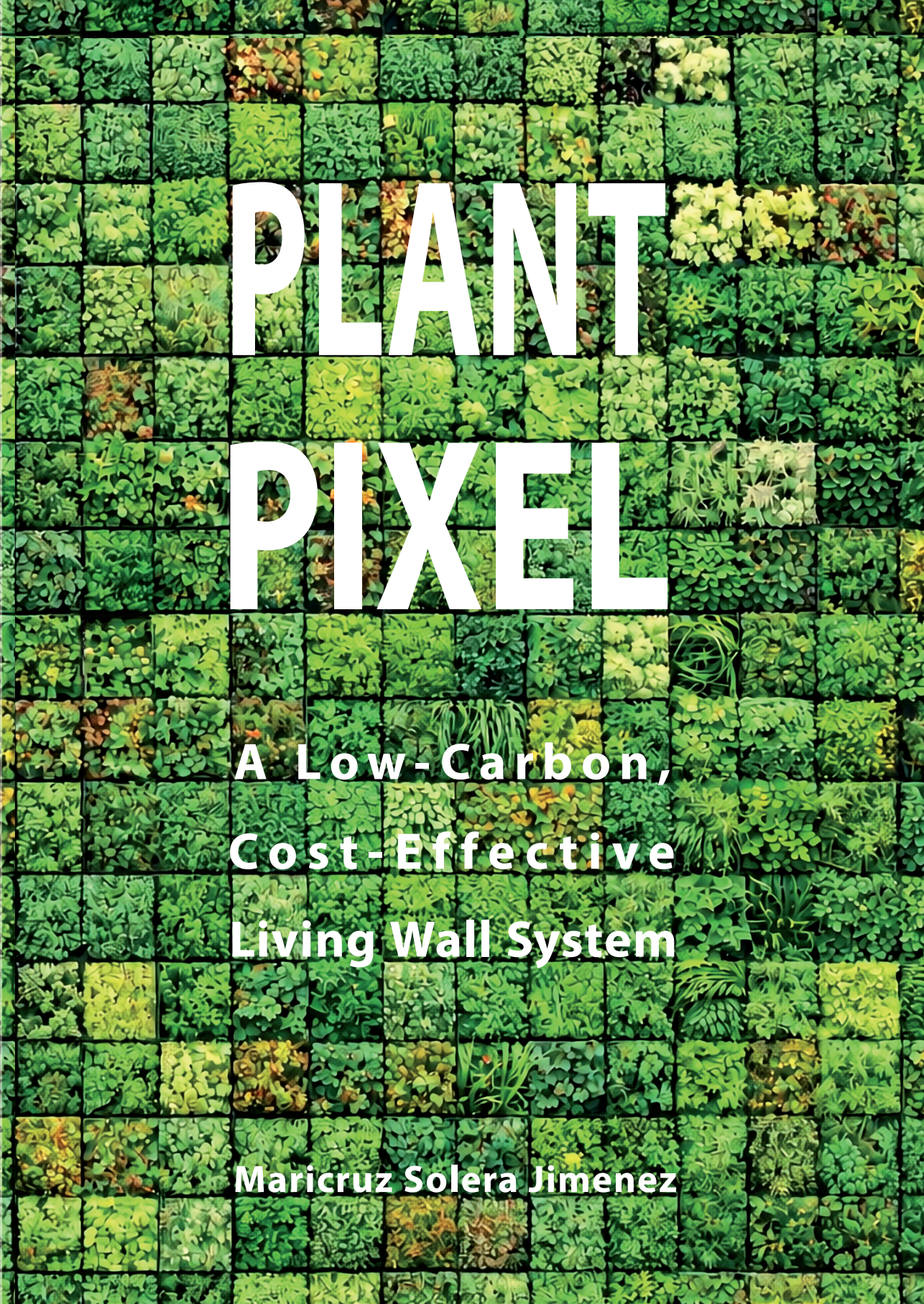
PLANT
PIXEL
A Low-Carbon,
Cost-Effective
Living Wall System
Maricruz Solera Jimenez

Propositions

1. The success of a living wall design is ultimately determined by plant species selection (this thesis).

2. Scientific industry-focused research is essential for developing real-world living wall products (this thesis).

3. Designing living wall systems with an end-of-life perspective improves continuous material circulation.

4. Simplicity is the foundation of clever design.

5. Nature-inspired design fosters innovative problem-solving approaches.

6. Clear and accessible communication of scientific research should be prioritized when the aim is to bridge the gap between academia, industry, and the public.

7. Openness to multiple design pathways in the early stages of design fosters breakthrough innovation.

Propositions belonging to the thesis, entitled:
"Plant Pixel. A Low-Carbon, Cost-Effective Living Wall System"

Maricruz Solera Jimenez

Wageningen, 10 September 2026

PLANT PIXEL

A Low-Carbon, Cost-Effective Living Wall System

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Plant Pixel

A Low-Carbon, Cost-Effective Living Wall System

Maricruz Solera Jimenez

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Contents

Summary		7
Foreword		10
1	Introduction	13
2	Methods	31
3	Early-stage design of a low-embodied carbon and cost-effective green facade system	45
4	Plant Pixel: an optimized bio-inspired living wall system	69
5	Microclimatic Performance of a Novel Living Wall System	105
6	Conclusion	145
Appendix		161
References		171
Acknowledgments		183
About the author		185
Sense diploma		187

Summary

Given projected increases in urbanisation and the intensifying impacts of climate change, urban heat stress has emerged as a critical challenge for cities. This challenge is particularly pronounced in high-density urban areas, where opportunities for soil-based and ground-level greening are limited. In this context, Vertical Greening Systems (VGS) are increasingly applied as building-integrated strategies to mitigate adverse climatic effects, particularly elevated air temperatures and heat stress. Previous studies demonstrate that VGS can reduce near-wall and near-surface air temperatures, lower mean radiant temperatures in street canyons, and contribute to mitigation of the urban heat island effect, thereby improving outdoor thermal comfort.

Within the VGS typology, Green Facade Systems (GFS) and Modular Living Wall Systems (MLWS) provide adaptable solutions for integration into building envelopes. MLWS, in particular, offer enhanced microclimatic potential due to the presence of additional material layers and growth substrates. However, despite increasing implementation, MLWS are associated with several challenges that remain insufficiently addressed in current research and practice, including low-embodied carbon material selection, hydrological and structural performance, plant performance, simple assembly-disassembly, and cost-effectiveness.

First, many existing MLWS designs do not sufficiently consider low-embodied carbon, reused, and recycled materials. Material selection is often insufficiently aligned with environmental performance and circular construction principles. To effectively reduce embodied carbon, material longevity and functional performance must be balanced, particularly for system lifespans exceeding 50 years. Second, MLWS often pose hydrological challenges because of high irrigation demands, resulting in increased water consumption and operational impacts. Third, MLWS face structural challenges from higher dead loads resulting from water saturation, restricting retrofit use.

Fourth, resources competition, incompatibilities between plant species, substrate properties, and local climatic conditions constrains plant performance in MLWS. Fifth, MLWS's complex assembly and disassembly processes hinder reuse, refurbishment, and recycling, opposing circular economy goals. Sixth, MLWS remain costly due to high installation, operation, and maintenance requirements. Finally, existing assessments of MLWS microclimatic performance are predominantly based on short-term summer measurements, while multi-season and long-term performance remains insufficiently documented.

To address these gaps, this PhD investigates the following research question: How to design a bio-inspired, cost-effective, and low-embodied carbon green facade system that improves urban microclimate?

This research adopts an iterative RTD methodology to develop, test, and refine a prototype MLWS-Plant Pixel. Five consecutive design-test iterations were conducted, followed by a post-design, multi-season microclimatic evaluation. The prototype was optimized regarding embodied carbon, hydrological and structural performance, plant performance, simple assembly-disassembly, and cost-effectiveness.

Iteration 1 developed three low-embodied-carbon GFS typologies: a facade-based system (FP1), two balcony-forest systems (BF1 and BF7), and a redesign of an existing patented product. Evaluation against embodied carbon, cost, and hydrological performance defined baseline geometry, material options, and a plug-in fixing strategy. FP1 prototype emerged as the most suitable candidate for further optimization.

Iteration 2 evaluated the designs using a life-cycle and cost analysis of three GFS typologies. The FP1 prototype achieved the lowest costs and embodied carbon by maximizing recycled PVC-U and minimizing steel use. The results showed that materials and the GFS typology had the most significant influence on reducing embodied carbon during the production stage. During the installation and maintenance stages, reductions in embodied carbon and costs were achieved through the ease of assembly-disassembly (plug-in). FP1 had the lowest embodied carbon due to its use of recycled materials, biomaterials, and material efficiency.

Iteration 3 verified hydrological and structural performance using a full-scale (1:1) mock-up. A recycled textile fiber substrate achieved a high water-retention capacity (61.02 l/m^{-2}), reducing irrigation demand while supporting plant health. Structural testing confirmed that recycled PVC-U and aluminium, combined with optimized geometry, provide sufficient load-bearing capacity under saturated conditions.

Iteration 4 developed MLWS designs inspired by the morphology of steep rock walls. The *Plant Pixel* prototype emerged as the most suitable candidate for further optimization. LCA index and mechanical properties showed that the utilization of recycled PVCU, recycled textile, and recycled aluminum can decrease up to 50% the embodied carbon in MLWS products.

Iteration 5 refined the *Plant Pixel* prototype through a full-scale installation of 500 modules and 500 plants in Wolfschlugen, Germany. The plug-in fixing system enabled rapid assembly and maintenance. Plant trials showed high survival and coverage for 20 of 22 low-maintenance species. LCCA confirmed reduced material and operational costs, achieving 256.1 $€/m^{-2}$ for materials and 105 $€/m^{-2}$ for plants.

Post-design, the microclimatic performance of the *Plant Pixel* was evaluated in Stuttgart across multiple seasons (June 20, 2022–January 1, 2023). Sensors were installed at 10cm and 40cm on three *Plant Pixel* facades (two south-facing, one west-facing) and on adjoining bare walls. During the summer, the reflection of short-wave radiation decreased by roughly 68%, along with an average near-wall temperature reduction of 2.5°C, a 5–7% increase in relative humidity at 10cm, and a 57% decrease in wind speed. During a heatwave, peak cooling reached 5.5°C at 10cm. During the winter season, temperature effects were minor, whereas wind velocity declined by up to 2.4m/s^{-1}, stabilizing near-wall conditions.

This study presents a validated MLWS prototype and a multi-season microclimatic evaluation within a temperate oceanic (Cfb) climate. The *Plant Pixel* design offers modularity, reduced embodied carbon, cost efficiency, and an innovative bio-inspired design for high-density urban settings. The microclimatic data suggests that the *Plant Pixel*'s optimized performance is significantly affected by module depth, facade orientation, and planting density.

Structure of this thesis

This thesis is structured into five chapters. Chapter 1 introduces state-of-the-art Vertical Green Systems (VGS). Chapter 2 explains the methodology adopted in this research. It provides a detailed examination of literature and market research on VGS, focusing on the selected criteria: low embodied carbon, hydrological and structural performance, plant performance, simple assembly and disassembly, cost-effectiveness, and microclimate performance.

Chapters 3-4 revolve around the five Research Through Design (RTD) iterations conducted to refine the *Plant Pixel* prototype. Chapter 3 discusses the preliminary design and development of GFS prototypes during the early RTD iterations (1–3).

Chapter 4 explores the design and evaluation process for creating the *Plant Pixel* MLWS prototype. Chapter 5 focuses on the post-design microclimatic evaluation, emphasizing the outcomes of the *Plant Pixel*. Chapters 2 to 4 are based on articles published in peer-reviewed journals. As a result, some overlap exists, particularly in the introductory sections.

Finally, Chapter 6 entails the conclusion, addressing the research questions and highlighting the contributions to academia and society. Additionally, it offers recommendations for future research and design practices.

Foreword

My journey with Living Wall Systems (LWS) began during my Master's program in Sustainable Building and Performance at Oxford Brookes University, where my thesis examined the impact of green walls on London's urban microclimate. This research highlighted the microclimatic potential of vegetated facades and sparked a long-term exploration of scalable, performance-driven greening systems.

During my industrial doctorate at Wageningen University, the development of Plant Pixel was conducted within a formal academia–industry collaboration that distinguishes it from a conventional PhD. The SOLOCLIM project integrated academic research with industrial R&D. This involved approximately two years of work embedded at ZinCo GmbH, a commercial producer of green roof and facade systems. The study had to address scientific inquiries and industrial challenges concerning manufacturing, cost, certification, maintenance, and market viability. Thus, the project was conducted through iterative design, prototyping, and materials testing, with ongoing industrial feedback (Figure 0-1).

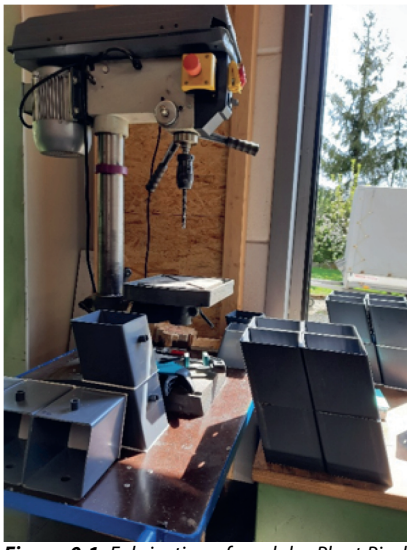


Figure 0-1. *Fabrication of modular Plant Pixel components using a drill press. (Source: Author)*

The project unfolded during the COVID-19 pandemic. This period was marked by material scarcity, supply chain interruptions, and limitations on movement. Navigating these constraints transformed my design methodology. The isolation experienced during the COVID-19 lockdowns provided an opportunity for an intense focus on materials and iterative improvements. We had to use a hands-on method to test locally sourced and repurposed materials. As a result, I deepened my commitment to design strategies centered on adaptability, circularity, and resilience. By incorporating flexible and adaptive manufacturing methods, I refined the system's modular design, irrigation, and thermal efficiency (Figure 0-2).

The development and evaluation of the Plant Pixel have been recognized in peer-reviewed journals, including Developments in the Built Environment and the Journal of Building Engineering. The project has received international acclaim, including nominations for the EarthShot Prize (2024) and the Green Product Award (2023), along with an honorable mention at the Design Intelligence



Figure 0-2. *Full-scale Plant Pixel modular living wall system after installation. (Source: Author)*

Award (DIA). Its visibility has been further enhanced through presentations at notable events, including the Eco-design Award in Berlin in 2023 and Dutch Design Week in Eindhoven in 2023 (Figure 0-3). Finally, I delivered a masterclass on living walls, hosted by Mobilane.

This project exemplifies how innovation often emerges under constraints, highlighting the importance of resilience in sustainable design amidst material, logistical, and climate uncertainties(Figure 0-4). This aligns with my broader research philosophy: resilient designs flourish not under perfect conditions, but through their capacity for adaptability, iteration, and effective problem-solving.



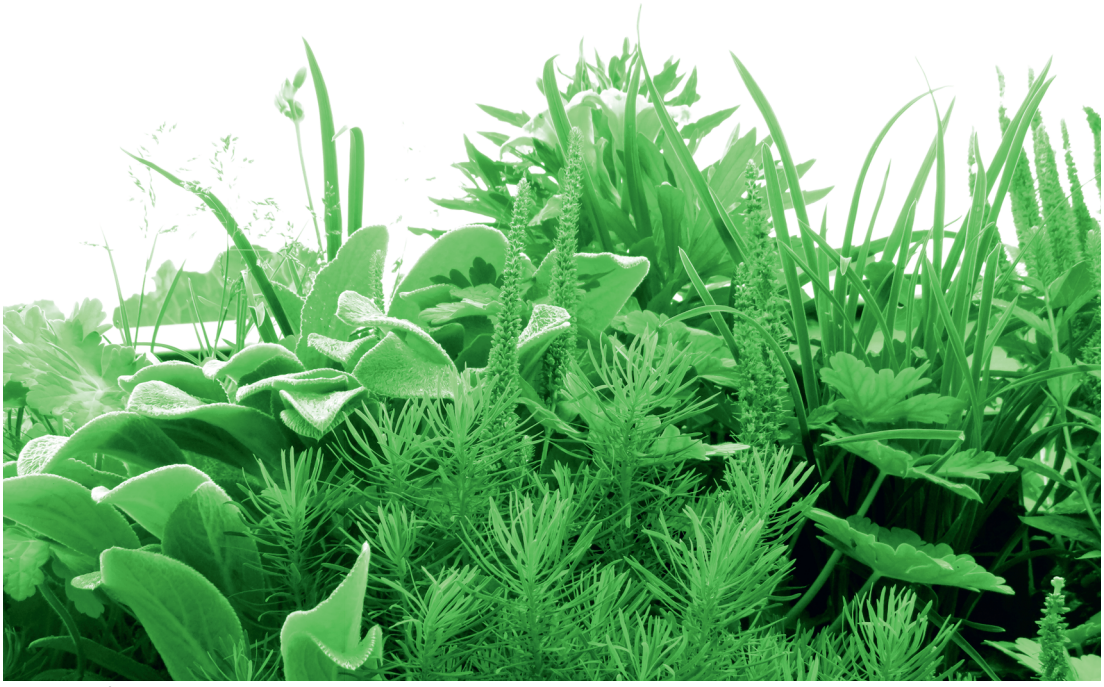
Figure 0-3. *Presentation of the Plant Pixel project at Dutch Design Week. (Source: Author)*



Figure 0-4 *Plant Pixel Prototype in Stuttgart, Germany. (Source: Author)*

1

Introduction



(Source: Author)

1.1 General Problem Statement

Cities are becoming increasingly vulnerable to urban heat stress (European Commission, 2011). High-density urban areas with limited space for traditional greening (such as soil-bound street trees, gardens, and parks) can benefit from Vertical Greening Systems (VGS). Evidence shows that VGS can improve air quality, reduce building energy demand, enhance urban biodiversity, and regulate local microclimates (Huang et al., 2019; Wong et al., 2009, 2010; Djedjig et al., 2015; Susorova et al., 2014; Tan et al., 2014).

VGS can mitigate adverse climate effects in a dense built environment, particularly heat stress. They have the potential to mitigate the urban heat island effect, modulate local climates, and improve outdoor thermal comfort (Tan et al., 2014). Djedjig et al. (2015) found that the application of VGS can lead to a 4°C decrease in ambient temperatures within street canyons. De Jesus et al. (2017) found that the surrounding air temperature could be cooled by as much as 4.5m away from the facade.

Despite its positive microclimatic effects, significant challenges characterize current VGS, particularly for Living Wall Systems (LWS) (Bianco et al., 2017). Current research highlights challenges related to high embodied carbon, long-term hydrological and structural performance, plant performance, and cost-effectiveness (high initial costs and maintenance). Solutions to these challenges require design strategies that improve resource efficiency, durability, and operational reliability without negatively impacting microclimatic performance.

LWS can be improved through nature-inspired design by drawing on principles observed in natural vertical ecosystems, including form, function, growth processes, and load-distribution strategies (Knippers & Speck, 2012). The study of cliff faces, gorges, and vegetated rock surfaces informs morphological configurations that enhance water capture, retention, drainage, and plant anchorage. These nature-derived principles primarily contribute to hydrological performance, structural efficiency, and plant vitality through optimisation of geometry and system organisation, rather than directly addressing material circularity or embodied carbon.

Circular-economy strategies complement these morphological principles by addressing material choice, lifecycle impacts, and resource efficiency (Prieto-Sandoval et al., 2018; Suchek et al., 2021). In LWS design, circularity is operationalised through the use of low-embodied-carbon and recycled materials, high-retention substrates and optimised irrigation strategies, lightweight and recyclable structural components with verified saturated-load capacity, resilient low-maintenance planting, and design for assembly and

disassembly. Together, nature-inspired design and circular-economy strategies form complementary frameworks that enhance system performance while reducing environmental burdens and supporting the feasibility of large-scale LWS deployment in dense urban areas. Therefore, the integration of nature-inspired design and circular-economy strategies is considered a relevant approach in this industrial PhD project.

1.2 State of the Art in Vertical Greening Systems

1.2.1 Vertical Greening Systems Typology

VGS are vegetated systems installed on vertical surfaces to enhance environmental, aesthetic, and climatic performance in urban areas. VGS are classified into two primary categories: Green Facade Systems (GFS) and LWS (Loh, 2008; Ottelé et al., 2011; Pérez-Urrestarazu et al., 2015; Manso & Castro-Gomes, 2015). This classification is based on differences in plant support structures, integration with the facade, and technological complexity (Figure 1-1).

GFS comprise climbing or hanging plants and are further divided into direct and indirect systems. These systems typically feature extensive vegetation rooted at the base or in planters and are characterized by relatively simple construction and low material requirements (Dunnett & Kingsbury, 2008). The implementation of GFS requires consideration of local climate conditions and light availability to ensure plant health and longevity (Dunnett & Kingsbury, 2008).

Direct green facades (GF) involve plants that grow directly on or along the wall surface without intermediary structures (Figure 1-2). Typically comprising deciduous or coniferous species, these systems are part of extensive designs that allow plants to climb and naturally adhere to the wall (Pérez et al., 2015). These plants can grow to heights of up to 25m (Dunnett & Kingsbury, 2008). These systems are cost-effective and lightweight but plants have slower growth rates and limited species diversity. Full Facade coverage may take several years, depending on species and local conditions (Dunnett & Kingsbury, 2008; Pérez et al., 2015).

Indirect green facades (IGF) use additional supporting structures to attach plants to walls, either rooted in the ground or planters (Loh, 2008; Manso & Castro-Gomes, 2015). These systems employ wire rope nets, metal meshes or modular trellises to support plant growth (Susorova, 2013). Indirect green facades are lightweight, easy to install, and provide basic integration between plants and building surfaces. The supporting structures create an air gap between the plants and the wall, preventing vegetation from adhering directly to the facade. This design improves structural resilience, protects the wall from rain, wind and snow, and facilitates natural plant growth.

