and abroad, moss concrete has the potential to evolve from experimental prototypes into mainstream sustainable building solutions. Its future will depend on bridging scientific innovation and practical deployment, supported by policy frameworks, commercialization pathways, and cross-disciplinary collaboration**.** The future of moss concrete may be summarised as shown in the **Table 5.**

Table 5 Future of moss concrete

Feature	***Outlook/Trend***	***Impact***
Urban Greening	Increasing adoption	Cooling, biodiversity, improved air quality
Environmental Benefits	Carbon reduction, insulation	Reduced carbon footprint, energy savings
Materials Innovation	Recycled/Circular content	Sustainability, closed-loop construction
Applications	Facades, walls, public spaces	Flexible, modular, easy retrofit
Challenges	Consistency, climate, standards	Research, regulation, reliability

10 Conclusions

This review establishes that moss concrete is a viable and distinct pathway for nature inclusive envelopes. Unlike planter-based living walls, it relies on a tuned cementitious skin and bryophyte covers that function without soil, irrigation networks or secondary frames once established. The evidence assembled here shows that success depends first on near surface water availability and micro texture and only second on chemistry. When the outer few mm of concrete are engineered to take up water rapidly, hold a short-lived moisture film and present millimetre scale texture, urban pioneer mosses can establish reliably and persist with modest husbandry.

A practical preparation canon emerges across methods. Intact colony transfer with a neutral adhesive such as methylcellulose provides the fastest route to adherent cover ready for testing in about three weeks under moderate light and daily misting. Fragment or spore seeding works when paired with a water positive textured skin and deliberate wetness management in the early phase. Pre vegetated panels de-risk site deployment by delivering a target level of adherent cover from the nursery. These routes are not mutually exclusive and should be chosen to match species structure, logistics and project risk appetite. Where community workflows are used, dairy carriers can be replaced by neutral gels to reduce competing microbes while keeping the hydration regimen that is proven in the field.

The case studies consolidate the methods into reproducible protocols on cementitious substrates. Post seeding transplant on acoustics grade bioreceptive discs demonstrates that species morphology and hydration state control frequency resolved absorption and shows how to define and verify hydration states during measurement. Tropical pre vegetation at panel scale confirms the primacy of surface texture and wetness over mix chemistry and quantifies early age strength trade-offs. Robotic spore deposition on magnesium phosphate cement with water routing geometry illustrates adhesive free seeding with precise spatial control. Geometry led greenhouse panels on slag cement document how orientation, misting frequency and macro features determine colonisation dynamics. Community based post seeding on cubes in Visakhapatnam provides a transparent, low capital workflow and a clear example of paired temperature reductions under warm Indian conditions. Together these studies define substrate recipes, seeding steps, environmental set points, monitoring metrics and acceptance checks that can be transferred to practice.

Species choice should follow exposure and wetness at the facade. Cushion forming acrocarps are the default for exposed sunny and wind affected aspects and mat forming pleurocarps suit shaded and protected aspects. The species selection framework in this paper operationalises that rule by mapping aspect, shade and time to surface dry to growth form and candidate taxa and by matching inoculation form to material availability. It also sets quantitative acceptance criteria that are species neutral and easy to audit: time to first visible cover, time to at least seventy percent adherent cover and no sloughing after a twenty-four hour dry down. When a function is targeted, the same framework extends to performance metrics such as average sound absorption over a stated band or a defined reduction in surface temperature under controlled irradiance and airflow.

Environmental and economic signals align in favour of moss concrete when the envelope is designed accordingly. The moss canopy and water positive skin add thermal and hydric capacity that can moderate surface temperature swings and dampen storm water peaks between rainfall events, while laboratory acoustics show credible mid to high frequency absorption where thick cushion layers are used. Because the system eliminates soil media, irrigation networks and secondary frames once established, capital and operating burdens are lower than for most living wall typologies. These advantages make moss concrete especially suitable for lightweight retrofits on existing masonry and concrete where budget, weight and maintenance are binding constraints.