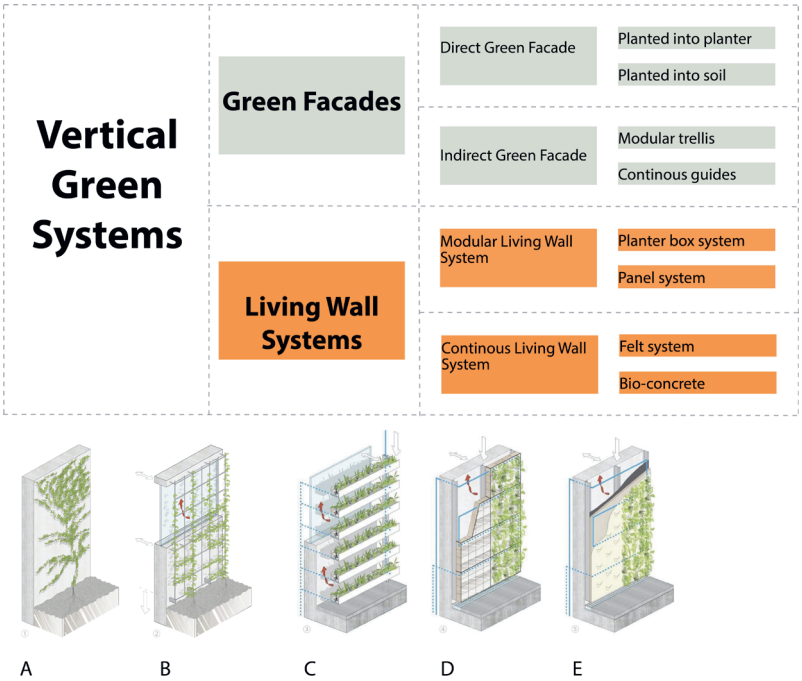


Figure 1-1. *Overview of the classification of the vertical green systems (top). Pfoser (2016) depicts different vertical green systems: (A) Direct green facade, (B) Indirect green facade, (C) Planter box system, (D) Panel system, and (E) Felt system (below). (Source: Author)*



Figure 1-2. *Direct green facade in Munich, Germany. (Source: Author)*

LWS are architectural elements that support vertical plant growth without the need for ground-level rooting (Figure 1-3) (Manso & Castro-Gomes, 2015; Charoenkit & Yiemwattana, 2016). These systems utilize diverse support structures, including pre-vegetated modules, geotextile felts, bio-concrete, or planters filled with growth media (Manso & Castro-Gomes, 2015; Charoenkit & Yiemwattana, 2016). Upon installation, pre-cultivated plants offer flexibility in design and species selection, accommodating a wide range of plant types, including evergreens, ferns, shrubs, flowers, vegetables, herbs, and fruits (Manso & Castro-Gomes, 2015; Ottelé et al., 2011).

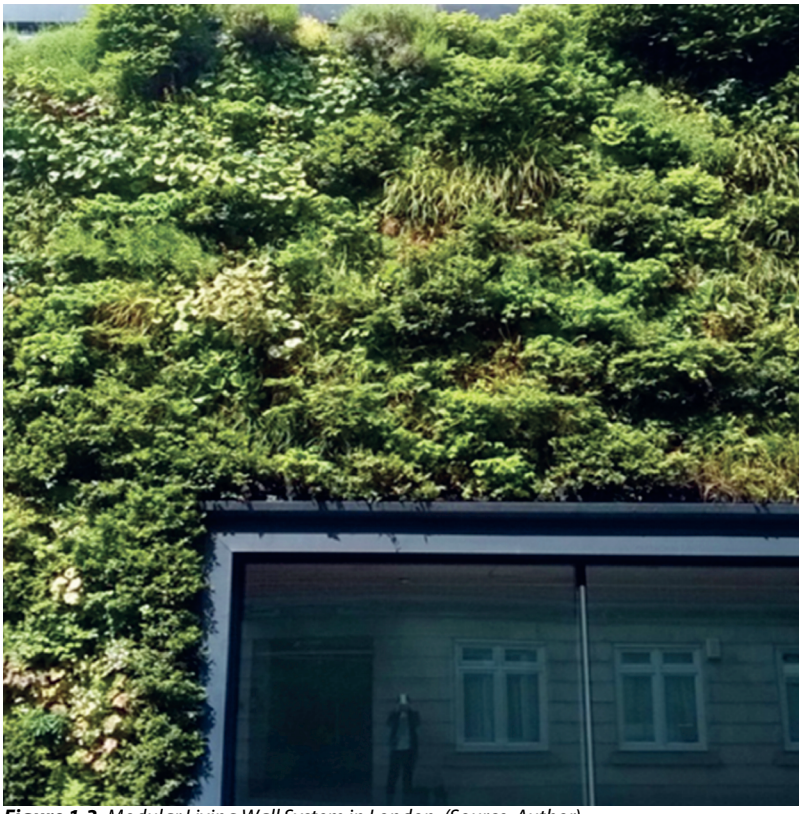


Figure 1-3. *Modular Living Wall System in London. (Source: Author)*

LWS are classified into two primary types: Modular Living Wall Systems (MLWS) and Continuous Living Wall Systems (CLWS) (Pérez et al., 2011; Manso & Castro-Gomes, 2015; Ottelé et al., 2011). MLWS comprises modules that can be pre-vegetated and assembled on-site, providing flexibility in maintenance and replacement. (Figure 1-4). CLWS replace traditional soil substrates with synthetic felt layers, creating a lightweight, permeable, and flexible growth medium (Susorova, 2013). The vegetated surface is mounted on a waterproof PVC sheet, which functions both as a building membrane and as a support for hydroponic irrigation (Charoenkit & Yiemwattana, 2016).

Patrick Blanc pioneered this approach with the *Mur Végétal* in 1994. His patented system employs a substrate-free hydroponic medium and integrated irrigation to sustain plant growth across diverse species (Susorova, 2013). This innovation demonstrated that vertical greenery could be deployed in dense urban contexts without reliance on soil. Blanc's work established the foundation for continuous living wall systems, positioning them as a viable architectural technology and influencing subsequent research and design practice.

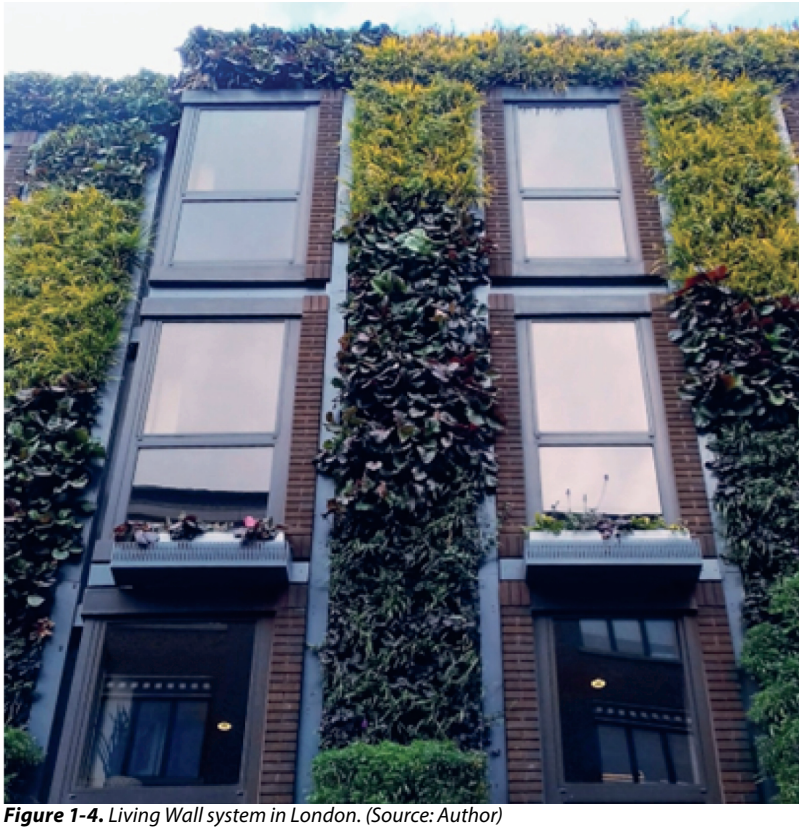


Figure 1-4. *Living Wall system in London. (Source: Author)*

Bio-concete LWS is an innovative addition to continuous systems. It eliminates the need for conventional soil-based mediums by employing hydroponic systems, facilitating the growth of mosses, lichens, and other small plants (Mustafa et al., 2021).

MLWS consist of pre-assembled units filled with growing medium and pre-vegetated plants (Figure 1-5)(Loh, 2008; Manso & Castro-Gomes, 2015). These systems offer flexibility in design, maintenance, and plant selection. Unlike CLWS, which rely on a continuous support structure, MLWS are designed for easy replacement and reconfiguration, making them particularly suitable

for projects requiring frequent updates or plant replacement (Pérez et al., 2011). Modules are made from various materials, including plastic, expanded polystyrene, synthetic fabric, clay, metal, or concrete (Pérez et al., 2011). The growing medium can range from soil to foam, felt, or mineral wool. Modular systems are typically classified into panel or planter box systems (Manso & Castro-Gomes, 2015; Charoenkit & Yiemwattana, 2016).



Figure 1-5. *Modular Living Wall System with Decayed Styrene Foam. (Source: Evolo, 2022)*

Recent innovations in modular living wall design have incorporated the adoption of 3D-printing technologies, enabling the creation of complex and customizable shapes for modules (Berardi, 2012; Farinea et al., 2015; He et al., 2020). These advancements enhance the aesthetic and functional capabilities of modular systems. Additionally, the multiple layers of materials and substrates in modular systems contribute to improved microclimatic benefits, such as enhanced insulation and cooling effects (Perini et al., 2011; Wong et al., 2010).

GFS are generally more cost-efficient and require less maintenance; however, their performance depends on plant growth over time, and facade coverage may take several years to develop (Pérez et al., 2015). As a result, there are still limitations in control over microclimatic processes. MLWS, by contrast, allow microclimatic performance to be addressed through engineered substrates, higher planting densities, and facade-scale irrigation control in compact urban contexts. Despite substantial advances in MLWS research and development over recent decades, key aspects-including embodied carbon, hydrological and structural performance, plant performance, ease of assembly and disassembly, cost-effectiveness, and microclimatic performance-remain insufficiently studied.

1.2.2 Embodied Carbon in Vertical Greening Systems

Assessing the environmental performance of vertical greening systems requires evaluating embodied carbon and operational carbon across the system's life cycle. According to Kirk et al. (2006), it is essential to consider the entire life cycle, encompassing raw material supply and manufacturing, use, maintenance, and disposal. Embodied carbon includes emissions associated with the extraction, processing, manufacturing, transport, construction, and end-of-life disposal of materials. Operational carbon encompasses emissions from maintenance activities, including irrigation, pruning, and replacement of components throughout the system's lifespan (Perini, 2018).

Within VGS, LWS generally exhibit higher embodied carbon than GFS because they integrate substrates, irrigation networks, and structural components (Table 1-1). Felt-based LWS can emit up to eleven times the embodied carbon of trellis-based GFS and approximately four times that of modular LWS panels (Feng & Hewage, 2014). In Mediterranean climates, energy savings from reduced cooling demand may offset embodied emissions within a decade; in temperate climates, the payback period may exceed the functional lifespan.

***Table 1-1**. Comparative overview of VGS typologies and performance characteristics.*

VGS (Vertical Green Systems)	VGS Category	Typology	Cost (€/m²)	Assembly/ disassembly	Hydrology	Structure (Weight)	Embodied carbon (relative)	Maintenance	Planting
	GFS (Green Facade System)	Direct (self-clinging)	Lowest (planting only)	No supports; pruning only	Relies on precipitation; low irrigation demand	Minimal (plant biomass)	Lowest	Pruning	Self-clinging climbers; ground or planter rooted
		Indirect (trellis/ mesh/ cables)	Low -moderate (supports required)	Mechanical supports; reversible if bolted	Precipitation; occasional supplemental irrigation	Low-moderate	Low (supports add embodied carbon)	Pruning; training on supports	Climbers/ hangers; ground or planter rooted
	LWS (Living Wall System)	CLWS — Continuous (felt-based)	400–1,200	Integrated layers; difficult to disassemble	High irrigation (~10 L/m²·day peak); low retention (~1.35 L/ m²·day)	Medium saturated weight: 35-60 Kg/ m²	Highest among VGS	Pruning, plant replacement, and continuous pumping	Shrubs, high density; nutrient dosing required
		MLWS — Modular	150–1,200	Mechanical supports; reversible if bolted	High retention substrate (e.g., 61.02 L/m²); zoned drip irrigation	High saturated weight: 70-150 Kg/ m²	Lower than CLWS; higher than GFS (recycled lowers EC)	Pruning; plant replacement; lower pumping	Shrubs, high density; substrate dependent, nutrient dosing may be required

To reduce embodied carbon, VGS should prioritize low-carbon materials (such as recycled or bio-based materials). The design of VGS must include design-for-assembly, plug-in connections, and specifications that support disassembly, reuse, and recycling. In parallel, operational carbon can be reduced through efficient irrigation, optimized water distribution, and low-maintenance regimes. A life-cycle assessment should address both dimensions to ensure VGS contribute to sustainable urban development (Perini, 2018; Chàfer et al., 2021).

1.2.3 Hydrological Performance in Vertical Greening Systems

Water management is a crucial component of vertical greening systems, particularly within living wall systems. The selection of a substrate is as important as the selection of plants. The substrate and design of irrigation systems have a significant impact on both plant health and overall system performance. Substrates with high water retention are essential for reducing irrigation frequency, enhancing plant vitality, and minimizing carbon emissions (Ottelé et al., 2011; Perini & Ottelé, 2014; Manso & Castro-Gomes, 2015).

Hydrological performance varies among VGS types. Direct Green Facades (DGF) and Indirect Green Facades (IGF) typically rely on natural precipitation and soil moisture, requiring minimal irrigation. In contrast, LWS require engineered substrates and automated irrigation to accommodate greater plant densities and species diversity. Felt-based systems are particularly water-demanding, with consumption rates reaching up to 10 l/m^2/day during peak summer in Mediterranean climates (Gunawardena & Steemers, 2020). However, these systems exhibit low water retention, averaging 1.35 l/m^2/day (Pérez-Urrestarazu et al., 2019). The need for frequent irrigation increases energy consumption for pumping, enhancing operational carbon impacts (Manso et al., 2013).

MLWS address these limitations by employing compartmentalized units and zoned irrigation strategies. This modular approach enables localized control over substrates and irrigation practices, reducing water waste and allowing for targeted watering that meets the specific needs of different plant species. Drip-line irrigation systems further improve water-use efficiency by directing moisture to the root zones, minimizing losses from evaporation and runoff (Medina et al., 2020).

Optimizing the hydrological performance of LWS requires substrates with adequate water retention to decrease irrigation frequency and maintenance needs. However, there is a lack of empirical research on how substrate characteristics interact with factors such as plant selection, structural design, and climatic variability. Additionally, the utility of recycled substrates should be assessed for both their material sustainability and their ability to retain water effectively.

Despite growing interest in MLWS, there remains a limited evidence base on systems that systematically integrate recycled materials and bio-inspired design features. In particular, the interactions between substrate properties, irrigation strategies, and modular configurations are insufficiently explored, constraining the optimization of water efficiency and long-term system durability. This gap limits the capacity to fully assess the role of MLWS in urban heat mitigation and to develop resilient, resource-efficient water management strategies for facade-integrated living wall applications.

1.2.4 Structural Performance in Vertical Greening Systems

Structural stability is a critical factor in the design and installation of VGS, particularly for MLWS, where water saturation significantly increases system weight (Figure 1-6). Existing studies emphasize the structural challenges posed by saturated systems, particularly the risk of overloading facades if mechanical requirements are not properly addressed during the design phase (Bianco et al., 2017; Manso & Castro-Gomes, 2015). However, systematic testing of novel substrate materials under maximum water load remains limited, highlighting a research gap in structural performance evaluation (Bianco et al., 2017).

Substrate weight directly influences the static load and structural demand of MLWS. Selecting lightweight substrates with high water retention is crucial for minimizing structural loads while ensuring adequate hydration (Prodanovic et al., 2018). Modular configurations offer benefits in distributing loads more evenly and facilitating attachment to support structures. Nonetheless, system scale and module weight must be calibrated to ensure safe integration with anchoring and facade systems.

A comprehensive understanding of the maximum weight thresholds for MLWS is necessary to assist designers in developing precise specifications for modules, anchorage points, and support systems. Addressing these parameters is essential to optimize structural performance, maintain facade safety, and ensure long-term functionality even under high water-saturated conditions.



***Figure 1-6**. Continuous living wall example in London, UK. (Source: Author)*

1.2.5 Plant Performance in Vertical Greening Systems

Plant selection is a key determinant of the ecological functionality and long-term viability of VGS. Therefore, it is essential to understand how plant species behave in local climates for better performance (Pérez et al., 2011). GFS, including direct and indirect green facades, supports a narrower range of climbing plant species, typically rooted in the ground or in planter boxes. Plant performance in GFS depends on the species' natural climbing ability, growth rate, and adaptability to local environmental conditions. In contrast, LWS allow for high planting densities, typically accommodating up to 30 plants per square meter (Manso & Castro-Gomes, 2015). Species selection must align with site-specific parameters such as microclimate, facade orientation, solar exposure, and local biodiversity (Bustami et al., 2019; Charoenkit & Yiemwattana, 2021).

In MLWS, the inert and inorganic substrate, as well as the limited volume of each modular unit, impose specific constraints on root development and nutrient availability. To support vegetation growth, integrated irrigation systems must deliver nutrient-enriched water (Koch et al., 2020). Incorporating drought-tolerant, low-maintenance species can reduce irrigation demands, lower saturated system weight, and decrease maintenance frequency. These advantages are relevant in structurally constrained or resource-limited urban environments.

Optimizing the interaction between plant species, substrate composition, and modular design is crucial for achieving resilient vegetation performance, minimizing operational inputs, and ensuring the long-term functional reliability of MLWS.

1.2.6 Simplicity of (dis-) assembling in Vertical Greening Systems

Simplified assembly and disassembly enable efficient end-of-use and end-of-life processes. Current practices often hinder this process by using adhesives, coatings, and integrated assemblies that complicate the separation and recycling of materials. The aim is to design systems that align with circular economy principles by maximizing resource efficiency and facilitating closed-loop material flows to reduce reliance on virgin resources. (Prieto-Sandoval et al., 2018; Suchek et al., 2021).

Simplifying assembly and disassembly offers benefits of material recovery, particularly by enhancing maintenance and repair processes. The ability to disassemble facade components enables the replacement of individual elements, extending the lifespan of building systems. For example, in LWS, modular designs allow for straightforward plant replacement and maintenance without disrupting the overall structure. Advanced modular systems with removable front covers further improve accessibility, facilitating efficient plant care and wall upkeep (Manso et al., 2015). Besides, maintenance

advantages, simplified assembly and disassembly reduce material and energy costs associated with transportation and installation. Modular components, which can be easily stacked and adapted, streamline logistics and accelerate construction processes.

Incorporating design strategies that facilitate assembly and disassembly aligns closely with the objectives of the circular economy, which aim to reduce waste, conserve resources, and extend the lifespan of building elements. By enabling the recovery and reuse of materials, such strategies promote closed-loop systems, enhancing sustainability while improving the adaptability and functionality of facade systems throughout their lifecycle.

1.2.7 Costs in Vertical Greening Systems

Cost structures within vertical greening systems vary considerably based on system typology, material selection, and complexity design. GFS, including direct and indirect configurations, typically involve lower installation and operational costs because of their reliance on climbing vegetation and minimal technical infrastructure. In contrast, LWS incur higher capital and maintenance costs (Loh, 2008).

LWS are the most technically advanced typologies within VGS. Installation and maintenance costs for LWS typically range from €150/m^2 to €1,200/m^2 (Santi et al., 2019). These costs are influenced by system types, materials, and design choices. For example, planter box systems range from €150/m^2 to €800/m^2. Specifically, planter box systems made from plastic materials cost between €100/m^2 and €150/m^2, while those with steel components can reach up to €800/m^2 (Perini & Rosasco, 2013). Felt pocket LWS costs vary from €400/m^2 to €1,200/m^2 and are associated with high operational costs (Perini & Rosasco, 2013; Santi et al., 2019).

Operational costs are determined by factors such as substrate durability, plant survival rates, and irrigation efficiency. Maintenance of LWS involves routine activities like pruning, irrigation, and component replacement, which increase lifecycle costs (Perini & Rosasco, 2013). For example, a felt-based LWS requires constant pumping and frequent irrigation, leading to higher energy consumption and long-term costs (Manso & Castro-Gomes, 2015). Conversely, MLWS facilitates targeted repairs and reconfiguration, which can potentially reduce labor and material costs. This underscores the necessity of a life cycle cost assessment focusing on optimizing cost-effectiveness by evaluating all cost factors throughout the life cycle.

Incorporating recycled materials and streamlined designs in MLWS prototypes can reduce embodied carbon and installation time, and present opportunities for cost optimization. Design optimization tailored to modularity, low

embodied carbon, or recycled materials, and simple assembly can reduce labor costs. Additionally, effective end-of-life management, which encompasses the disposal of plants and components, has a significant impact on overall costs, highlighting the importance of cost-effective end-of-life strategies. Innovative MLWS designs that incorporate bio-inspired principles and circular economy strategies may offer viable pathways for reducing total lifecycle costs, enhancing scalability, and promoting widespread adoption.

1.2.8 Microclimate in Vertical Greening Systems

Vertical greening systems contribute to urban microclimate regulation because of their extensive vertical surface area, often exceeding that of green roofs (Rosenzweig et al., 2006). This surface-to-volume ratio makes them particularly effective for climate-responsive urban design (Beatley & Newman, 2013). The following sub-sections examine the main microclimatic mechanisms associated with VGS: evapotranspiration, solar radiation attenuation, air temperature regulation, and wind speed reduction.

1.2.8.1 Evapotranspiration in Vertical Greening Systems

Evapotranspiration is a key cooling mechanism in VGS. Evapotranspiration is the process by which plants lose water through reducing air and surface temperatures near the facade (Neil, 2015). Evapotranspiration efficiency depends on foliage density and Leaf Area Index (LAI), which collectively lower temperatures and increase humidity (Neil, 2015).

Research on VGS indicates that during the photosynthetic-evapotranspiration phase, 71.5% of incoming solar energy is absorbed, with energy losses occurring via convection (40%), transpiration (42%), and long-wave radiation (16%) (Di et al., 1999). This process helps mitigate temperature spikes caused by solar radiation, reducing surface temperatures (Di et al., 1999).

LWS have shown to provide significant thermal advantages compared to GFS, such as improved evaporative cooling and enhanced solar energy absorption. This contributes to lowering indoor and outdoor temperatures and alleviating urban heat stress (Bakhshoodeh et al., 2022; Perini et al., 2017). For instance, LWS that incorporate vegetation are 7.38 times more effective at cooling compared to soil evaporation alone (Kim et al., 2023).

1.2.8.2 Solar Radiation in Vertical Greening Systems

Solar radiation is a critical factor in the thermal performance of VGS. VGS help mitigate solar heat gain by reflecting, transmitting, and absorbing solar energy. Research has shown that LWS can reduce radiant temperatures by up to 11.5°C within 0.5m of the wall, significantly enhancing outdoor thermal comfort (Tan et al., 2014).

VGS absorbs up to 50% of solar radiation in urban settings, reducing surface and air temperatures around buildings (Zhang et al., 2019). By emitting long-wave radiation during peak sunlight hours, GFS reduces heat gain, a crucial factor in optimizing cooling strategies for climate-adaptive urban designs (Hoelscher et al., 2016). Studies in Germany and China report VGS can reduce surface temperatures by 20.8°C, contributing to a 12% reduction in cooling energy consumption (Chen et al., 2013).

1.2.8.3 Outdoor Air Temperature in Vertical Greening Systems

VGS are increasingly used to mitigate the urban heat island effect and regulate outdoor microclimates, particularly in dense urban areas such as street canyons (Beatley & Newman, 2013; Ali-Toudert & Mayer, 2007). Studies across various climates show the effectiveness of VGS in lowering outdoor air temperatures. For example, in Chicago, GFS reduced outdoor air temperatures by 0.8 to 2.1°C near the facade (Susorova et al., 2014). Similarly, vertical greenery systems in Singapore lowered temperatures by 3.3°C within 0.15m of the installation (Wong et al., 2010). In France, greenery reduced overheating in urban canyons by one-third (Djedjig et al., 2015).

Furthermore, Tan et al. (2014) found an 11.5°C decrease in radiant temperature at a distance of 0.5m from the LWS, with cooling effects observed up to 1m away. In winter, ivy-covered walls in Manchester resulted in air temperatures that were 0.5°C warmer than non-vegetated walls, leading to an 8% reduction in heating energy consumption (Bolton et al., 2014).

1.2.8.4 Wind Speed in Vertical Greening Systems

VGS contribute to urban microclimate performance by reducing wind speed, which enhances thermal comfort and stabilizes temperature fluctuations around building facades. Studies indicate that wind velocity can decrease significantly near VGS installations. For example, Perini et al. (2011) found that wind speed declined from 0.56m/s at 10cm from the facade to 0.10m/s within the air cavity, representing a reduction of 0.46m/s. Similarly, Bakhshoodeh et al. (2022) reported that LWS can reduce wind speeds by more than 50%.

Wind speed reduction is particularly beneficial during winter, as it minimizes convective heat loss and improves thermal comfort for building occupants. However, in the summer, care must be taken to ensure that VGS do not obstruct cooling breezes, which are essential for maintaining a comfortable microclimate (Pérez et al., 2011). By creating a stationary air layer, VGS enhances thermal resistance by increasing it by up to 0.09 m^2K/W (Perini et al., 2011). Furthermore, LWS act as thermal barriers, reducing infrared radiation loss by as much as 79% (Convertino et al., 2020). Additional research is necessary to fully assess the effectiveness of VGS under winter conditions, addressing existing limitations in current studies (Susca et al., 2022).

1.3 Knowledge Gap and Innovation Gap

Despite advancements in MLWS research, critical knowledge, and innovation gaps persist, hindering optimization across key criteria, including low-embodied carbon, hydrological and structural performance, plant selection, assembly-disassembly processes, cost-effectiveness, and microclimatic regulation.

Low-Embodied Carbon: Material selection in MLWS often fails to prioritize low-embodied carbon and recycled materials, despite their critical role in reducing environmental impacts (Perini & Ottelé, 2014). The production phase, particularly material usage, contributes significantly to the environmental footprint of MLWS (Oquendo-Di Cosola et al., 2020). Choosing low-embodied carbon materials and incorporating reused or recycled components are essential strategies for improving environmental performance. However, achieving these goals requires a careful balance between material longevity and functionality, especially for systems with lifespans exceeding 50 years. Comprehensive life cycle analyses (LCA) during the design phase are indispensable for assessing and mitigating environmental impacts.

Integrating circular economy (CE) principles, such as material reuse and recycling, could further enhance sustainability by reducing embodied carbon and energy consumption. Despite its potential, research on embedding CE strategies into MLWS design remains limited, leaving a significant gap in sustainable material innovation. Expanding research in this area is crucial to develop materials and systems that minimize environmental impacts and align with circular economy objectives, ensuring the long-term viability and scalability of MLWS in urban environments.

Hydrological Performance: MLWS face significant economic and environmental challenges due to their high-water demands, often resulting in unsustainable levels of consumption (Manso & Castro-Gomes, 2015; Ottelé et al., 2011). High-water retention substrates offer a promising solution by extending water availability, reducing irrigation frequency, and ensuring plant survival even under arid conditions (Manso & Castro-Gomes, 2015). Despite this potential, research on innovative substrates remains limited, particularly in developing materials that optimize water retention while ensuring efficient water distribution. Future studies should focus on advancing substrate technologies that minimize water consumption, promote robust plant growth, and lower operational costs, aligning MLWS with broader sustainability objectives.

Structural Performance: Water-saturated MLWS present significant structural challenges due to the increased weight of saturated substrates, which can strain infrastructure and exceed mechanical limits (Bianco et al., 2017; Manso & Castro-Gomes, 2015). Despite this, limited research has focused on testing innovative materials for their mechanical strength under these conditions. Addressing these challenges requires the development of lightweight yet durable materials

capable of supporting saturated substrates without compromising safety or performance. Effective designs must consider maximum saturation weight, anchorage systems and structural stability across diverse environmental conditions. Incorporating bio-inspired principles and advanced composites offers promising pathways for enhancing the structural resilience of MLWS.

Plant Performance: Plants within MLWS face significant challenges, including competition for limited resources, incompatibility with substrates, and unsuitable climatic conditions (Bustami et al., 2019). Effective plant selection must prioritize climatically adapted species that are drought-tolerant and require minimal maintenance to ensure long-term viability and functionality. Poor species selection can exacerbate plant resource competition, reducing survival rates and compromising system performance. Research on plant performance in MLWS under different seasons is limited.

Expanding studies on plant-substrate interactions and their influence on plant health is important for optimizing MLWS designs. Understanding these interactions can guide the development of substrate formulations that enhance water retention, nutrient availability and overall plant resilience. Furthermore, addressing the knowledge gaps in species selection and climate suitability is essential to tailor MLWS for specific regions and environmental contexts. These efforts will improve plant survival on MLWS, making this a crucial area for future research and innovation.

Simple Assembly and Disassembly: Many existing MLWS systems rely on adhesives and coatings that obstruct disassembly and recycling, undermining their compatibility with circular economy (CE) principles. The inefficiency of current assembly-disassembly processes increases time and labor costs. Adopting modular designs that enable seamless separation of components for reuse, refurbishment, and recycling is crucial. Prioritizing lightweight construction and standardized modules can significantly enhance the efficiency of disassembly processes; however, research in this domain remains limited and requires urgent attention.

Cost-Effectiveness: High installation, operation and maintenance costs remain a significant barrier to the widespread adoption of MLWS (Manso et al., 2018; Ottelé et al., 2011). These expenses are further compounded by the frequent replacement of structural components and plants, significantly impacting their economic viability (Perini & Rosasco, 2013). Such cost-intensive factors limit the feasibility of MLWS for large-scale urban applications, restricting their contribution to sustainable urban development.

Addressing these challenges requires integrating life cycle cost analyses (LCCA) during the design phase to systematically identify and prioritize cost-saving opportunities. LCCA can guide the development of adaptable, low-maintenance

systems, ensuring efficient resource use and reducing long-term expenses. However, there is a pressing need for research into innovative materials and modular technologies to reduce installation, operation, and maintenance.

Microclimatic Performance: Existing research on MLWS primarily focuses on their performance during summer, with limited understanding of their year-round effects on outdoor air temperature, solar radiation, humidity, and wind speed. Comprehensive, long-term microclimatic measurements are needed to evaluate their seasonal variability, particularly in temperate climates.

While the impact of MLWS on surface temperature is well-documented (e.g., Chen et al., 2013; Hoelscher et al., 2016), studies examining the effects of LWS on ambient air temperature and solar radiation remain scarce in temperate climates. This highlights a significant research gap, especially regarding the seasonal microclimatic performance of LWS in temperate climates.

1.4 Research Questions

To start filling in the gap regarding low-embodied carbon, hydrological and structural performance, plant performance, simple assembly-disassembly, cost-effectiveness, and microclimate performance, this study addresses the main research question: How to design a bio-inspired cost-effective, and low-embodied carbon green facade system that improves urban microclimate? To answer this question, the following sub-research questions (SQ) were set:

- **SQ1:** How do different system types and material selections, including recycled materials, influence the embodied carbon of GFS and MLWS throughout their lifecycle?
- **SQ2**: How do different materials, including recycled substrates, influence the hydrological performance of GFS and MLWS?
- **SQ3**: How do material properties, such as lightweight and recycled materials, influence the structural performance of GFS and MLWS?
- **SQ4**: How do low-maintenance plant species perform regarding survival rates and growth in bio-inspired MLWS?
- **SQ5**: How do distinct system types and design strategies, including simple assembly and disassembly, influence the costs of GFS and MLWS across production, installation and maintenance?
- **SQ6**: How do MLWS influence outdoor air temperature, humidity, solar radiation, and wind speed during summer and winter in a temperate oceanic climate?

2

Methods



(Source: Author)

2.1 Research Through Design Overview

This research employs a Research Through Design (RTD) method. RTD is a practice-based research approach that generates knowledge through the iterative process of designing, prototyping, and evaluating artifacts. In RTD, an array of designs are tested through scientific analysis and evaluated through an iterative process until an effective design solution is reached (Lenzholzer et al, 2013).

In this study, RTD enabled the iterative development and evaluation of the *Plant Pixel* prototype. Each iteration addresses specific research questions (SQ) and aligns with the six primary criteria: low-embodied carbon, hydrological performance, structural performance, plant performance, ease of assembly-disassembly, and cost-effectiveness. The process is divided into five iterations, each building on the findings of the previous stage (Figure 2-1). Before I describe the RTD process in more detail, I provide an overview of the different phases and how they relate to the design criteria and sub-research questions.

2.1.1 Iteration 1: Early-Stage Prototype Development

The first iteration focused on conceptualizing and designing cost-effective and low-embodied carbon GFS prototype to address SQ0. These were categorized into three typologies: facade-based systems, balcony forest systems, and a redesign of an existing patented GFS product. Evaluation criteria included potential to meet low-embodied carbon, cost-effectiveness and functional requirements, serving as a foundational framework for further refinement.

2.1.2 Iteration 2: Embodied Carbon and Cost Evaluation

This iteration involved comprehensive Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) of the prototypes developed in Iteration 1 to address SQ1 and SQ5. These analyses quantified embodied carbon and economic feasibility, informing material selection and design refinements to improve environmental and financial performance.

2.1.3 Iteration 3: Hydrological and Structural Performance

In the third iteration, the prototypes were tested for hydrological efficiency and structural integrity to address SQ3-SQ4. Substrate materials were evaluated for water retention, drainage efficiency and maximum saturation weight. Structural performance tests evaluated the load-bearing capacity and stability under various environmental conditions. However, this prototype focused on functional performance while neglecting aesthetic considerations.

2.1.4 Iteration 4: Bio-Inspired Modular Living Wall System

Iteration 4 introduced bio-inspired designs for MLWS. The bio-inspired designs were developed to address functional and aesthetic limitations identified in earlier iterations. This iteration addressed SQ1, SQ2, and SQ3 by drawing inspiration from the morphologies of steep rock walls. Prototypes were tested for low-embodied carbon materials, hydrological performance and structural integrity. Trial mock-ups were constructed using recycled materials and tested for hydrological performance, structural resilience and visual appeal. LCA was employed to assess material impact. These bio-inspired designs emphasized visual appeal and adaptability, addressing aesthetic and functional objectives.

2.1.5 Iteration 5: Optimization of Assembly, Plant Selection and Cost-Effectiveness

The fifth iteration refined the MLWS prototype, named "*Plant Pixel*", by enhancing its assembly-disassembly mechanisms and plant performance to address SQ4 and SQ5. A full-scale mock-up, consisting of 500 modules and 500 plants, was constructed in Wolfschlugen, Germany. *Plant Pixel*'s modular design facilitated efficient assembly and maintenance, which were tested through assembly-disassembly trials and plant survival assessments. The LCCA evaluated production, installation and maintenance costs, further optimizing economic feasibility.

While the COVID-19 pandemic introduced challenges such as supply chain disruptions and limited collaboration, it also necessitated adaptive problem-solving and the integration of innovative materials in the mock-up construction. This highlighted the importance of resilience and adaptability in design and research processes.

2.1.6 Post-design evaluation 6: Microclimatic Performance Assessment

The final step evaluated the microclimatic performance of the *Plant Pixel* prototype to address SQ6. Long-term monitoring was conducted from June 20, 2022, to January 1, 2023, on a full-scale *Plant Pixel* prototype installed on the south and west facades of a container in Stuttgart. Measurements focused on outdoor air temperature, solar radiation, humidity, and wind speed near the *Plant Pixel* and adjacent bare walls with south and west orientations. Sixteen sensors were deployed over six months to capture seasonal variability. The assessment demonstrated significant cooling effects during heat waves, exceeding those reported for traditional LWS. *Plant Pixel* offers a scalable, cost-effective solution for urban climate adaptation, supporting green building standards and informing urban policy.

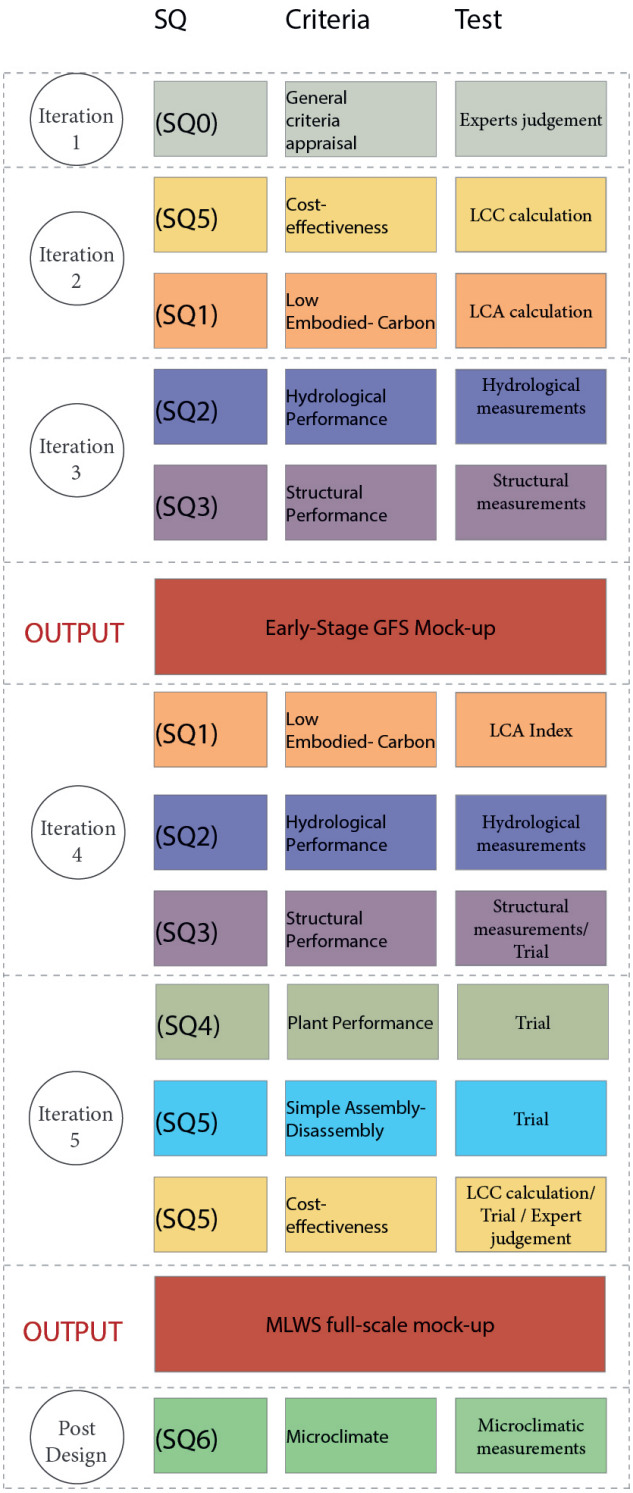


Figure 2-1. *Research through design methodology followed in the study. (Source: Author)*

The five iterations of the RTD process and the post-design evaluation were strategically aligned with the criteria of low embodied carbon, hydrological and structural performance, plant performance, simple assembly and disassembly, cost-effectiveness, and microclimate performance. Subsequent sections will provide a more detailed explanation of these iterations.

2.2 Literature review and market research

Before the design and testing work started, an extensive literature review was conducted on existing GFS to establish the research framework. This review explored multiple factors, including their cost-effectiveness, embodied carbon, composition, architectural qualities, hydrological properties and structural properties. The literature search, conducted on Google Scholar in June 2020, used combinations of terms related to GFS, such as "green wall system," "living wall," "green facades," and "vertical greenery system," combined with Boolean operators like "AND" to terms including "microclimate," "prototype," "life cycle assessment," "life cycle costs," "low carbon," and "design." Papers retrieved were categorized based on study criteria, excluding duplicates, non-peer-reviewed papers, or those irrelevant to the study's focus.

Market research aimed at comparing various GFS typologies and their properties. An online search across Google, google Patents and Free Patents databases identified preliminary GFS products and materials/substrates. Forty representative and innovative GFS products were shortlisted based on relevance to the study's objectives, encompassing planter boxes, modular panels, felt pockets, and novel products using new materials, 3D printing and innovative technologies. These products were compiled into an Excel database and organized into a comparative table with ten key categories: structure, materials, design, connection, irrigation, plant species, climate, weight, GFS typology and costs. More detailed information can be found in Chapter 3.

2.3 Research Through Design Framework

2.3.1.1 Identifying Performance Criteria (Chapter 3)

In the initial phase, the primary aim was to identify relevant criteria for designing optimized cost-effective and low-embodied carbon prototypes. To refine these criteria, a workshop was organized with industry experts from ZinCo, comprising R&D and marketing specialists. Through collaborative discussions during the workshop, the criteria were categorized into six distinct areas: low-embodied carbon, hydrological and structural performance, plant performance, ease of assembly-disassembly, cost-effectiveness, and microclimate performance. This structured approach ensured that critical criteria were evaluated and

integrated into the design process. The criteria selected addressed the gaps and limitations of current living wall systems regarding sustainability, costs and functional requirements.

2.3.1.2 RTD: Iteration 1 General Criteria Appraisal (Chapter 3)

In iteration 1, the primary goal was to create cost-effective, low-embodied carbon, optimized hydrological and structural GFS early-stage prototypes, which were categorized based on the GFS typology. Collaborative workshops with the industry partner were conducted, complemented by 3D-virtual and printed models (Figure 2-2, 2-3). Leveraging Building Information Modelling (BIM) technology, initial prototypes were developed, focusing specifically on investigating various facade geometrical properties, such as panel shape and size, using the BIM platform Revit. Integrating virtual and 3D-printed models was crucial in refining concepts and providing visual representations for evaluation (Figure 2-2). Additionally, the GFS design strategies enabled the exploration of multiple design options.

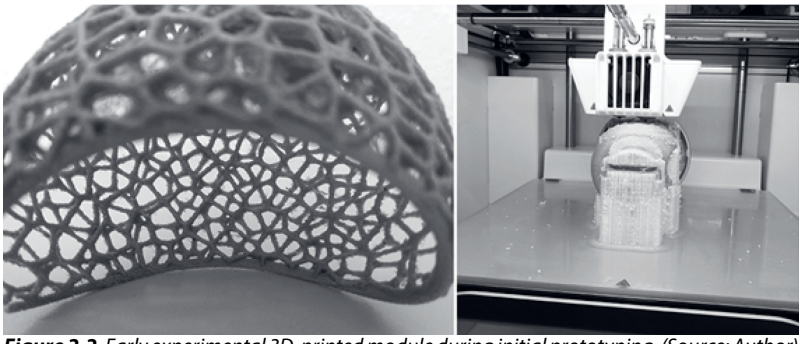


***Figure 2-2**. Early experimental 3D-printed module during initial prototyping. (Source: Author)*

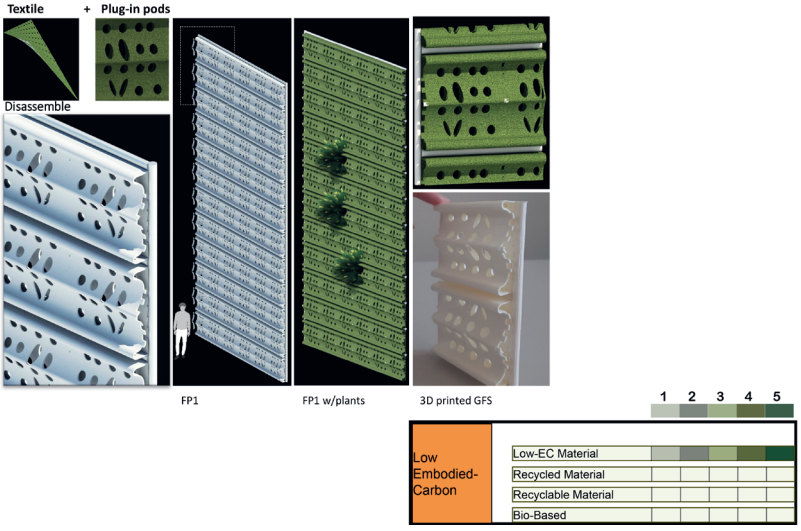


***Figure 2-3**. Evaluation workshops were used to assess the various early-stage GFS prototypes utilizing 3D-printed models and BIM visualizations. (Source: Author)*

The primary emphasis during this iteration was to explore and test a diverse range of GFS early-stage prototypes before finalizing a definitive solution. The GFS early-stage prototypes were evaluated through workshops that included R&D and marketing experts from ZinCo. The workshops aimed to select the prototype alternatives that best met the research criteria (low-embodied carbon, cost-effective, hydrological and structural performance) through a criteria assessment matrix (Figure 2-3).

2.3.1.3 RTD: Iteration 2 (SQ1 & SQ5) - Costs and Embodied Carbon (Chapter 3)

In iteration 2, two main themes were addressed: costs and embodied carbon. The aim was to diminish the costs and embodied carbon of the GFS early-stage prototypes by opting for low-embodied and cost-effective materials. To accomplish this, a life cycle cost analysis (LCCA) was conducted to address SQ1, and a life cycle analysis (LCA) was carried out to address SQ5. The GFS early-stage prototypes were classified into three main typologies according to their main characteristics: facade-based typology (vertical substrate plane GFS), balcony forest typology (horizontal substrate plane GFS) and re-design of a GFS patented facade-based system (Vertigreen 2.0.). The prototypes selected from iteration 1 (facade-based prototype FP1 and the balcony-forest prototypes BF1 and BF7) underwent refinement in terms of geometry and materials. They were then evaluated based on their cost-effectiveness and embodied carbon (Figure 2-4).