For India, the path to deployment is clear. The immediate post monsoon window offers favourable ambient humidity and cleaner surfaces for establishment in hot dry interiors such as Delhi, while coastal cities can leverage frequent light rainfall and water routing geometry to prevent wash off. A two-layer design that confines growth to a replaceable outer skin over a structural core suits local construction practice and simplifies maintenance. A short commissioning plan can formalise success: daily misting for two to three weeks, temporary shade for west and south faces, a day seven adhesion check, and sign off at the acceptance thresholds above.

Important gaps remain and they set the agenda for the next phase. Standardised material side tests for sorptivity, surface roughness and near surface pH should be paired with biological acceptance metrics so that laboratories and pilot projects report outcomes on a common basis. Long term durability under dust, heat, and intense rainfall typical of Indian cities needs systematic study, as do load effects of mature colonies, freeze free but high temperature cycles, and cleaning or patch repair methods for the bioreceptive skin. Cost effectiveness should be evaluated in pilot portfolios using matched control facades, with capital and operating costs recorded alongside biological and functional performance. Ethical sourcing and taxonomic verification protocols should be embedded from the outset to ensure that only local ecotypes are used and identified correctly.

In sum, moss concrete has matured from concept to a set of tested preparation methods, substrate levers and species selection rules that can be specified and audited. With standardised metrics, targeted pilots in Indian climates and transparent reporting of costs and outcomes, agencies and practitioners can now move from prototypes to programmes and deliver measurable environmental and economic benefits at facade scale.

11 Future work

Panchagavya as a nutrient-carrying adhesive for post seeding moss inocula

We propose a controlled evaluation of Panchagavya as the aqueous phase in a neutral, nontoxic adhesive for post seeding on bioreceptive concrete. Panchagavya is a fermented consortia of cow dung, urine, milk, curd and ghee that contains plant growth promoting microbes and metabolites (including indole-3-acetic acid and gibberellins) together with macro and micro nutrients; its microbiome and bioactive profile vary with fermentation duration, which must be standardised for reproducibility (Brahmandam et al., 2025; Gajera et al., 2024; Muthukapalli Krishnareddy et al., 2022). The experimental design would replace water in a 0.5 to 1.0 percent methylcellulose adhesive (the intact colony transplant medium validated for moss concrete) with Panchagavya at graded volume fractions (for example 0, 5, 10, 20 percent), with parallel arms using microfiltered and gently pasteurised Panchagavya to decouple nutrient effects from live bioburden; endpoints should include time to first visible cover, time to at least seventy percent adherent cover, absence of sloughing after a twenty four hour dry down, contamination incidence, and chlorophyll-fluorescence recovery after rewetting. Recent work demonstrates that Panchagavya performs in high alkalinity mineral matrices, supporting its relevance for cementitious skins and motivating panel scale trials under Indian warm humid and warm dry conditions (Brahmandam et al., 2024).

Based on the lessons learned and future study requirements identified in the case studies, here are three suggested research project titles to be undertaken in near future:

1. Optimizing Bioreceptive Concrete: A Parametric Study of Surface Geometry and Material Composition for Enhanced Moss Colonization and Durability
    - This project would investigate the relationship between concrete mix design (e.g., pH, porosity) and surface features (e.g., macro/micro grooves, fissures) to find the ideal combination for promoting moss growth while ensuring the long-term structural integrity of the material.
2. Long-Term Performance Evaluation of Moss Concrete: Assessing the Durability and Biomechanical Effects of Moss on Concrete Facades in Different Climatic Zones
    - This research would focus on understanding how moss growth affects the concrete over time. It would include monitoring factors like freeze-thaw resistance, water ingress, and compressive strength, and comparing these effects in various climates (e.g., temperate, tropical) to assess the material's viability as a durable building component.
3. A Comparative Analysis of Inoculation Methods for Moss Concrete: Standardizing Protocols and Evaluating Long-Term Effectiveness of Slurry vs. Spore Application
    - This project would aim to standardize the process of "seeding" moss concrete. It would compare the growth rates, long-term persistence, and cost-effectiveness of different methods, such as community-sourced dairy slurries and precise robotic spore deposition, to develop a reproducible and scalable protocol for wider adoption.

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