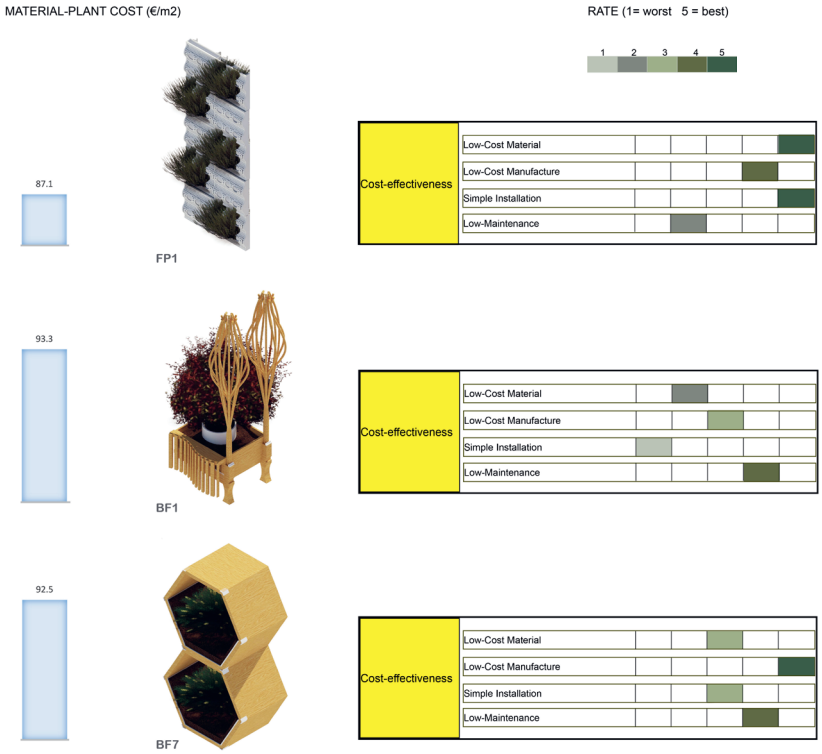


***Figure 2-4**. Cost assessment chart of different typologies of GFS early-stage prototypes. (Source: Author)*

2.3.1.4 RTD: Iteration 3 (SQ2- SQ3) - Hydrological and Structural performance (Chapter 3)

Iteration 3 was divided into two main themes: hydrological and structural performance. These criteria were assessed through hydrological tests to address SQ2 and structural tests to address SQ3. The layers comprising the GFS early-stage prototype were analyzed to discern their effects within the GFS module and on building facades. A 3D GFS printed mock-up was constructed by assembling 3D printed components to facilitate this examination. The utilization of 3D printing technology has been shown to optimize material usage, reducing waste throughout the production process (Sarakinioti et al., 2018). Constructed at a 1:1 scale, the 3D printed GFS mock-up was crafted from PLA (Polylactide) filament, an organic substrate and a degradable mat (Figure 2-5). This mock-up enabled the execution of hydrological and structural tests, aiding in identifying any hydrological and structural concerns.



***Figure 2-5**. 3D printed GFS early-stage prototype. (Source: Author)*

2.3.1.5 Bio-inspiration in natural steep rock walls (Chapter 4)

During this next stage, the research focused on creating designs for modular living wall systems that draw inspiration from nature's aesthetics and ability of plants to thrive in challenging environments. Iterations 1-3 satisfied the technical criteria; however, they exhibited a deficient aesthetic attractiveness, especially when the plant coverage was minimal during dormancy or seasonal die-off. As a result, the following iterations 4-5 integrated bio-inspired designs that drew inspiration from the textures and shapes in natural steep rock walls.

The objective was to amplify visual appeal, even in the absence of vegetation. The bio-inspired designs balanced functionality, ecology and visual appeal. Bio-inspiration involves studying and replicating natural elements' form, function and mechanisms, providing a pathway to innovative and efficient design solutions (López et al., 2017).

The initial MLWS designs drew inspiration from the morphology of steep rock walls, such as gorges, cliffs, and high-altitude mountains. Steep rock walls were chosen for their ability to support vegetation despite challenging microclimates. Before developing the designs, investigations into bio-inspiration were conducted. The focus was to find morphological principles on steep rock walls that can apply to MLWS design. The examination included studying the aesthetics, design effectiveness and plant survival mechanisms observed in steep rock walls. Moreover, their hydrological and structural properties were studied in extreme climatic conditions.

2.3.1.6 RTD: Iteration 4 (SQ1- SQ3) - Low-embodied Carbon Material, Hydrological and Structural Performance (Chapter 4)

Iteration 4 was subdivided into three themes: low-embodied carbon material, hydrological performance and structural performance. The objective was to choose low-embodied carbon materials with appropriate hydraulic and mechanical properties for the modular living wall system prototype.

The primary environmental impacts of MLWS are linked to material selection (Oquendo-Di Cosola et al., 2020). In Europe, recycling plastics, steel and aluminum offers an opportunity to mitigate carbon emissions and improve circularity (Materials Economics, 2018). Therefore, opting for low-carbon or recycled-recyclable materials is crucial to minimize the embodied carbon of MLWS. To address SQ1, we used the life cycle analysis (LCA) index to assess low-embodied carbon materials. Additionally, materials underwent hydrological tests to address SQ2 and structural tests to address SQ3.

Two trial mock-ups, constructed from 2.5mm PVCU extruded square profiles, were manually fabricated to evaluate water retention, storage capacity, distribution, maximum dry weight and maximum saturated weight (Figure 2-6). Subsequently, a decision matrix was used to compare results, considering embodied carbon, hydraulic, and mechanical properties, to identify the most suitable materials for the MLWS prototype.

2.3.1.7 RTD: Iteration 5 (SQ4- SQ5) – Plant Performance, Simple Assembly and disassembly, Cost-effectiveness (Chapter 4)

Iteration 5 aimed to assess plant performance, assembly and disassembly, and cost-effectiveness. To address SQ4, the selected plant species were evaluated through a plant performance test conducted on the full-scale mock-up. The costs of constructing the full-scale prototype were also examined during the



Figure 2-6 *Visualizations of the water distribution on the substrate for the hydrological tests performed on the MLWS trial mock-ups. (Source: Author)*

manufacturing, installation and maintenance stages. Testing encompassed the Life Cycle Cost Analysis (LCCA) and the ease of assembly-disassembly of the full-scale mock-up to address SQ5.

In June 2022, the *Plant Pixel* full-scale mock-up was constructed on the south and west walls of a container located in Wolfschlugen, Germany. The west and south facades were selected based on their high solar radiation exposure, significantly influencing plant growth. The mock-up comprised 500 square profile modules paired with an equal number of plants. These modules were divided into two variations: *Plant Pixel* 1, with module lengths ranging from 110mm to 210mm, and *Plant Pixel* 2, featuring module lengths between 150mm and 310mm. Both variations, measuring 1200mm wide and 2400mm high, were installed on the south wall of the container (Figure 2-7, 2-8). Additionally, *Plant Pixel* 1 was installed on the western wall, with a width of 600mm and a height of 2400mm.

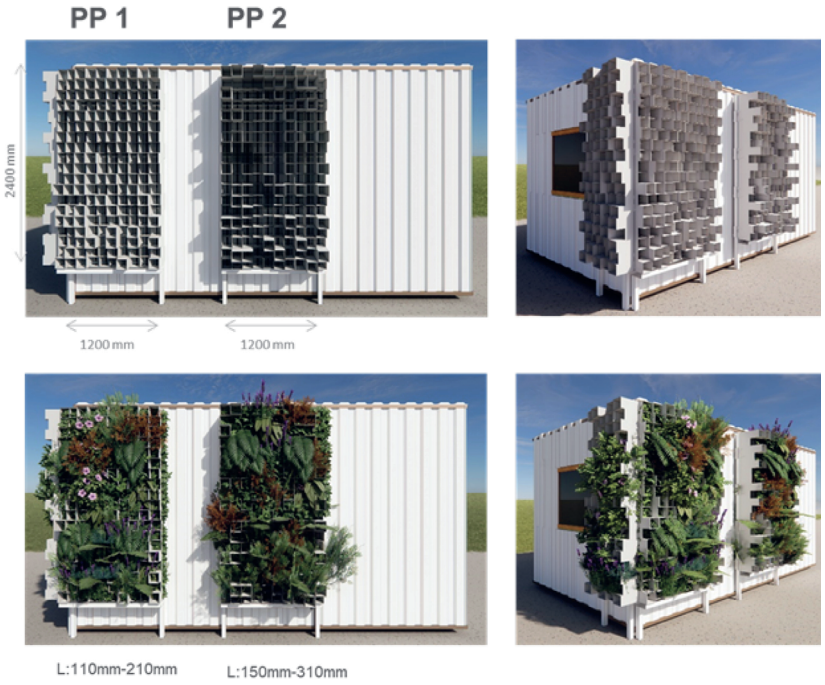


Figure 2-7 *Plant Pixel full-scale mock-up elevation (left-hand side) and 3D model (right-hand side) for the PP1 (module lengths 110–210 mm) and PP2 (module lengths 150–310 mm) variations. (Source: Author)*



Figure 2-8 *Result of the installation of the structural components of the Plant Pixel full-scale mock-up. (Source: Author)*

Plant selection was done in collaboration with ZinCo experts and tested in the MLWS mock-up using a plant survey. The plant survey is a systematic assessment based on standardized observational criteria. The aim was to evaluate the survival rate of 22 pre-cultivated plant species chosen for their suitability. This real-world testing environment provided valuable insights into the resilience and adaptability of the selected plant species (Figure 2-9).

Afterwards, the assembly and disassembly processes were evaluated. Designing for disassembly can extend the life of an object by enabling the removal and replacement of parts when necessary, using plug-ins, screws or clamp connections. Connections play a crucial role in disassembly and reusability. Therefore, optimizing the plug-in connections in the MLWS prototype was essential. Testing was conducted on the LWS full-scale mock-up to evaluate plug-in connections (Figure 2-9). The evaluation included assessing the ease of assembly and disassembly processes, as well as analyzing the structural integrity and deformations that occurred during disassembly.

A Life Cycle Cost Analysis (LCCA) was employed to calculate costs for the full-scale mock-up's manufacturing, installation and maintenance phases. Material costs, including PVCU, recycled textiles, aluminum profiles, screws, pipes, adhesives and plants, were all locally sourced. Transportation expenses were factored into the total expenditure, and labor costs were calculated based on hourly wages and construction hours. Maintenance costs, which included pruning, feeding, watering, and expenses for repairs or upgrades, were also considered. Finally, the total costs were benchmarked against similar products available on the market to determine cost-effectiveness.



Figure 2-9 *Full-scale mock-up of the Plant Pixel prototype (Source: Author)*

2.3.1.8 Post-design evaluation (SQ6) - Microclimate (Chapter 5)

The post-design evaluation aimed to assess the microclimatic performance of the *Plant Pixel* in mitigating urban heat stress during summer and its influence during winter. Continuous field measurements of outdoor air temperature, relative humidity, wind speed, and solar radiation were conducted, comparing the *Plant Pixel* with an adjacent bare wall (Figure 2-10). The mock-up was divided into two sections (PP1 and PP2) for comparative testing. Sensors were installed at 10cm and 40cm on the south and west facades to capture immediate and extended microclimatic effects. This setup, consistent with established LWS research protocols, provided the basis for evaluating and comparing the seasonal microclimatic performance of the *Plant Pixel*.



Figure 2-10 *Measurement instruments at the Plant Pixel Full-Scale Mock-up. (Source: Author)*

3

Early-stage design of a low-embodied carbon and cost-effective green facade system



(Source: Author)

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3

Highlights:

- Innovative research through design is conducted to develop a green Facade prototype.
- A life cycle and cost analysis are employed to optimize a green Facade prototype.
- A 3D-printed mock-up was built to test the hydrological and structural performance.
- Manufacturing phase, associated to the materials, had the highest embodied carbon.
- Recommendations for low costs and embodied carbon early-stage green Facade designs.

Abstract

Green facade systems (GFS) are a growingly popular resource in climate adaptation. However, current GFS are characterized mainly by high costs, high embodied carbon and short life span materials. This study presents the early-stage design of a cost-effective and low-embodied carbon GFS prototype. This prototype was developed and tested with a research-through-design (RTD) methodology. The first RTD iteration focused on cost-effectiveness and low embodied carbon. It categorized the prototypes into three main GFS design typologies: facade-based typology, balcony forest typology, and the redesign of a GFS-patented facade-based product. In iteration 2, the designs produced in iteration 1 were evaluated through a life cycle and cost analysis of the three typologies and the existing designs were refined. Finally, in iteration 3, the hydrological and structural performance was tested as a 3D-printed GFS mock-up. This process resulted in a modular, cost-effective, low-embodied carbon early-stage GFS prototype. It was found that the selected materials (recycled), plants, substrate (with high water-holding capacity), GFS typology (Facade-based with a lightweight structure), and its fixing system (modular) lowered the costs and embodied carbon of the GFS prototype compared to other GFS products.

3.1 Introduction

The design of facades is a complex process involving an array of aspects, such as aesthetics, stability, energy performance and indoor thermal comfort of users (Strauss, 2013). The way a facade is designed is important to climate-responsive design since it acts as the interface between indoors and outdoors and, thus, plays a role in both indoor and outdoor thermal comfort.

Among current climate-responsive spatial design elements (Cameron et al., 2014; Lenzholzer, 2015), GFS have become an increasingly popular way of countering adverse climate phenomena within the dense built environment, particularly heat stress (Loh, 2008a; Pérez-Urrestarazu et al., 2015). Several cities around the world have been encouraging the implementation of GFS motivated by the numerous climatic, environmental and social benefits vegetation holds (Wong et al., 2010; Ottelé, 2011; Sheweka & Magdy, 2011; Pulselli et al., 2014). Studies have established a positive relationship between GFS and a reduction in outdoor temperature (Tan et al., 2014). In line with this, GFS are considered a key component of urban green infrastructure, holding positive effects for mitigating the urban heat island (Bianco et al., 2017), regulating urban microclimates, and improving human outdoor thermal comfort (Beatley & Newman, 2013a; Cheng et al., 2010). For example, ambient temperatures in the street canyons can decrease by 4°C due to GFS (Djedjig et al., 2015). Despite its microclimatic positive effects, current GFS are characterized by high costs and a high embodied carbon footprint.

New GFS should integrate circular economy principles and align with the "Roadmap 2050" published by the European Union (European Commission, 2011), or similar frameworks elsewhere on the globe. Circular economy principles focus on resource efficiency, striving for closed-loop systems crucial to developing a sustainable, low-carbon society (European Commission, 2022). To achieve this, GFS should first aim for a low-embodied carbon, energy-efficient integrated approach to help cities reduce their carbon footprint. Secondly, criteria such as economic feasibility and environmental impact should be addressed in optimizing the design. Lastly, GFS are often not considered economically sustainable due to high installation, operation and maintenance costs (Ottelé et al., 2011; Perini & Rosasco, 2013; Manso & Castro-Gomes, 2015). The high costs associated with GFS are due to the need for replacement of support panels, irrigation systems and plant maintenance (Perini & Rosasco, 2013). In addition, GFS should be more flexible and adaptable to the building's envelope, while being simple to install and maintain to reduce embodied carbon and costs (Ottelé, 2011)There is also a lack of studies on reused or recycled materials and the implementation of circular economy principles in the development of GFS. Materials with lower energy and CO_2 emissions can improve a product's environmental performance (Manso & Castro-Gomes, 2015). Furthermore, these aspects should be addressed in ways that contribute to climate adaptation in urban areas.

Additionally, there are many gaps concerning hydrological and structural performance in GFS. Regarding hydrological performance, GFS can pose an economic and environmental challenge due to their high water requirements (Manso & Castro-Gomes, 2015; Ottelé et al., 2011; Perini & Ottelé, 2014). Adequate water-holding capacity, water retention, and water distribution of the substrates are critical for the survival of plants. Additionally, GFS with high water retention capacity can hold more water for a longer time, reducing the need for frequent watering and ensuring the survival of plants (Manso & Castro-Gomes, 2015; Ottelé et al., 2011; Perini & Ottelé, 2014). However, few GFS studies have focused on different substrates that can ensure optimal water-holding capacity, water retention, and water distribution. Regarding structural performance, GFS can challenge the structure due to weight issues in water-saturated zones (Manso et al., 2013; Bianco et al., 2017). Therefore, the structural design of GFS should consider the implications of increased weight due to water. Few GFS studies have tested the structural performance of new materials and the mechanical strength required to bear the weight of the substrate under maximum water saturation weight (Manso et al., 2013; Bianco et al., 2017). Additionally, there is still a lack of knowledge on the structural performance of new GFS built with 3D printing technology.

Despite numerous developments in GFS over the past few decades, little research has investigated the cost-effective and low-embodied carbon aspects of GFS. Some exceptions exist, such as a study conducted in Portugal that developed a low-embodied carbon modular system (Manso et al., 2013), and a study in Italy that created a modular box composed of recycled and natural materials (Bianco et al., 2017). However, research is needed on economically feasible, low-embodied carbon GFS that address circular economy principles (from the early design phases through their operational life) and contribute to climate adaptation in urban areas.

To start filling in the gap regarding cost-effectiveness, embodied carbon, hydrological and structural performance, this paper addresses the main research question: How to design a cost-effective, low-embodied carbon green facade system? To answer this question, the following sub-research questions (SQ) are set:

- SQ1: How do distinct types of systems influence the costs of GFS?
- SQ2: How do distinct types of systems influence the embodied carbon of GFS throughout the production, installation and maintenance stages?
- SQ3: How do distinct materials influence the hydrological performance of the GFS?
- SQ4: How do the selected materials influence the structural performance of the GFS?

To address these questions, this study presents an early-stage, cost-effective, low-embodied carbon GFS early-stage prototype developed as part of the ongoing Solutions for Outdoor Climate Adaption (SOLOCLIM) project.

Prototypes can stand as a product goal or serve as a working hypothesis that is tested and modified (Stappers, 2006). In this research, a prototype should be regarded as a proof-of-concept prototype. This GFS early-stage prototype was developed with research through design (RTD): an iterative design and testing process anchored on clear performance criteria and that cut across the academic and the industrial sectors.

This paper starts by presenting the RTD process and methods employed. Subsequently, the results obtained are presented and discussed, referencing previous GFS studies and comparable GFS products in the market. The paper concludes by recommending strategies to create a cost-effective and low-embodied GFS prototype that incorporates optimized hydrological and structural performance.

3.2 Methods

RTD was selected to conduct this study because it has proven resourceful in developing innovative design knowledge (Cortesão et al., 2019; Lenzholzer et al., 2013). In RTD, an array of designs are tested through scientific analysis and evaluated through an iterative process until an effective design solution is reached (Lenzholzer et al, 2013). RTD offers, therefore, opportunities to generate innovative and effective strategies while dealing with the complexity intrinsic to facade systems, such as shown in previous research (Dalsgaard, 2010; Gasparri & Aitchison, 2019).Furthermore, RTD can support cooperation between academia and industry to develop an evidence-based, market-driven GFS product.

This paper describes the first three iterations of an RTD process, focusing on the criteria of cost-effectiveness, low-embodied carbon, and hydrological and structural performance (Figure 3-1).

The RTD process was preceded by a systematic literature review and market research to answer the main research question. During this phase, cost-effective strategies, low-embodied carbon, GFS construction and technology were studied to develop GFS early-stage prototypes aligned to the criteria defined: cost-effectiveness, low-embodied carbon, and hydrological and structural performance.

3.2.1 Literature Review and Market Research

As a basis, a literature review explored existing GFS, their cost-effectiveness, embodied carbon, composition, architectural qualities, hydrological and structural properties. The literature search was conducted on Google Scholar in June 2020. The combinations of terms related to GFS were "green wall system" OR "living Wall", OR "green facades" OR "vertical greenery system".



Figure 3-1. *Diagram depicting the three RTD iterations employed in this study. (Source: Author)*

These terms were combined and related with the Boolean operation "AND", to the terms "microclimate", "prototype", "life cycle assessment", "life cycle costs", "low carbon" and "design". The papers found with this search were categorized according to the criteria addressed in this study (cost-effectiveness, low-embodied carbon, hydrological and structural performance). Duplicated papers, non-peer-reviewed papers or papers irrelevant to the topic addressed in this study, were excluded.

The market research was carried out to compare different typologies of GFS products and study their properties. An online search of GFS was conducted for products available in the market and preliminary GFS products. The online search was conducted on Google search and invention databases such as Google Patents and Free Patents. Additionally, potential materials and substrates were selected and compared across each other according to their costs and embodied carbon. 40 representative and innovative GFS products in the market were shortlisted based on their relevance to this study (i.e., GFS products made of planter boxes, modular panels, felt pockets and novel GFS products made of new materials, 3D-printed, and innovative technologies) and

compiled in an Excel database. The products were sorted into a comparative table sub-divided into ten key categories: structure, materials, design, connection, irrigation, plant species, climate, weight, GFS typology and costs.

3.2.2 Research Through Design

The RTD process comprised three iterations to test the cost-effectiveness, low-embodied carbon, hydrological and structural performance of the GFS early-stage prototypes (Figure 3-1). In iteration 1, the aim was to develop and compare cost-effective and low-embodied carbon GFS early-stage prototypes. Testing included expert judgments by the R&D and marketing specialists from ZinCo using a general criteria appraisal matrix. In iteration 2, the focus of the GFS design was to explore cost-effective, low-embodied carbon materials. These criteria were evaluated through a LCCA and LCA. In iteration 3, the aim was to test the hydrological and structural performance of the GFS early-stage prototype. Testing involved a moisture content evaluation on two substrates and a water holding capacity and maximum saturation weight of the 3D-printed GFS mock-up.

3.2.2.1 Criteria

The aim in this very first stage was to select relevant criteria to design cost-effective and low-embodied carbon early-stage prototypes. The criteria mentioned above (cost-effectiveness, low-embodied carbon, hydrological and structural performance) were reviewed through a workshop with the industry partner, ZinCo, which gathered R&D and marketing experts. After the workshop, the criteria were allocated in four categories: cost-effectiveness, low-embodied carbon, hydrological and structural performance.

3.2.2.2 GFS Design Strategies

In this stage, the aim was to create a clear brief for the design process by selecting GFS design strategies to meet the criteria (cost-effective, low-embodied carbon, hydrological and structural performance). The GFS design strategies were connected to the criteria and selected to provide a useful starting point to create new optimized GFS designs. These strategies were integrated in the research as overarching concepts to assist the GFS early-stage prototypes design. Based on the findings of the market research, two workshops were carried out with ZinCo experts to define these strategies. Five GFS design strategies aligned to the criteria were selected by identifying the gaps and limitations of current GFS technologies:

- *Texture and patterns*. A critical aspect of GFS is the survival of plants during extreme climate phenomena (e.g., heat waves, frost, heavy precipitation or drought). To deal with the climatic constraint, the texture and pattern strategy aimed at developing an aesthetically pleasant GFS for periods when plants do not fully cover the system. This deals with climate, plant survival, aesthetics and structural design.

- *Plug-in system and R-strategies* (reduce, reuse, refurbish, recycle, and recyclable). This strategy was chosen to develop the GFS with regard to the circular economy. Design for disassembling can maximize the life of an object by removing and replacing, when required, parts of an object by plug-in, screw, or clamp connections. Plug-in systems are modular integrated systems which are prefabricated and tested off-site and then inserted into position on site (Plug and Play Skyscrapers – Designing Buildings, n.d.). Additionally, plug-in systems simplify the disassembly process, at the end of the life of the GFS product. Therefore, the components and materials of the GFS product can be separated easily to be re-used, refurbished and recycled to extend the product's utilization phase. Incorporating recycled materials in the production stage of GFS reduces embodied carbon and costs on the raw materials. This deals with modularity, structural design, assembly-disassembly and circularity.
- *Hybrid GFS technologies*. Hybrid GFS technologies refer to combining two (or more) features of distinct GFS concerning the choice of materials, design, irrigation or structure. This strategy was selected to resolve design and technical constraints in GFS by developing new GFS that combine design and technologies from distinct GFS based on the criteria (cost-effective, low-embodied carbon, hydrological and structural performance). This was done by analyzing the GFS, extracting unique features and reconfiguring the materials, design, irrigation or structure of the GFS. To create innovative designs, use a wider range of plants and develop cost-effective and low-embodied carbon GFS prototypes.

After selecting these strategies, the GFS early-stage prototypes were classified into three main typologies according to their main characteristics (Figure 3-2): facade-based typology (vertical substrate plane GFS), balcony forest typology (horizontal substrate plane GFS) and re-design of a GFS patented facade-based system (Vertigreen 2.0).

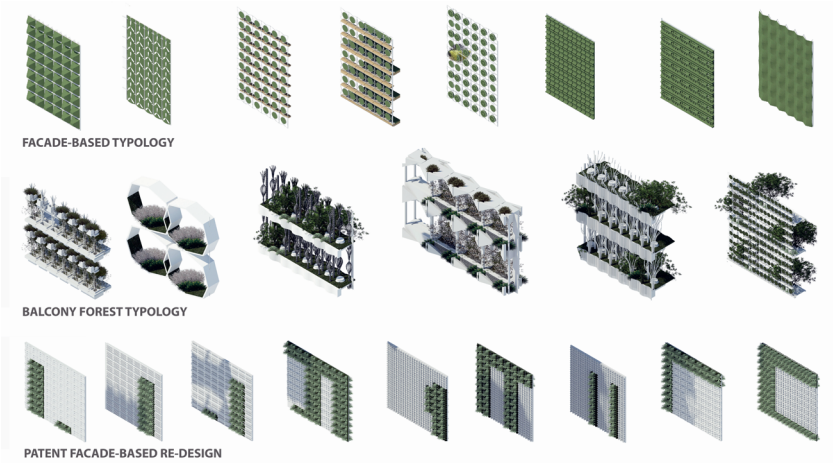


Figure 3-2. *Design alternatives developed in iteration 1 for the GFS early-stage prototypes, categorized by GFS typology. (Source: Author)*

3.2.2.3 RTD: Iteration 1 – General Criteria Appraisal

In iteration 1, the aim was to design cost-effective and low-embodied carbon GFS early-stage prototypes classified by GFS typology. The tools employed were workshops with the industry partner and 3D-virtual and printed models. Early-stage prototypes were designed with BIM (Building Information Modelling) technology and fabricated with 3D-printing. A BIM working environment, namely Revit, was used to experiment with different facade geometrical properties, such as panel shape and panel size. The virtual and 3D-printed models helped to develop the ideas further and represent them visually to be assessed. Additionally, the GFS design strategies facilitated the development of several designs. Throughout this iteration, it was important to identify and test a wide range of approaches before committing to a solution.

Testing involved workshops to evaluate the GFS early-stage prototypes with the R&D and marketing experts from ZinCo. The workshops aimed to select the prototype alternatives that best met the research criteria through a criteria assessment matrix (Appendix A). The matrix consisted of a 5-point rating scale (1=worst; 5=best). During the workshop, the team reflected on the various GFS early-stage prototypes and critically recorded issues arising from the discussion. Three GFS prototypes scoring the best were selected to be refined in the next iteration: facade-based prototype FP1, and the balcony-forest prototypes BF1 and BF7.

3.2.2.4 RTD: Iteration 2 – Costs and Embodied Carbon

Iteration 2 was subdivided into two themes: costs and embodied carbon. In iteration 2, the aim was to reduce the costs and embodied carbon of the GFS first stage prototypes by selecting low-embodied carbon and cost-effective materials. These criteria were evaluated through a life cycle cost analysis (LCCA) to answer SQ1, and a life cycle analysis (LCA) to answer SQ2. The prototypes chosen from iteration 1 (FP1, BF1 and BF7) were refined regarding geometry and materials and assessed on their cost-effectiveness and embodied carbon (Figure 3-3).

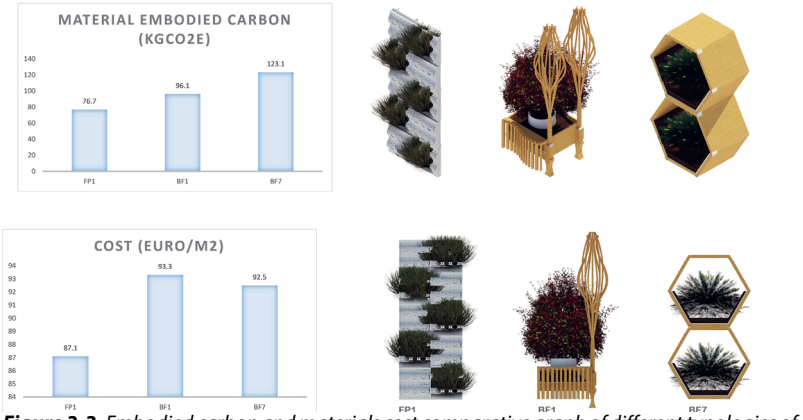


Figure 3-3. *Embodied carbon and materials cost comparative graph of different typologies of GFS early-stage prototypes. (Source: Author)*

The LCCA method was used to measure the costs attributed to each GFS design alternative and to support decision-making. The LCCA was calculated by, first, selecting various materials based on the data gathered from the literature review and market research and, second, by compiling data on the materials to estimate lifecycle costs of the GFS early-stage prototypes. The sums of all relevant costs were compared to determine the prototype with the minimum lifecycle cost and make a final decision (Appendix B).

The LCA method was used to measure the embodied carbon attributed to each GFS early-stage prototype (Figure 3-4). The calculation was based on the International Standardization Organization (ISO) 14040:2006. The selected unit for the LCA was 1m2 of the surface area of the prototypes. The LCA was employed with the aim of comparing and reducing the embodied carbon of the GFS early-stage prototypes in the production stage (A1-A3). H/B:ERT embodied carbon tool plug-in for Revit 2021 software was used to assess the embodied carbon impact of the GFS early-stage prototypes. The H/B:ERT embodied carbon tool uses the University of Bath Inventory of Carbon and Energy (ICE) database 2011 (Hammond et al., n.d.). In the first phase of iteration 2, the H/B:ERT embodied carbon tool was selected because it enables the designer to rapidly test the embodied carbon emissions of different material options. H\B:ERT works by measuring the volume of all materials labeled in the Revit model (Bowles et al., 2021). H\B:ERT embodied carbon tool, then, classify the embodied carbon data into life cycle stages (Appendix C). Moreover, a circular product canvas, a visual diagram based on the circular business canvas was used to develop a circular

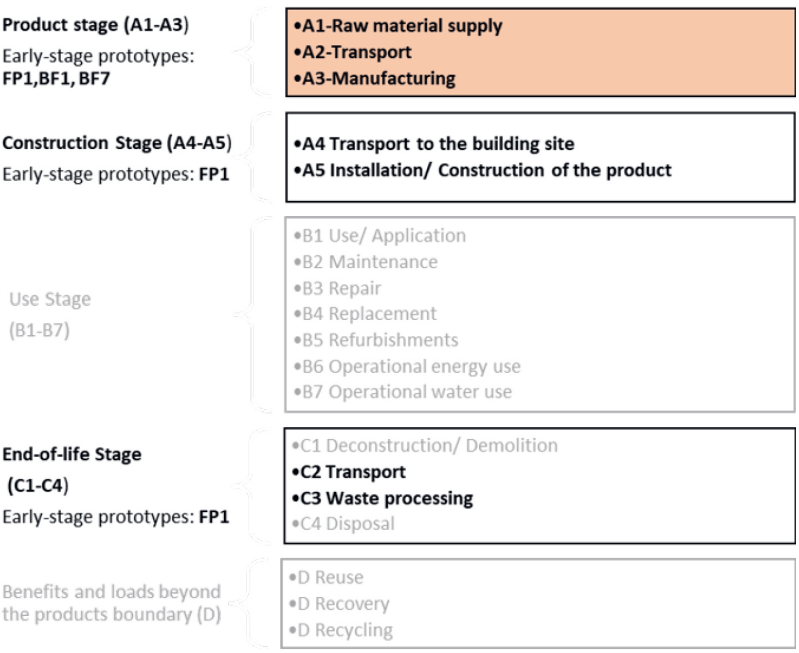


Figure 3-4. *System boundary for the LCA of the early-stage GFS prototypes. (Source: Author)*

product framework. A circular product canvas provides structure to designers to transform their products into a circular product alternative (van Stijn & Gruis, 2020).

Additionally, a LCA was conducted for the final most optimized early-stage GFS prototype (FP1) with the One Click LCA tool plug-in for Revit 2021, considering the production, construction and end of life stage (C2 Transport and C3 Waste processing). For the FP1 early-stage prototype the following environmental impact categories were considered: Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), Eutrophication Potential (EP), Abiotic Depletion Potential – Elements (ADPE), Abiotic Depletion Potential – Fossil fuels (ADPF), Use of net freshwater (FW), Primary Energy, renewable used as raw materials (PERM), Primary Energy Renewable Total (PERT), Primary Energy Non-Renewable Total (PENRT).

Testing involved the LCCA, LCA and a workshop to evaluate the GFS early-stage prototypes with the industry partner through the criteria assessment matrix used in the previous iteration. The prototype with the best score was selected to be optimized and further developed in the next iteration.

3.2.2.5 RTD: Iteration 3 – Hydrological and Structural performance

Iteration 3 was subdivided into two themes: hydrological and structural performance. These criteria were evaluated through hydrological tests to answer SQ3, and a structural test to answer SQ4. The layers of the GFS early-stage prototype were examined to understand their impact within the GFS-module and the facades of buildings (Figure 3-5). A 3D-GFS-printed mock-up was built by fitting together 3D-printed parts. Using 3D-printing technology has proven to use material more purposefully, therefore, minimizing waste material throughout the production process (Sarakinioti et al., 2018). The 3D-printed GFS mock-up was built at a 1:1 scale and was made of PLA (Polylactide) filament, an organic substrate and a degradable mat (Figure 3-6). The 3D-printed mock-up allowed hydrological and structural tests to be performed and helped identify hydrological and structural issues.

Hydrological testing was performed to evaluate water holding capacity and moisture content on two substrates, and the hydrological performance of the 3D-printed GFS mock-up. Regarding the former, first, samples of cork granulates and organic mixture were used and weighed to the nearest 0.01g. Second, the samples were saturated in water and weighted to the nearest 0.01g. Third, the samples were oven-dried at 100°C for 24 hours and weighed again to the nearest 0.01g. Lastly, the water-holding capacity and moisture content of two substrates (cork granulates, and organic mixture) was assessed by comparing the original weight, saturated weight and dry oven weight. The results of the water-holding capacity and moisture content of the cork granulates, and organic mixture were compared to other selected substrates (coconut fiber and stone wool)



Figure 3-5. *Virtual model of the layers and connections of the FP1 early-stage prototype (top image) and a visualization of the GFS early-stage prototype installed in a building (bottom image). (Source: Author)*

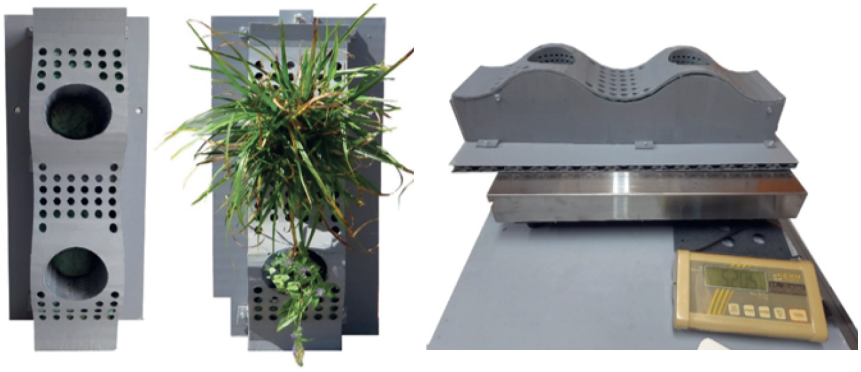


Figure 3-6. *The GFS early-stage prototype and its maximum weight when fully saturated. (Source: Author)*

in relation to their water-holding capacity, cost-effectiveness, and embodied carbon and employed again the assessment matrix previously used. Afterward, the 3D-printed GFS mock-up was filled with the best-performing substrate. Regarding the hydrological performance of the 3D-printed GFS mock-up, a drip irrigation system was installed to test the water retention, water distribution and maximum saturation weight.

Structural testing was performed to evaluate the structural performance of the 3D-printed GFS mock-up under maximum saturation weight to test critical water load conditions. Regarding the structural test, first, the GFS mock-up was weighed when dry. Second, with the drip irrigation system the GFS mock-up was irrigated until reaching maximum water saturation. Afterwards, the GFS mock-up was left to drain and irrigated until reaching maximum saturation again. The test was repeated three times to ensure the 3D-printed GFS mock-up did not fail or undergo large deformations during the full loading of water. It was necessary to test the structural performance of the 3D-printed material selected (PLA), and the thickness of the layers of the 3D-printed GFS mock-up regarding its structural purpose and maximum saturation weight. Additionally, a selection of porous substrates suitable for holding the plants in the mock-up were tested and analyzed through their binding capacity.

3.3 Results and Discussion

The results are presented in this section per research question considered in this study. The results obtained for each question are discussed by reference to previous GFS studies and comparable products in the market.

3.3.1 (SQ1) How do distinct types of systems influence the cost of GFS?

The literature review and market research revealed systems with different technologies, materials, characteristics and design trends of GFS in recent years. It was found that GFS innovations related to recent technology included GFS with active air purifiers, electricity generation and biomaterials ((CASE), n.d.; Bianco et al., 2017; Manso et al., 2013; Talaei et al., 2020)(Cortês, Almeida, et al., 2021). GFS innovations related to aesthetics and design included complex shapes developed through 3D-printing technology (Berardi, 2012; He et al., 2020)(Farinea et al., 2015). Moreover, the literature review and market research allowed to understand materials, design and construction requirements at an early-stage to evaluate feasible GFS design solutions. For instance, Manso et al. (2013) and Cortês et al. (2021) observed that the use of expanded cork boards reduced environmental impacts related to the materials of the GFS prototypes. Another study conducted by Mårtensson and Fransson (2015) investigated two GFS systems in which the system with rockwool panel showed a high-water holding capacity decreasing the risk of water runoff.

The literature review showed that there are many GFS products with a wide range of costs. For example, Santi et al (2019) showed that costs can vary from 150–1200 €/m^2 depending on the design. Based on this, the GFS costs were classified by typology to compare the GFS according to their characteristics. However, only GFS typologies relevant to the topic under research were taken into consideration such as GFS made of planter boxes, modular panels and felt pockets. These GFS typologies were used to compare the early-stage design costs. GFS made of planter boxes cost from 150–800 €/m^2 (Santi et al., 2019). GFS consisting of modular panels cost from 400–1,200 €/m^2 depending on the system and material (Perini & Rosasco, 2013; Santi et al., 2019). GFS made of felt pockets cost from 400–1,200 €/m^2 (Perini & Rosasco, 2013; Santi et al., 2019). Additionally, GFS made of felt pockets require energy to operate its irrigation pumps of water and nutrients continuously, which increases embodied energy and maintenance costs (Manso & Castro-Gomes, 2015).

The market research and literature review assisted in identifying the gaps in current GFS products regarding costs, embodied carbon, hydrological and structural performance. Based on the findings of the market research the first designs of the GFS early-stage prototypes were developed aligned to the criteria.

The results of the LCCA analysis (Appendix B) showed the design with the lowest materials and plant cost was the facade-based early-stage prototype (FP1) system, with a cost of €87.1/m^2 (Figure 3-7). Similar systems (considering the panels and plant species) cost around 130–200€/m^2 without installation and maintenance (Köhler, 2008; Perini & Rosasco, 2013)(Manfred Köhler and Cristian Rares Nistor, 2015). In the FP1 prototype, materials were 69% of the total costs, and the pre-grown plants were 31% (Figure 3-8). In the BF1 prototype, materials accounted for 57% of the total costs and plants (shrubs) 43%. For the BF7 prototype, materials accounted for 97% of the total costs, and the plant seeds 3% (Figure 3-8). The maximized use of recycled polyvinyl chloride (PVC) in the FP1 prototype and reduced use of steel, created a cost-effective prototype by reducing the acquisition costs of the raw materials. These results show that the direct costs of the GFS early-stage prototypes were influenced the most by the material followed by the plants selected. Huang et al (2021), obtained comparable results in a research conducted in Singapore, where the materials and plants contributed the most to the life-cycle cost when compared to other components. The results of two other studies have shown that the costs of GFS were influenced the most by the materials selected, the design complexity and the maintenance required by the plants (Perini & Rosasco, 2013; Perini & Ottelé, 2014).

GFS with complex systems have high installation costs and require more maintenance. Reduced installation costs can be achieved by a system of modular panels that are easy to assemble and disassemble (Bianco et al., 2017). To solve the high installation costs the FP1 prototype consists of a module

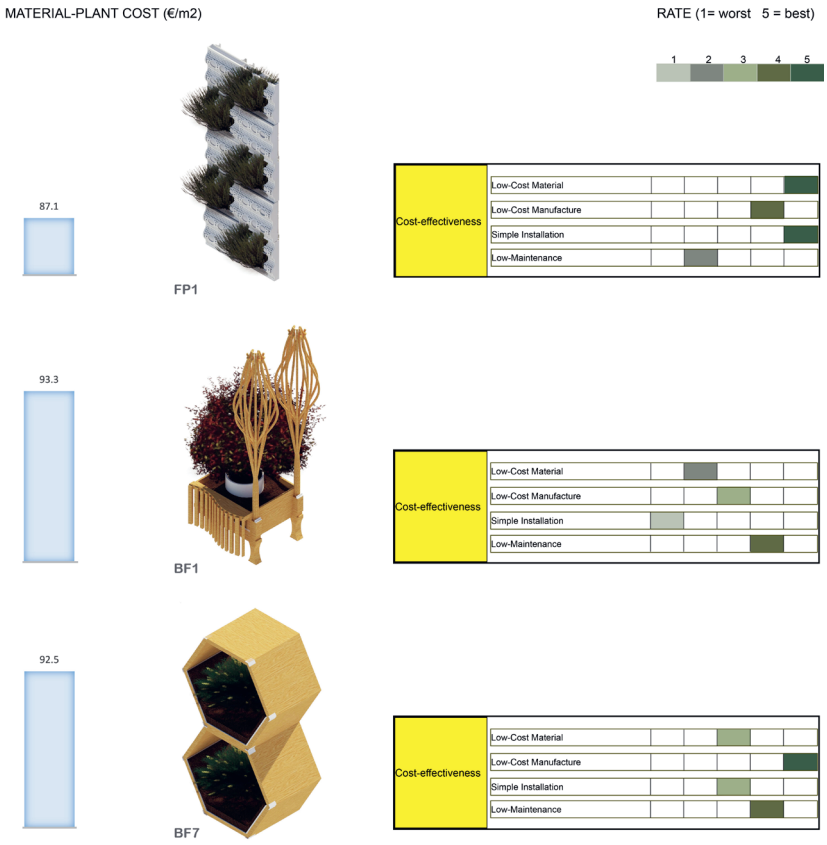


Figure 3-7. *Materials cost comparative graph and criteria matrix of the different typologies of GFS early-stage prototypes. (Source: Author)*

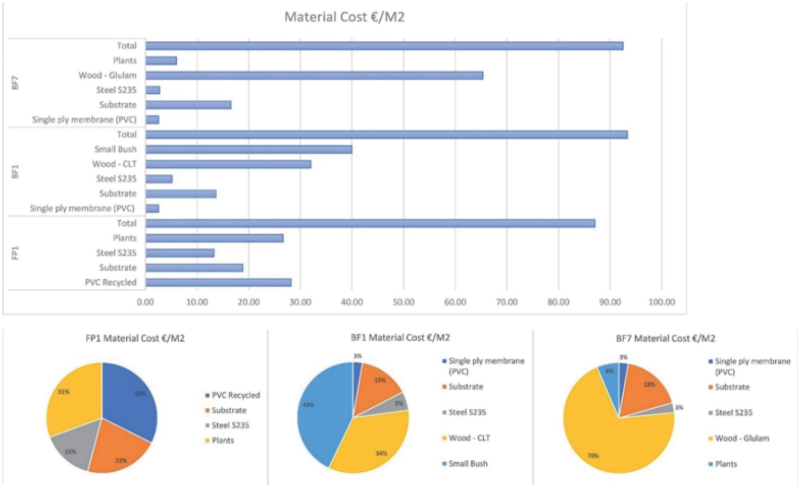


Figure 3-8. *LCCA results and comparison of material costs and percentages of 3 GFS typologies in the early-stage of the designs. (Source: Author)*

of 500mm x 500mm to reduce costs by decreasing the labor force time for installation. GFS can sustain a diverse range of plants but are also more costly to install than direct climbing plants and require regular maintenance because living plants need replacing during the life span of the system (Yoshimi, 2016). There have been cases in which improper maintenance of the GFS have had additional costs related to the plants (Huang et al., 2021; Papadopoulou, 2013). The GFS plug-in design strategy used in the FP1 prototype can reduce the maintenance costs by facilitating the removal of panels and the replacement of plants. Additionally, to reduce the costs of maintenance, plant species with reduced water and pruning needs should be selected.

The assessments made during the workshops with ZinCo experts revealed that the best performing GFS prototype was the facade-based FP1 due to its lightweight, easy assembly-disassembly, and modularity that makes it adaptable to the facade of a building. Light-weighted facade-based systems lowered costs through reduced dimensions of the structure and connectors (Figure 3-7). Additionally, this type of system has a higher degree of adaptability to buildings with load restrictions (older buildings), different geometric shapes, and can be installed on tall buildings. Balcony Forest BF1, from a technical point of view this prototype was not a viable solution due to weight issues and high costs. In turn, the Balcony Forest BF7 prototype was a less flexible system offering limited design options to architects. For these reasons, the facade-based FP1 prototype was selected as the best performing prototype.

Materials were identified as the most critical elements to lower the costs of the GFS early-stage prototypes. Plant choice, GFS typology and maintenance of the system were selected to further lower costs. Furthermore, costs were reduced by the easy installation and reduced maintenance of the plug-in system and R-strategies. Design for disassembly maximized the life of the GFS early-stage prototype (FP1) through the removal and replacement of GFS components. At the end of the product's life, the materials and components can be separated to be re-used, refurbished and recycled. This is of relevance as the design for future re-use can significantly reduce costs (Bakker et al., 2019; Kio & Ali, 2021).

3.3.2 (SQ2) How do distinct types of systems influence the embodied carbon of GFS throughout the production, installation and maintenance stages?

The simulations made in HBERT (Appendix C) suggest, from the early design stages, that materials and typology had the most influence on reducing the embodied carbon (Figure 3-9, 3-10). The recycled PVC material significantly decreased the total embodied carbon. The results are consistent with three GFS prototype studies developed in Portugal, Italy and the United States, that showed that the embodied carbon of GFS prototypes could be lowered by using lower embodied carbon materials, recycled materials and industrial waste (Manso et al., 2013; Bianco et al., 2017; Kio & Ali, 2021).

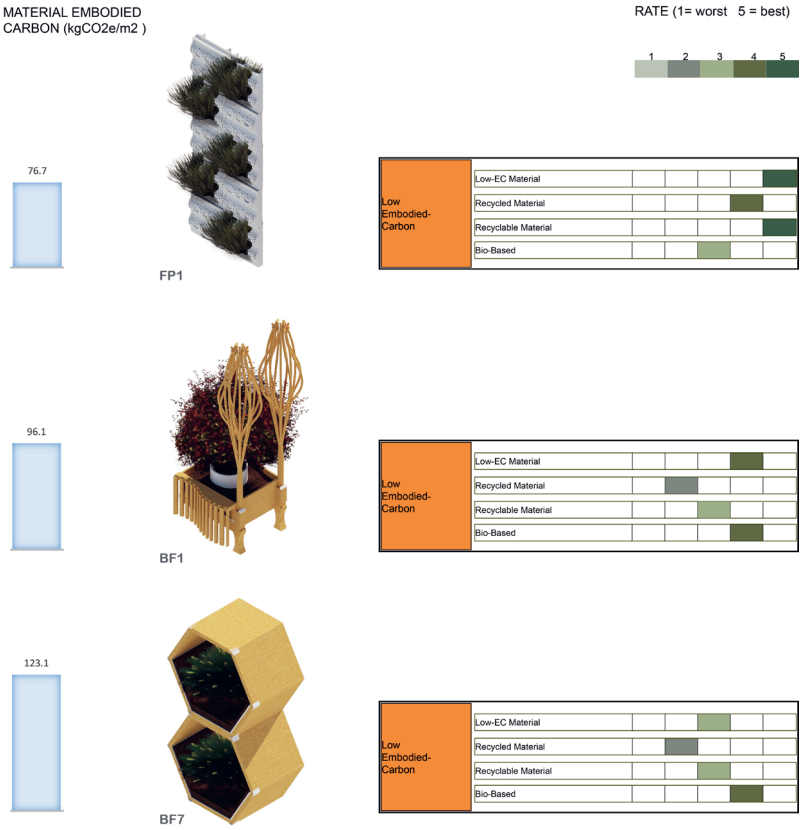


Figure 3-9. *Materials embodied carbon comparative graph and criteria matrix of different typologies of GFS early-stage prototypes (Source: Author)*

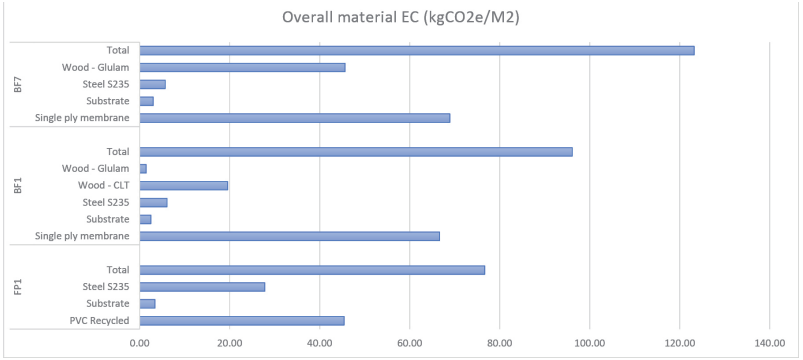


Figure 3-10. *LCA comparison of embodied carbon of 3 typologies of GFS in the early-stage of the designs. (Source: Author)*

3.3.2.1 Production Stage

Based on the LCA, the FP1 prototype had the lowest embodied carbon (Figure 3-9) as it consists of a combination of recycled material, biomaterials and design efficiency in material allocation. The results in this stage yielded GFS early-stage prototypes with lower embodied carbon from 76.7–123.1 $kgCO_2e/m^2$ (Figure 3-9, 3-10). The embodied carbon of similar systems can range from 141–147 $kgCO_2e/m^2$ in the material stage (Hui & Chung, 2015).

The FP1 prototype achieved lower embodied carbon by reducing the overall material used (dematerializing) and increasing the use of recycled PVC material in the design. The FP1 prototype considerably reduced the environmental impact by using biomaterials and recycled PVC. Additionally, PVC can be easily recycled, and is also recyclable allowing the material to be continuously circulating and in use. Furthermore, the components and materials of GFS have an impact on the environmental burden and environmental advantages (Perini & Ottelé, 2014). In a study comparing two types of GFS, the LCA shows that the main environmental impacts are associated with the production and use phase, which accounted for more than 80% of the total environmental impact in almost all the categories analyzed (Oquendo-Di Cosola et al., 2020a). Furthermore, the environmental impact results for prototype FP1 revealed that the manufacturing phase, associated to the materials, had the highest environmental impact (between 70% and 90%) in all the categories analyzed (Figure 3-11). Furthermore, in the manufacturing phase, the Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP) and Eutrophication Potential (EP) categories showed the highest impact in this phase (Figure 3-11).

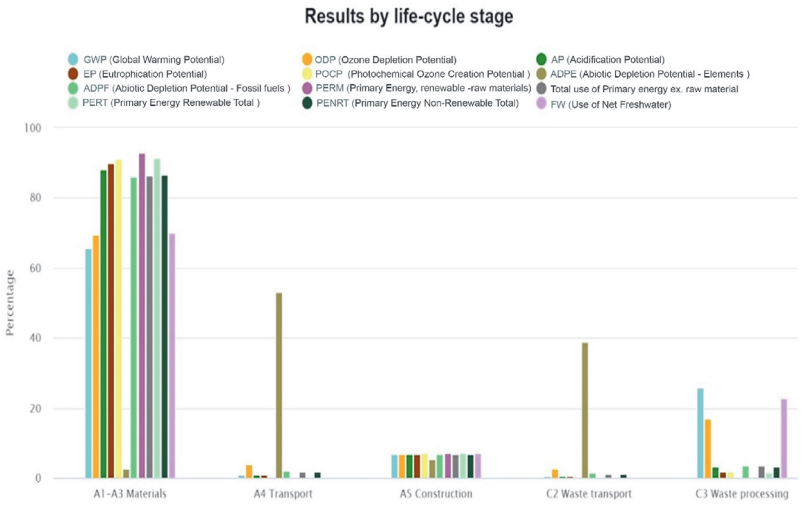


Figure 3-11. *LCA results of the environmental impacts potential by life-cycle stage of FP1 GFS early-stage prototype. (Source: Author)*

3.3.2.2. Installation Stage

The use of modular panels and supporting structure for the installation can decrease the waste of material, hence reducing the embodied carbon of the product (Appendix D). Moreover, previous research concluded lightweight materials reduce the embodied carbon by reducing the requirements of the structural loads (Manso & Castro-Gomes, 2015; Oquendo-Di Cosola et al., 2020). The above facts indicate that the embodied carbon of the structure of the GFS early-stage prototype (FP1) prototype is reduced by the low weight when fully saturated (52.57 kg/m^2) and its modular design (500mm x 500mm).

Additionally, the ease of assembly and disassembly in the structure maximized the life of the GFS early-stage prototype (FP1) by allowing to easily remove or replace parts of the GFS components (Figure 3-11), hence lowering its embodied carbon: at the end of the product's life, its materials and components can be separated to be re-used, refurbished or recycled. This is of relevance as previous research shows that the primary environmental burden in GFS depends on the materials used for construction (Ottelé et al., 2011, Oquendo-Di Cosola et al., 2020).

3.3.2.2 Maintenance Stage

The GFS maintenance includes pruning, feeding and watering plants, where the irrigation system must be planned to increase the subsistence of the plants (Loh, 2008a). The embodied carbon in the maintenance phase is mainly attributed to the use of fertilizers (Oquendo-Di Cosola et al., 2020). Meanwhile, the operational carbon and costs in the maintenance phase of the GFS are attributed to water consumption and pumps (Manso & Castro-Gomes, 2015; Ottelé et al., 2011; Perini & Ottelé, 2014). Therefore, selecting substrates with high water holding capacity reduces the water consumption throughout the GFS life, hence, reducing the operational carbon and costs of GFS.

3.3.3 (SQ3) How do distinct types of materials influence the hydrological performance of the GFS?

The highest ranked substrate was the organic mixture because of its low-embodied carbon (-1 kgCO_2e/kg), low costs (0.9 €/kg) and high-water holding capacity (86%) (Figure 3-12). The GFS mock-up (filled with the organic mixture) reached water saturation after 51 minutes and weighed 52.57 Kg/m^2. It was observed that the FP1 GFS early-stage prototype can store a large volume of water (13.1 l/m^2), therefore, reducing irrigation needs. In comparison, a study by Kew, Pennypacker, Echols (2014) observed a similar GFS retained an average of 4.8 l/m^2. GFS comprising felt layers have a low-water holding capacity (1.35 l/m^2), which results in frequent irrigation needs (Pérez-Urrestarazu et al., 2019), and has a high environmental impact due to the need for fertilizers and energy used to operate its water irrigation pumps (Manso et al., 2013; Oquendo-Di Cosola

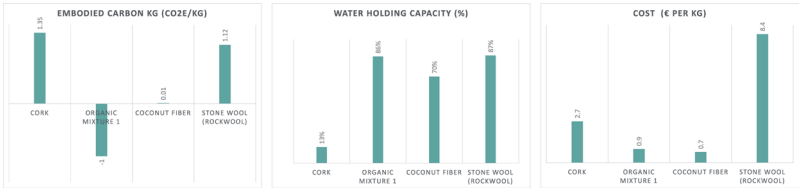


Figure 3-12. *Comparison of the percentage of embodied carbon, water holding capacity and costs of four substrates used in the GFS early-stage prototypes. (Source: Author)*

et al., 2020(Fernández-Cañero et al., 2012). Therefore, selecting a substrate with high-water holding capacity reduces the cost of irrigation, increases the plants' access to water, and the probability of plants thriving.

3.3.4 (SQ4) How do the selected materials influence the structural performance of the GFS?

A new modular GFS must ensure structural resistance to its own weight and support the maximum saturated weight. The 3D-printed GFS mock-up provided evidence on the overall structural behavior when reaching the maximum saturated weight (52.57 Kg/m^2). It was observed that the 3D-printed GFS mock-up withstands the maximum saturated weight transferring the water load and the applied water pressure amongst the 3D-printed components without failure or undergo large deformations. Therefore, the selected material (PLA), layer thickness (6mm) and material infill (40%) for the fabrication of the 3D-printed GFS mock-up generated a stiff, still lightweight structure. This is of relevance because the structural performance of the 3D-printed GFS mock-up can vary according to the chosen material.

Similar systems in the market weigh 40–150 Kg/m^2 (ANS Global; Modulo Green). The early-stage GFS prototype is in the lower range (52.57 Kg/m^2); therefore, it requires less structural material to support the maximum saturated weight. The results indicate the organic substrate due to its low bulk density reduced the weight of the GFS mock-up. This is of relevance because reducing the weight and material decreases the embodied carbon of the early-stage GFS prototype. Finally, it is worth noting the 3D-printed GFS mock-up provided evidence on the potentials and weaknesses of the prototype concerning hydrological and structural performance.

The construction of the FP1 GFS early-stage prototype constitutes the proof of the concept, as it demonstrated that it is possible to 3D-print a lightweight and material efficient GFS early-stage prototype capable to withstand the weight of the substrate under the maximum water saturation (Figure 3-13). In GFS, the weight of the substrate is critical to ensure structural stability of the GFS structure and building. Therefore, by selecting a lightweight substrate with high-water retention the weight of the system was reduced. Additionally, the

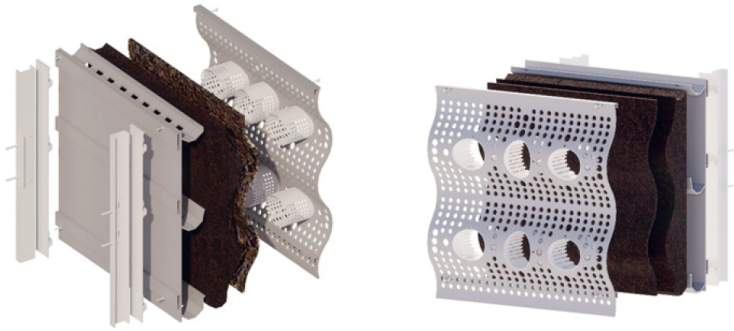


Figure 3-13. *Virtual model of the layers and connections of the FP1 early-stage prototype. (Source: Author)*

selection of a modular system consisting of lightweight materials for the FP1 GFS early-stage prototype improved the structural performance by allowing weight distribution and reducing the risk of overloading a building's structure.

3.4 Limitations

There are several limitations and constraints in this research. First, regarding the LCA there are difficulties in obtaining accurate data to be used in the life cycle inventory for the embodied carbon calculations of the early-stage GFS prototypes. To overcome this difficulty, various databases such as ICE embodied energy and embodied carbon database, EPDs and embodied carbon software were examined. Second, regarding the LCCA uncertainty and assumptions are considered for the analysis at the installation and maintenance stage of the early-stage GFS prototypes. For example, the maintenance costs including repair costs to the specific materials. Third, 3D-printing technology is a cost-effective tool for developing complex shapes but is time-consuming. For this reason, a single 1:1 scale module was 3D-printed for the GFS mock-up. However, it is recommendable to test the structural and hydrological performance on several 1:1 scale GFS modules.

3.5 Conclusion

This paper describes the RTD process to generate a new GFS early-stage prototype that meets the following criteria: low-embodied carbon, cost-effectiveness, hydrological and structural performance. This paper addressed the question: How to design a cost-effective and low-embodied carbon green facade system? To answer this question, the RTD consisted of addressing SQ 1-SQ 4 throughout three iterations. The first RTD iteration dealt with low-embodied carbon and cost-effectiveness categorized into three main GFS design typologies. In iteration 2, the designs were evaluated through a life cycle and cost analysis of three GFS typologies. Finally, in iteration 3, the hydrological and structural performance were tested as a 3D-printed GFS mock-up. The

results indicate the FP1 GFS early-stage prototype (Figure 2-13) is cost-effective and has low-embodied carbon in the production, installation and maintenance stages. Furthermore, it has been found the embodied carbon and the costs of the FP1 GFS early-stage prototype is lower when compared to other GFS products currently in the market.

Regarding SQ1, it was found the materials were the most influential aspects to reduce costs, specifically in the production stage. FP1 early-stage prototype had the lowest cost as it maximized the use of recycled polyvinyl chloride (PVC) and reduced the use of steel, therefore, reducing the acquisition costs of the raw materials. Regarding SQ2, materials and GFS typology had the most influence in decreasing the embodied carbon of the GFS systems analyzed in the production stage. In the installation and maintenance stage, the reduction of the embodied carbon and costs was achieved through the ease in assembling-disassembling (plug-in). FP1 early-stage prototype had the lowest embodied carbon as it consists of a combination of recycled material, biomaterials and design efficiency in material allocation. Regarding SQ3, the substrate (organic mixture) minimized the irrigation requirements and provided optimal conditions for plants to grow through high water holding capacity (13.1 l/m^2). Regarding SQ4, the selected material (PLA) and layer thickness influence the structural performance of the GFS positively. In addition, the 1:1 scale GFS mock-up was able to withstand the maximum saturated weight resulting in structural robustness. Additionally, the selection of a modular system consisting of lightweight materials improved the structural performance by allowing weight distribution and reducing the risk of overloading a building's structure.

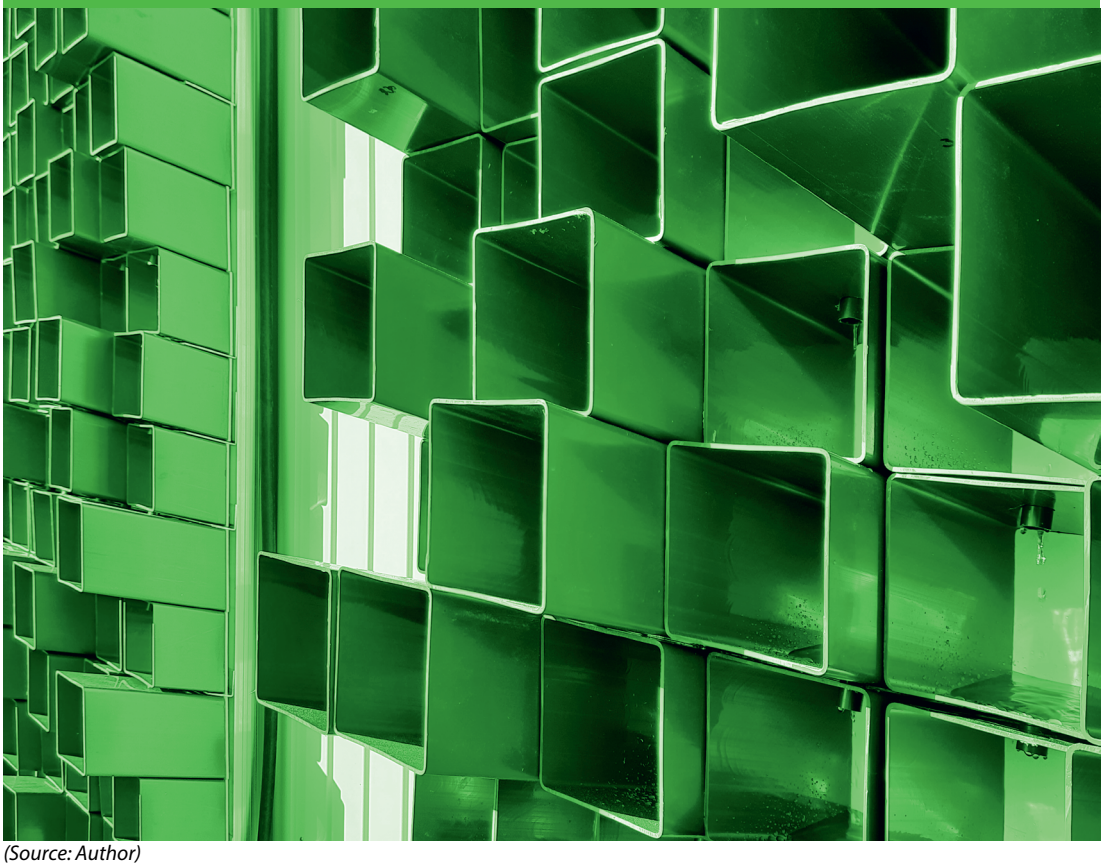
The final design is a modular, cost-effective and low-embodied carbon GFS early-stage prototype (Figure 2-13). It was found that the selected materials (recycled), plants, substrate (with high-water holding capacity), GFS typology (Facade-based with a light structure) and its fixing system (modular) lowered the costs and the embodied carbon of the FP1 GFS early-stage prototype (Figure 2-13).

To design a cost-effective and low-embodied carbon green facade system it is necessary to test and compare materials, GFS typologies, substrates, and fixing systems. It is also necessary to cross-examine economic and environmental benefits with a LCCA and LCA to overcome economic and environmental limitations in GFS. Additionally, future studies should also expand on how RTD can assist with creating cost-effective and low-embodied GFS products, particularly in the context of a circular economy. Finally, these results can guide designers, architects and GFS manufacturers in creating efficient cost-effective and low-embodied carbon GFS prototypes.

The prototype developed did not yet address criteria of importance such as visual impact and the enabling of different habitats (serving plants and small animals). Likewise, the micrometeorological effects of the final GFS prototype should be assessed.

4

Plant Pixel: an optimized bio-inspired living wall system



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4

Highlights

- Innovative research through design is conducted to develop a bio-inspired, low-embodied carbon, and cost-effective modular living wall prototype.
- A life cycle and cost analysis are employed for optimizing Plant Pixel, a modular living wall prototype.
- Evaluation of a full-scale mock-up (500 modules and plants) to test hydrological and structural performance, ease of assembly-disassembly, and plant performance.
- Recycled materials and a high-water holding substrate reduced embodied carbon emissions (66.7 $kgCO_2e/m^2$) and improved performance.
- Lower material costs (256.1 $€/m^2$), positioning Plant Pixel as a cost-effective modular living wall prototype.

Abstract

Current Modular Living Wall Systems (MLWS) have many benefits but are often also characterized by high costs, high-embodied carbon and short life span materials. To address these issues a bio-inspired MLWS prototype was developed: Plant Pixel. The prototype aimed at improved performance on criteria: low-embodied carbon, hydrological and structural performance, plant performance, simple assembly-disassembly and cost-effectiveness. The Plant Pixel was built in a full-scale mock-up comprising 500 modules and 500 plants. It was found that the selected recycled materials (recycled PVCU, recycled textile, and recycled aluminum), a high-water holding capacity (61.0 l/m^2) substrate, low-maintenance plants, and a plug-in fixing system, reduced embodied carbon (66.7 $kgCO_2e/m^2$) and improved the hydrological and structural MLWS performance. Additionally, the Plant Pixel prototype had lower material costs (256.1 $€/m^2$) compared to other MLWS products. The Plant Pixel prototype met all the design criteria and exhibited the potential to become a marketable product.

Keywords: Climate adaptation; green Facade system; embodied carbon; prototype; research through design

4.1 Introduction

Green Facade Systems (GFS) have gained popularity to mitigate adverse climate effects in high-density urban areas, particularly heat stress(Loh, 2008c; Pérez-Urrestarazu et al., 2015). The implementation of VGS has been encouraged in numerous cities worldwide, motivated by the varied climatic, environmental, and social benefits of vegetation (Huang et al., 2019; Wong et al., 2009, 2010). Previous research has demonstrated a positive correlation between VGS and a decrease in outdoor temperature (Djedjig et al., 2015; Susorova et al., 2014; Tan et al., 2014). VGS are a vital component of urban green infrastructure that can lessen the urban heat island phenomenon (Bianco et al., 2017), regulate urban microclimates and lead to improved outdoor thermal comfort (Chen et al., 2013). For example, the mean radiant temperature in the street canyons can decrease by 4°C due to VGS (Djedjig et al., 2015).

Researchers categorize green facade systems into two primary types based on vegetation and supporting structure: green facades and living wall systems (Loh, 2008; Pérez-Urrestarazu et al., 2015; Manso & Castro-Gomes, 2015; Ottelé et al., 2011). Green facades employ climbing or hanging plants, divided into direct and indirect systems (Figure 4-1). In direct systems, plants are attached to walls, either rooted in the ground or in planters. In comparison, indirect systems make use of additional structures like wire rope nets, metal meshes and modular trellises.

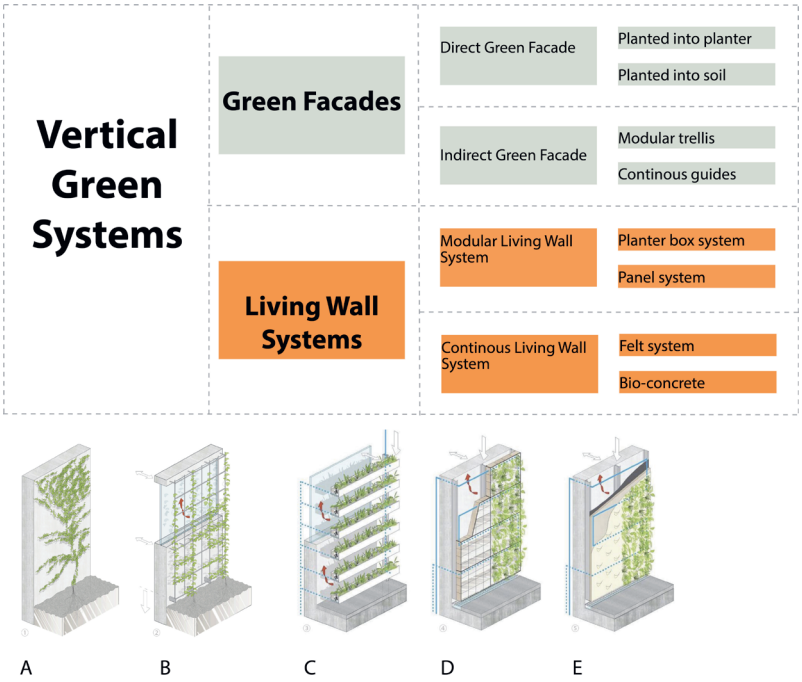

Figure 4-1. *Overview of the classification of the vertical green systems (top). Pfoser (2016) depicts different vertical green systems: (A) Direct green facade, (B) Indirect green facade, (C) Planter box system, (D) Panel system, and (E) Felt system. (Source: Author)*

Living Wall Systems (LWS) comprise different support structures that allow plants to grow without being rooted at ground level (Manso & Castro-Gomes, 2015; Charoenkit & Yiemwattana, 2016). Plants are pre-cultivated and then installed, providing varied design and plant options (Manso & Castro-Gomes, 2015; Ottelé et al., 2011). Living wall systems are further classified into Modular Living Wall Systems (MLWS) and Continuous Living Wall Systems (CLWS) (Pérez et al., 2011; Manso & Castro-Gomes, 2015; Ottelé et al., 2011). Continuous living wall systems, pioneered by Patrick Blanc, use synthetic felt layers with pockets to insert the plants (Susorova, 2013). A recent innovation in continuous systems is the introduction of bio-concrete.

Modular living wall systems comprise a modular container system, growth substrate, waterproof layer, supporting frame, and irrigation system (Loh, 2008; Manso & Castro-Gomes, 2015). Modular living wall systems can be classified into panels or planter box systems (Manso & Castro-Gomes, 2015; Charoenkit & Yiemwattana, 2016). Recent innovations in the design of modular living wall systems incorporate the use of 3D-printing to produce complex shapes (Berardi, 2012; He et al., 2020).Notably, MLWS offer improved energy efficiency and microclimate benefits because of the use of additional layers of materials and the substrate (Perini et al., 2011; Wong et al., 2010).

Despite the many developments in MLWS research and development in the past few decades, current MLWS are associated with a number of issues that remain understudied: low-embodied carbon, hydrological and structural performance, plant performance, simple assembly-disassembly and cost-effectiveness.

First, many MLWS designs do not consider low-embodied carbon, reused or recycled materials and designers of MLWS underestimated the importance of material selection for environmental performance (Perini & Ottelé, 2014). The production phase related to the use of materials and the usage phase are the main contributors to MLWS environmental impact (Oquendo-Di Cosola et al., 2020). Therefore, choosing low-embodied carbon, reused or recycled materials is key to improving MLWS environmental performance. Additionally, to minimize embodied carbon, it is important to balance material longevity and functionality, especially for lifespans of 50 years and longer.

Second, MLWS can pose an economic and environmental challenge concerning water consumption due to their high-water requirements (Manso & Castro-Gomes, 2015; Ottelé et al., 2011; Perini & Ottelé, 2014). MLWS with high-water retention substrate can hold more water for a longer time, reducing the need for frequent watering and ensuring the survival of plants (Manso & Castro-Gomes, 2015; Ottelé et al., 2011; Perini & Ottelé, 2014). However, few MLWS studies focus on different substrates that can ensure optimal water retention and water distribution.

Third, MLWS entail structural challenges due to weight issues in water-saturated conditions (Manso & Castro-Gomes, 2015; Bianco et al., 2017). Nevertheless, little attention has been paid to testing the structural performance of new materials and the mechanical strength needed to bear the weight of the substrate under the maximum water saturation weight (Bianco et al., 2017).

Fourth, plants in MLWS face challenges like competition and limited resources. When selecting plants, it is important to consider climate fitness and native species (Bustami et al., 2019). Compatibility with the chosen substrate is also vital for successful plant performance. However, few studies have evaluated the plant's performance on MLWS.

Fifth, MLWS lack simple assembly and disassembly processes, a crucial factor to align with circular economy principles. Circular economy principles focus on resource efficiency and closed-loop systems to create a sustainable, low-carbon society (Prieto-Sandoval et al., 2018; Suchek et al., 2021). Simple assembly and disassembly allow for separating MLWS components for reuse, refurbishment, and recycling. However, there is a gap in MLWS studies addressing simple assembly and disassembly to promote a circular use of materials.

Sixth, MLWS are often too costly due to high installation, operation and maintenance costs (Manso et al., 2018; Ottelé et al., 2011; Perini & Rosasco, 2013). The high costs associated with MLWS are mostly due to the need for the replacement of support panels, irrigation systems and plant maintenance(Perini & Rosasco, 2013).

We assumed that MLWS designs can be optimized (i.e. address the issues above) by following bio-inspired morphological principles to improve hydrological, structural and plant performance. Principles derived from steep rock walls (e.g., gorges, cliffs, canyons and rock formations in high-altitude mountains), as the morphology of these natural structures enables vegetation to grow despite adverse microclimatic conditions (Larson et al., 2009). Furthermore, the verticality, colors and patterns created by the various minerals, rock shapes and vegetation found in steep rock walls can enrich the aesthetical appeal of MLWS. Apart from that, we assume that an easily (dis-) mountable modular system can be beneficial for reducing embodied carbon and costs.

Motivated by these needs and potentials, this paper addresses the question: How to design an optimized bio-inspired living wall system? To answer this question, the following sub-research questions (SQ) are set:

- (SQ1) How much do recycled materials reduce the embodied carbon of MLWS?
- (SQ2) How much do recycled substrates influence the hydrological performance of MLWS?
- (SQ3) How do lightweight materials influence the structural performance of MLWS?

- (SQ4) How do low-maintenance plant species perform regarding survival rates in a bio-inspired MLWS?
- (SQ5) How do the materials selected and the design for simple assembly-disassembly influence the cost of a bio-inspired MLWS throughout the production, installation and maintenance stages?

To address these questions, a bio-inspired MLWS prototype developed as part of the project "Solutions for Outdoor Climate Adaption (SOLOCLIM)". This MLWS prototype was developed with research through design (RTD): an iterative design and testing process anchored on clear performance criteria cutting across the academic and industrial sectors (Cortesão & Lenzholzer, 2022). RTD was used throughout the designing, manufacturing, construction and verification of a full-scale MLWS prototype built in Germany. This MLWS prototype was named *Plant Pixel*.

This paper starts by presenting the RTD process and methods employed to design and build *Plant Pixel* as a full-scale mock-up. Subsequently, the results obtained are presented and discussed by reference to previous MLWS studies and comparable MLWS products in the market. The paper concludes by recommending strategies to create bio-inspired optimized MLWS prototypes that address the issues of low-embodied carbon materials, improved hydrological performance, improved structural performance, improved plant performance, simple assembly-disassembly, and cost-effectiveness.

4.2 Methods

RTD was selected for this study because it has proven resourceful in developing innovative design knowledge and solutions (Cortesão & Lenzholzer, 2022; Lenzholzer et al., 2013). In RTD, multiple designs are created and tested through an iterative process until an effective design solution is reached (Lenzholzer, 2010). RTD was founded on a structured approach to learning and designing originated from practice (Godin & Zahedi, 2014) that supports the cooperation between academia and industry. This cooperation was essential for conducting this study: developing an evidence-based, market-driven MLWS product.

The RTD process comprehended four steps, divided into two iterations (A-B) of designing and testing the designs, focused on the following criteria: low-embodied carbon, hydrological and structural performance, simple assembly-disassembly, plant performance and cost-effectiveness (Figure 4-2). Steps I and II represent the first iteration. Step I dealt with the design of the MLWS prototype, inspired by the morphological characteristics of natural steep rock walls. Step II, the MLWS designs inspired by steep rock walls were evaluated for low-carbon materials, hydrological performance and structural performance using trial mock-ups. Embodied carbon was tested with the Life Cycle Assessment Index, while hydrological and structural performance were tested with water retention, water distribution and maximum water saturation weight.

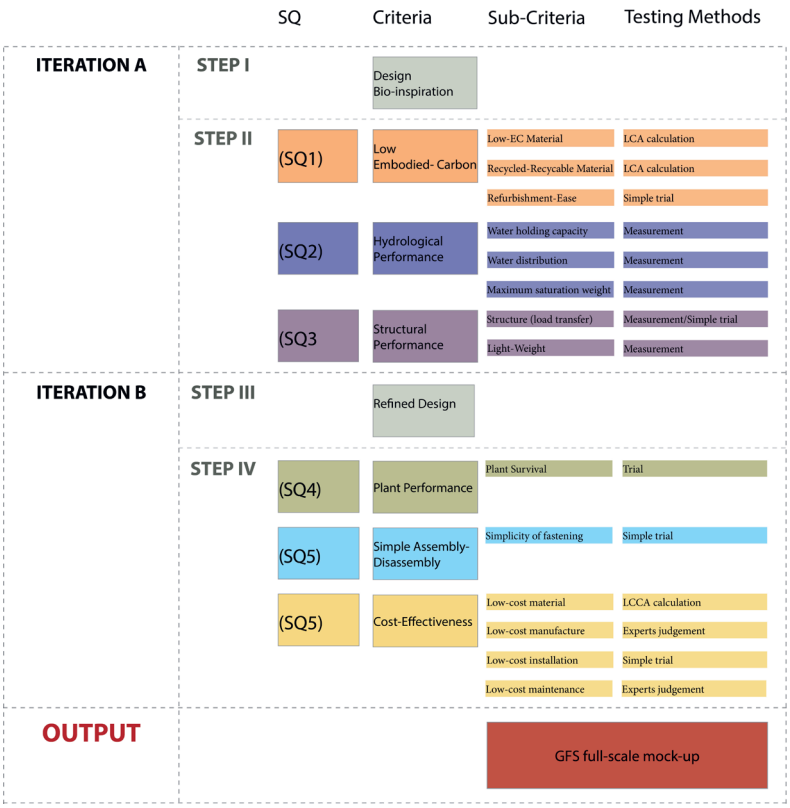

Figure 4-2. *Overview of the RTD methodology employed in this study. (Source: Author)*

Similarly, steps III and IV represent the second iteration. Step III, the MLWS prototype was further refined to enhance assembly-disassembly processes and plant species selection. The optimized MLWS was implemented in a full-scale mock-up comprising 500 modules and 500 plants, built in Wolfschlugen, Germany. In Step IV, the full-scale mock-up was tested for plant performance, simple assembly-disassembly and cost-effectiveness. The evaluations entailed assembly-disassembly trials, plant survival rate assessment, and an LCCA of the full-scale mock-up. The LCCA included the manufacturing, installation and maintenance phases.

4.2.1 RTD: Step I – Design (Bio-inspiration in natural steep rock walls)

The focus of step I was to generate initial MLWS designs inspired by nature. Nature has developed strategies to overcome the environmental challenges to which it is exposed (Magna et al., 2013). Thus, taking inspiration from nature can be useful to optimize MLWS products. Bio-inspiration is the study and imitation of the form, function, kinetic mechanism, growth process, methods, materials and structure of natural elements (López et al., 2017) and facilitates design,

creates innovative solutions and optimizes geometry by mimicking nature (Helms et al., 2009; Lienhard et al., 2011; Magna et al., 2013; Sheil et al., 2011; Schleicher et al., 2015).

The initial MLWS designs were inspired by the morphology of steep rock walls (e.g., gorges, cliffs, canyons and high-altitude mountains). Steep rock walls were selected as their geometry enables vegetation to grow despite adverse microclimatic conditions (Larson et al., 2009). Investigations for bio-inspiration preceded the design development and included the identification of morphological principles that could be abstracted from steep rock walls and transferred to the design of MLWS. The morphology of steep rock walls was examined to address the aesthetics, design effectiveness and survival of plants in MLWS. The hydrological and structural properties of steep rock walls were also investigated as an inspiration for plant survival in extreme climatic conditions. This examination process was divided into three stages:

- *Fieldwork*. In this stage, areas in the German and Austrian Alps were selected and visited to investigate vertical plant growth in steep rock walls in harsh environments. Photographic data was collected at various elevations to identify vegetation cover and density patterns between steep rock faces and plants.
- *Identification of morphological principles*. The morphological principles of the steep rock walls examined in the previous stage were abstracted and translated into the design of the MLWS designs. This was performed by analyzing the photographs taken during the fieldwork with the ImageJ program (an image-processing software for scientific image analysis and editing). The ImageJ software was used to analyze the following parameters: geometry, percentage of vegetation coverage, and pattern of steep rock walls. The analysis results of these parameters served as the basis for all subsequent designs.
- *Parametric design*. This consisted of generating MLWS designs inspired by the morphology of steep rock walls. The principles retrieved in the previous stage were abstracted to develop computer-assisted designs (Figure 4-3). BIM (Building Information Modelling) working environment, namely the software Revit, was used to transfer the morphology principles. The Dynamo plug-in for Revit was used to address the irregularity found on steep rock walls. The Dynamo plug-in facilitates shape optimization and parametric modeling, which was needed to simulate the complex geometry and patterns of steep rock walls. Various geometrical shapes (square, hexagon, triangle, rectangular) and parameters (length, width, height, scale) were employed to experiment with different design options. The MLWS design best meeting the criteria of this study (low-embodied carbon, hydrological and structural performance, plant performance, simple assembly-disassembly and cost-effectiveness), was further refined in subsequent iterations (Figure 4-4).

After evaluating the nine designs, the P6 prototype, later named Plant Pixel, was selected to be refined in the subsequent iterations.

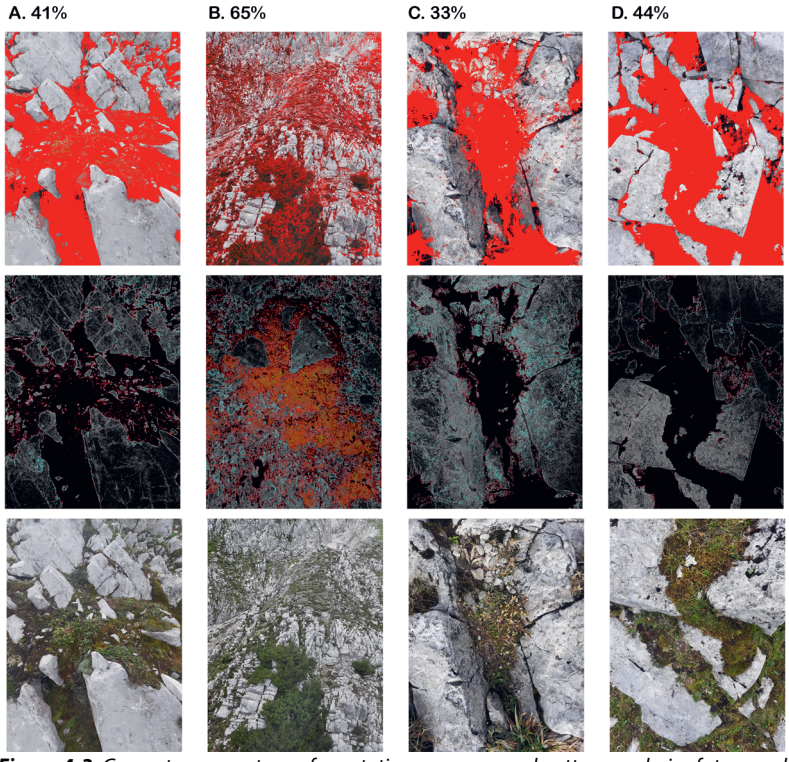

Figure 4-3. *Geometry, percentage of vegetation coverage, and pattern analysis of steep rock walls collected during the field work and processed with ImageJ. (Source: Author)*

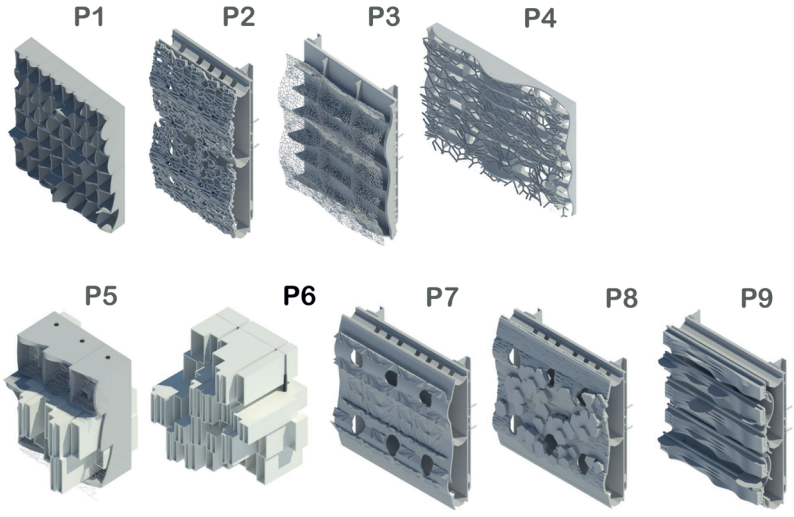

Figure 4-4. *MLWS parametric designs inspired by the morphology of steep rock walls. (Source: Author)*

4.2.2 RTD: Step II – Testing: Low-embodied Carbon Material, Hydrological and Structural Performance

Step II aimed at selecting low-embodied carbon materials with suitable hydraulic and mechanical properties for the bio-inspired MLWS prototype. The main environmental impacts of MLWS are associated with the selection of the materials (Oquendo-Di Cosola et al., 2020). Low-embodied carbon or recycled-recyclable materials can reduce carbon and improve circularity (Gaustad et al., 2018; Suchek et al., 2021). Hence, opting for low-embodied carbon and recycled materials for the MLWS prototype was crucial to offset their environmental impact. The MLWS designs developed incorporated this principle. The low-embodied carbon materials were evaluated with the life cycle analysis (LCA) index to answer SQ1. Materials were further evaluated through hydrological tests, to answer SQ2, and a structural test to answer SQ3. Two trial mock-ups were manually fabricated from 2.5mm PVCU extruded square profiles during this phase. The trial mock-ups were made to test water retention, storage capacity, distribution, maximum dry weight and maximum saturated weight (Figure 4-5, 4-6).

The substrate layer incorporated the following properties: lightweight, low-embodied carbon materials with high hydraulic potential. Suitable materials were: recycled synthetic fibers (polyester), recycled non-woven geotextile fibers,

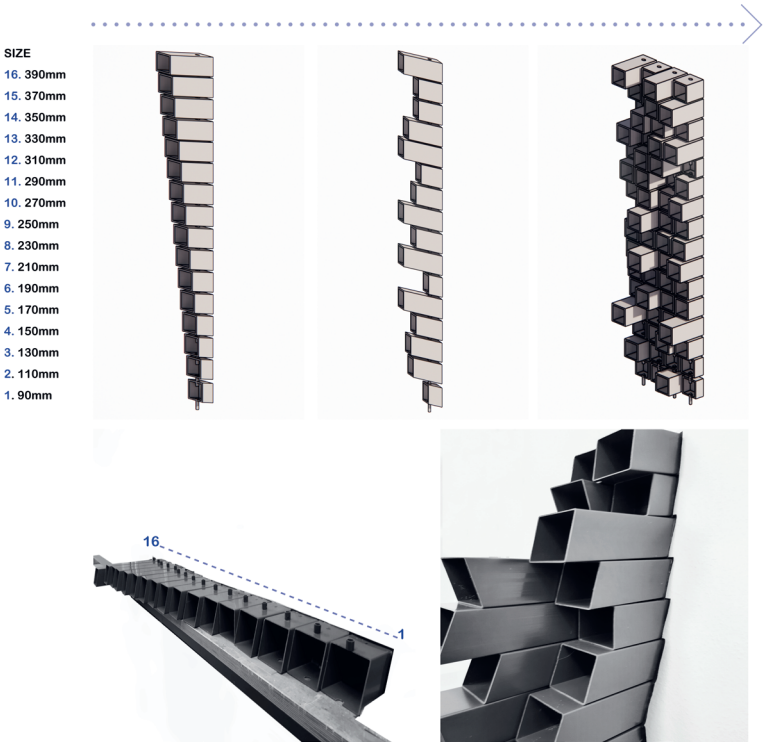

Figure 4-5. *Tested square profile modules and their lengths. (Source: Author)*



Figure 4-6. *Visualizations of the water distribution on the substrate for the hydrological tests performed on the MLWS trial mock-ups. (Source: Author)*

recycled textile fibers (acrylic, cotton, wool mixture), coco, stone wool and glass wool. The following lightweight, low-embodied carbon, water and weather-resistant materials were selected for the external layer: recycled PVC, PVCU, ABS and recycled HDPE. For the structural layer and fastening components, the properties were: low-embodied carbon, water, weather-resistant and able to withstand the weight of the substrate and the plants and accordingly the materials were selected: recycled steel, recycled aluminum and stainless steel.

The life-cycle analysis index was used to collect data on the embodied carbon attributed to materials during the manufacturing phase. For this phase, the Inventory of Carbon and Energy (ICE) database and EPDs (Environmental Product Declarations) literature, data sheets and H/B:ERT embodied carbon software were used to compare the selected materials. H/B:ERT embodied carbon tool plug-in for Revit 2022 software was used to assess the embodied carbon impact of the *Plant Pixel* prototype. The H/B:ERT embodied carbon tool

uses the University of Bath Inventory of carbon and Energy Circular Ecology (ICE) database 2011 (Hammond et al., n.d.). Regarding mechanical properties of the materials, literature, data sheets and information obtained from manufacturers were used to compare the selected materials. Testing was based on the values of embodied carbon, hydrology and mechanics from Tables 4-1 and 4-2. Testing also included expert judgments by R&D industry experts.

Table 4-1. *LCA index, density and hydraulic conductivity of different substrates considered for the MLWS prototype.*

Material: Substrate layer	Density (kg/m^3)	Embodied Carbon ($kgCO_2e/kg$)	Hydraulic conductivity (m/s)
Synthetic fiber TSM 32 polyester	NA	0.23	10^-7
Non-woven geotextile SSM 45	NA	0.2619	10^-7
Recycled textile fibers (acrylic, cotton, wool mix)	53,3	0.1	10^-7
Coconut Coir	100-150	0.01	10^-3
Stone wool	30-180	1.05	10^-5
Glass wool	13-100	1.35	10^-6

Table 4-2. *LCA index and mechanical properties values for the external layer, structural layer and fastening components considered for the design of the MLWS prototype.*

Material: External layer	Density (kg/m^3)	Embodied Carbon ($kgCO_2e/kg$)	Compressive Strength (Mpa)	Compressive Modulus (Gpa)	Tensile Strength (Mpa)	Tensile Modulus (Gpa)	Elongation at break (%)	Durability (years)
PVCU Recycled	1380	0.90-2.00	NA	NA	NA	NA	NA	NA
PVCU	1350-1450	2.50	65	1.50-3.50	55	3.00	15-60	50
PVC	1380	2.41	55-89	2.80	35-60	2.40-4.00	10-40	50
ABS	1115	3.10	60-80	2.50	30-45	1.00-2.50	20-50	20
Polyethylene (HDPE)	970	1.93	35-50	1	30-40	0.50-1.10	500-700	50
Material: Structural Layer	**Density (kg/m^3)**	**Embodied Carbon ($kgCO_2/kg$)**	**Compressive Strength (Mpa)**	**Compressive Modulus (Gpa)**	**Tensile Strength (Mpa)**	**Tensile Modulus (Gpa)**	**Elongation at break (%)**	**Durability (years)**
Steel (S235)	7800	2.73	370-470	160-190	360-510	190-210	23	50
Recycled steel	7800	0.43	370-470	160-190	360-510	190-210	23	50
Stainless steel (304)	7800	6.15	205-310	193	515	193	45	50
Aluminum (6061-T6)	2700	8.24	570	45-96	276	71.7	11-13	50
Recycled Aluminum alloy (7075-T6)	2700	1.69	487	45-96	250	NA	9.4	50

Material: Fastening components	Density (kg/m^3)	Embodied Carbon ($kgCO_2e/kg$)	Compressive Strength (Mpa)	Compressive Modulus (Gpa)	Tensile Strength (Mpa)	Tensile Modulus (Gpa)	Elongation at break (%)	Durability (years)
Stainless steel (304)	7800	6.15	205-310	193	515	193	45	50
Aluminum (6061-T6)	2700	8.24	570	45-96	276	71.70	11-13	50

The materials with the best properties, including density, embodied carbon, compressive strength, tensile strength and durability, were selected to build two trial mock-ups. These mock-ups were used to evaluate the material choices and designs regarding hydrological and structural performance. The trial mock-ups were subdivided into two: trial mock-up 100 and trial mock-up 120 (Figure 4-6). Trial Mock-up 100 comprised square profiles with a width of 100 mm and lengths ranging from 90mm to 390mm, with a height of 1800mm. Similarly, Trial Mock-up 120 comprised square profiles with a width of 120mm, maintaining the same length and height as the former. Testing involved 16 different lengths, spaced at intervals of 20mm (e.g., 90mm, 110mm, 130mm, …, 390mm).

Hydrological testing of both types was performed to evaluate the water retention (l/m^2), water storage capacity (Vol%), and water distribution on four substrates. The selected substrates were recycled synthetic fiber (polyester), recycled non-woven geo-textile fiber, recycled textile fiber (acrylic, cotton, wool mix) and coconut coir substrates. Inorganic substrates with the exemption of the coconut coir were selected because these substrates are durable and lighter compared to organic substrates(Graceson et al., 2014; Ju et al., 2016;Raviv and Leith 2008). Hydrological testing was performed on the PVCU in the external layer of the trial mock-up for watertightness.

Structural testing was performed on the trial mock-ups (1) to evaluate the maximum dry weight (kg/m^2) and maximum saturated weight (kg/m^2) of the trial mock-ups, (2) the size of the PVCU square profile aperture regarding its structural function and maximum saturation weight, and (3) the capacity of the aluminum profiles to withstand the maximum saturated weight and their impact on the facade of buildings. To this end, the trial mock-ups were first filled with the selected substrates when dry and weighed using a scale accurate to the nearest 0.01g. Second, a drip irrigation system was installed at the top of the structure. Third, the samples were irrigated until reaching maximum water saturation and weighted accurately to the nearest 0.01g. Visual inspections were conducted on the four substrate layers (to appraise the presence of water moisture in the substrates to determine water distribution) and the PVCU external layers (to appraise the presence of water drops on the exterior to ensure water tightness). Fourth, the trial mock-ups were left to drain and were irrigated until reaching maximum saturation again to compare the weight of the four different substrates, to assess whether the trial mock-ups did not fail or undergo large deformations during the full loading of water.

The maximum saturated weight was tested on 4 iterations of Trial Mock-up 120 (1 for each substrate), and 1 iteration of Trial Mock-up 100. Therefore, 5 different columns with a height of 1800mm were tested (4 for the 120mm mock-up and 1 for the 100mm mock-up). Each column comprised 16 different lengths, spaced at 20mm intervals (e.g., 90mm, 110mm, 130 mm, …, 390mm). A visual inspection was conducted to check the water distribution on the substrate (Figure 4-6). Afterwards, simulations and calculations were performed using SkyCiv structural analysis software to assess the thickness of the secondary 15-degree aluminum profile. Factors such as deflection, stress limits, and material strength were examined to validate the structural integrity of the secondary 15-degree aluminum profile.

This process was applied for the trial mock-ups and the four substrates selected. The results obtained for the substrates were evaluated with a decision matrix which allowed comparing the embodied carbon of the chosen materials and their hydraulic and mechanical properties (i.e., water retention, water capacity, water distribution and the substrates' maximum saturated weight).

4.2.3 RTD: Step III – Refined Design

Step III involved identifying suitable plant species for the MLWS. Additionally, in this phase, the designs were refined to simplify the assembly and disassembly of the square profile modules. In June 2022, the *Plant Pixel* full-scale mock-up was constructed on the south and west walls of a container in Wolfschlugen, Germany. The west and south facades were selected for their high solar radiation exposure, which influences plant growth. The full-scale mock-up included 500 square profile modules and 500 plants, divided into *Plant Pixel* 1 (110mm to 210mm module lengths) and *Plant Pixel* 2 (150mm to 310mm module lengths). Both variations, each 1200mm wide and 2400mm high, were installed on the container's south wall. Additionally, *Plant Pixel* 1 was installed on the west wall, measuring 600mm in width and 2400mm in height (Figure 4-7,4-8).

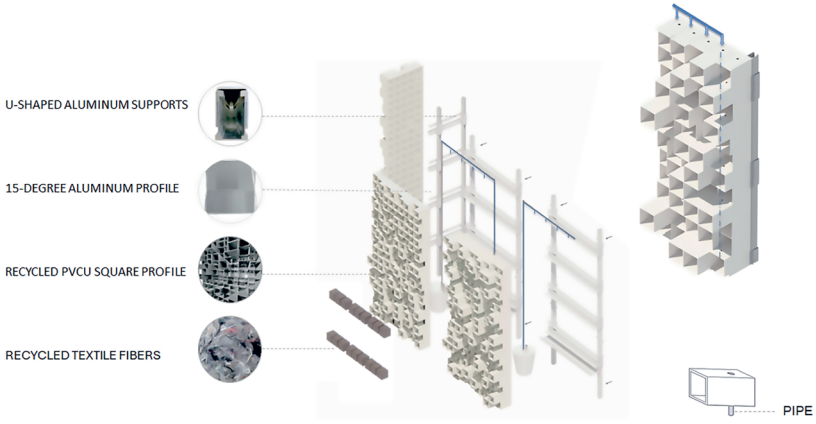

Figure 4-7. *Structural design of the Plant Pixel prototype. (Source: Author)*

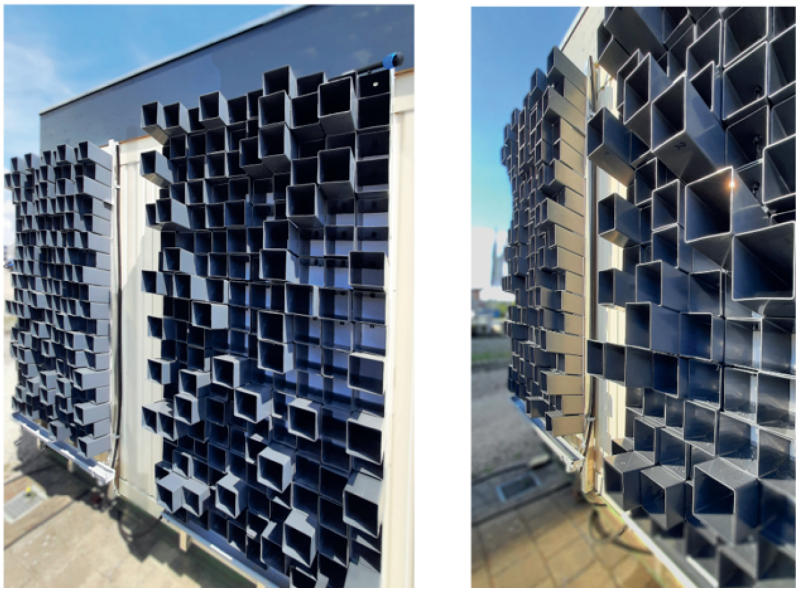

Figure 4-8. *Result of the installation of the structural components of the Plant Pixel full-scale mock-up. (Source: Author)*

The manufacturing process involved preparing the 500 square profile modules. These modules were produced manually in 8 sizes, with dimensions of length=120mm, width=120mm, 2.5mm thick, and depth ranging from 110-310mm, and involved: (1) cutting the square profile modules at 15-degree angles; (2) drilling two openings, one on the superior surface and one on the inferior surface, in the same location to align seamlessly; (3) attaching a 16 mm diameter plug-in pipe (20mm length) and a back surface to each square profile module; (4) testing the water tightness of each module.

The installation of the profile modules on the container (Figure 4-7) involved: (1) fixing the aluminum profiles vertically to the container with screws and U-shaped aluminum supports; (2) attaching the 15-degree aluminum profile with two self-drilled screws to the U- shaped aluminum supports; (3) assembling the profile modules above the 15-degree angle aluminum profiles; (4) sliding the profile modules onto one another; (5) inserting the plug-in pipe into the holes drilled previously until forming a secure connection; (6) inserting the substrate into each profile module; (7) positioning the plants within the substrate of each profile module.

The irrigation system positioned at the top of the mock-up structure supplied water to the plants. A single drip line with a flow rate of 8 l/m^2 and 20 drip emitters was installed on the southern side of the mock-up. An additional drip irrigation system, with a flow rate of 8 l/m^2 with 6 drip emitters, was installed on the western side. Water is delivered to the plants through a pipe connecting the square profile modules, enabling water transfer between modules (Figure 4-7). A water storage tank was utilized to store and recirculate the water. An electronic

timer was utilized to monitor the irrigation. During the summer, the full-scale mock-up was watered three times a day for 5 to 10 minutes, while no watering was needed during winter. To ensure vegetation survival, organic fertilizer was added manually to the water every 2 weeks.

Plant selection was conducted with ZinCo plant experts and tested in the full-scale mock-up with a plant performance assessment comprehending the criteria: tolerance to sun, frost resistance, drought tolerance, low-maintenance, ornamental appeal, dense foliage, hardiness, deep-rooting, suitability compatible with the selected substrate and, ideally, native to rocky or mountainous sites. Eventually, 22 pre-cultivated plant species were selected (Table 4-3) and subdivided into: 12 perennial herb species, 4 ornamental grasses, 2 perennial ground cover, 2 perennial shrubs, 1 perennial bulb species and 1 perennial fruit species. Planting took place in July 2022. To prevent root competition, plants were planted individually in one of the 500 modules based on the compatibility between root length and module dimensions. The distribution spanned the upper, middle, and lower sections of the full-scale mock-up. Next to this, plants were positioned to create an appealing pattern of colors and foliage (Figure 4-9).

Table 4-3. *The 22 plant species selected for the full-scale mock-up.*

Scientific name	Common name	Hardiness	Plant Type
Ajuga reptans	Bugleweed	USDA zones 3-9	Perennial ground cover
Alchemilla epipsila	Alpine lady's mantle	USDA zones 3-8	Perennial herb
Allium x Millenium	Millenium ornamental onion	USDA zones 4-8	Perennial bulb
Antennaria dioica	Mountain everlasting	USDA zones 3-8	Perennial herb
Armeria maritima 'White'	Sea thrift - White variety	USDA zones 4-8	Perennial herb
Artemisia schmidtiana 'Nana'	Dwarf silver wormwood	USDA zones 3-8	Perennial herb
Carex morrowii	Japanese sedge	USDA zones 5-9	Ornamental grass
Centranthus ruber	Jupiter's beard	USDA zones 4-9	Perennial herb
Ceratostigma plumbaginoides	Leadwort	USDA zones 5-9	Perennial shrub
Euphorbia cyparissias	Cypress spurge - Fens Ruby	USDA zones 3-9	Perennial herb
Festuca gautieri	Golden fescue	USDA zones 4-8	Ornamental grass
Festuca glauca	Blue fescue	USDA zones 4-8	Ornamental grass
Fragaria x ananassa	Strawberry	USDA zones 4-8	Perennial fruit-bearing plant
Geranium macrorrhizum	Bigroot geranium	USDA zones 3-8	Perennial herb
Hemerocallis	Stella de Oro	USDA zones 3-9	Perennial herb
Saponaria ocymoides	Rock soapwort	USDA zones 3-8	Perennial ground cover
Sesleria caerulea	Blue moor grass	USDA zones 4-8	Ornamental grass
Stachys byzantina	Lamb's ear	USDA zones 4-8	Perennial herb
Stachys officinalis	Betony - Saharian Pink	USDA zones 4-9	Perennial herb
Teucrium chamaedrys 'Nanum'	Dwarf germander	USDA zones 5-9	Perennial shrub
Thymus serpyllum	Creeping thyme	USDA zones 4-9	Perennial herb
Veronica spicata	Spike Speedwell	USDA zones 3-8	Perennial herb

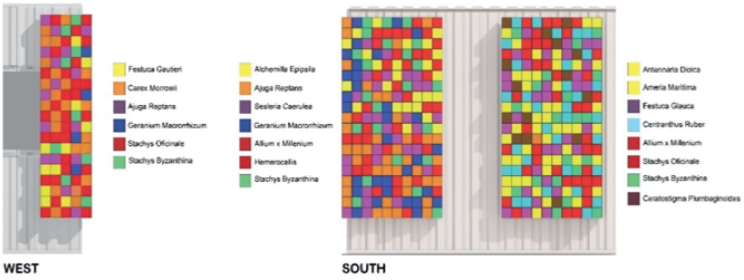

Figure 4-9. *Selected plants and planting scheme of the full-scale mock-up in Germany. (Source: Author)*

4.2.4 RTD: Step IV – Testing plant performance, simple assembly-disassembly and cost-effectiveness.

This step aimed to evaluate plant performance, assembly-disassembly, and cost-effectiveness. The plant species selected were evaluated through a plant performance test on the full-scale mock-up to answer SQ4. Additionally, the costs of constructing the full-scale prototype were assessed during the manufacturing, installation and maintenance stages. Testing involved the LCCA and the ease of assembly-disassembly of the full-scale mock-up to answer SQ5.

Plant testing was performed to evaluate the plant survival rate of the 22 pre-cultivated plant species selected. To evaluate the plant survival rate, the full-scale mock-up was divided into PP1 and PP2 (Figure 4-10). PP1 consists of profiles with lengths between 110mm and 210mm, while PP2 consists of profiles with lengths between 150mm and 310mm. Plant survival was evaluated visually using a Likert scale ranging from 0 to 5, where: 0 = Dead plant, 1 = Plant with few-to-no healthy leaves and no signs of new growth, 2 = Plant with browning leaves, 3 = Healthy plant with slow growth, 4 = Healthy plant showing growth with green leaves, 5 = Plant displaying exceptional growth and fullness. This scale was adapted from (Dvorak et al., 2021; Rowe et al., n.d.).

Simple assembly-disassembly testing was performed on the full-scale MLWS mock-up. Specifically, plug-in connections were examined for ease of assembly-disassembly to reduce on-site labor costs by implementing time-saving measures in the assembly process. A section of the full-scale mock-up, measuring 1200mm long and 360mm high, was used for the simple assembly-disassembly tests. On-site structural testing included checking the assembly and disassembly time to extract a component and evaluating the ease of disassembly of the modules: (1) the primary aluminum vertical profiles and the aluminum 15-degree secondary profile were installed; (2) the modules were stacked and interlocked one above the other; (3) the square profile modules were disassembled to check deformations.

The LCCA method was used to calculate the cost per square meter incurred during the manufacturing, installation and maintenance phase of the full-scale mock-up. The materials employed (PVCU, recycled textile, aluminum vertical and

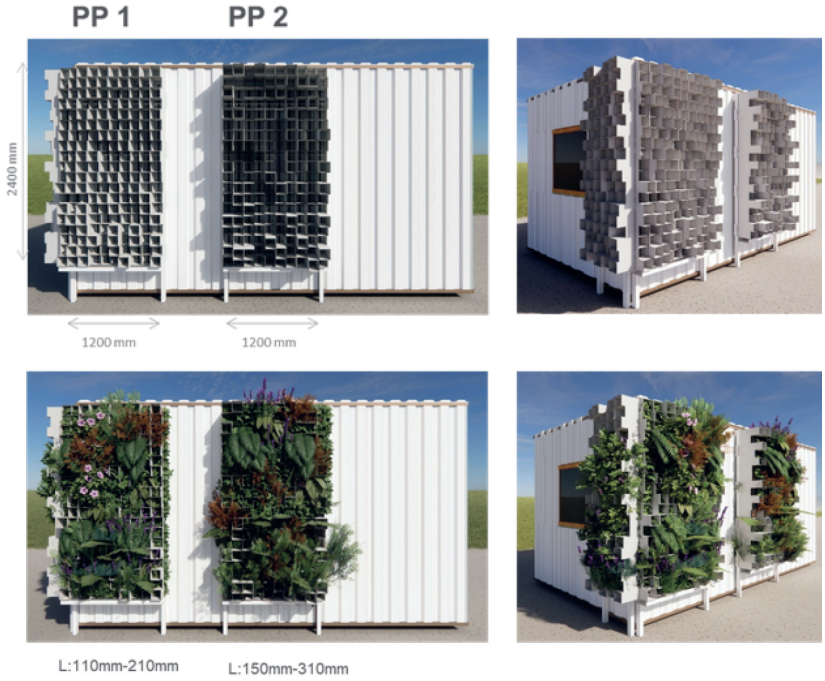

Figure 4-10. *Plant Pixel full-scale mock-up elevation (left-hand side) and 3D model (right-hand side), for the PP1 (module lengths 110–210mm) and PP2 (module lengths 150–310mm) variations. (Source: Author)*

horizontal profiles, screws, pipes, adhesives and plants) were purchased from local suppliers. Material costs included prices and quantities of components used in the full-scale mock-up. Transportation costs have been accounted for in the bill of expenses. Labor costs were calculated by dividing monthly wages in Germany into hourly salaries and multiplying the hours of work spent in building the full-scale mock-up. Maintenance costs included pruning, feeding, and watering plants, as well as the costs of repairing or upgrading materials. Plants were pruned twice a year, and a 10% substitution rate was assumed for cost estimation (Perini et al., 2011). The total costs were compared to similar products on the market.

4.3 Results and Discussion

This section presents and discusses the results of this study by reference to its research questions and to previous studies on MLWS and similar market products. It is important to highlight that there are no comparable MLWS currently on the market since *Plant Pixel* introduces novel design and technical solutions.

4.3.1 The bio-inspired easily assemblable MLWS designs

The literature review and photographic analysis of the morphology of steep rock revealed the features and irregularities that provide a structure for plants. Kuntz and Larson's (2006) research revealed that ledges, crevices, and pockets sustaining vascular plants had a larger area than those with lichens. This shows that small-scale variations on the surfaces of steep rock walls result in richer patterns of vegetation, regarding range of species and densities, serving as inspiration for *Plant Pixel*.

Key morphological aspects of steep rock walls that influence the design of *Plant Pixel* regarding aesthetics and plant survival include:

- *Features in steep rock walls*: formations such as caves, ledges, overhangs, cracks, joints or pockets provide small platforms that collect and store water. These formations gather rock fragments, sediment and organic matter, supporting vegetation growth (Souque et al., 2019).
- *Irregularities on the surface*: Irregularities like caves, ledges, overhangs, cracks, joints or pockets create suitable spaces for plants to secure their roots (Larson, Matthes and Kelly 2000; Kuntz and Larson 2006; Williams 2010).
- *Plant adaptation*: Plants in rocky environments have developed strategies to endure drought and frost. Alpine plants' roots extend far into the ground to find moisture and protection, as roots thrive with consistent moisture and temperature levels underground(Jørgensen et al., 2018; Körner, 2021).

Several MLWS prototypes (Figure 4-4) were developed aligned with the specific criteria (low-embodied carbon, hydrological and structural performance, simple assembly-disassembly, plant performance and cost-effectiveness). The design feedback from ZinCo and Wageningen University experts revealed the P6 prototype, (renamed *Plant Pixel* after optimization) was the best performing MLWS because of its simple geometry, easy assembly-disassembly (plug-in system), and modularity that makes it highly adaptable to the facade of a building. In contrast, P2-P4 and P7-P9 prototypes had complex geometry, leading to fabrication and cost concerns. Meanwhile, P1 and P5 exhibited limited design flexibility. *Plant Pixel* differentiates itself from traditional flat MLWS through its unique design that integrates varying lengths, imitating the irregularities found on steep rock walls.

Previous studies have recognized the effectiveness of nature-inspired solutions to address technical challenges arising from conflicting design criteria (Helms et al., 2009; Lienhard et al., 2011, 2015; T. Šuklje et al., 2015; T. Ž. Šuklje et al., 2013). The Plant Pixel MLWS (Figure 4-11) was developed using a nature-inspired approach that translated the features of steep rock walls into a pixel-like design. By incorporating square profile modules of varying lengths (W x H x L, where W=H and L=110mm-310mm), the Plant Pixel design mimics the irregularities of steep rock walls.



Figure 4-11. *Steep rock walls that served as an inspiration to Plant Pixel (left-hand side) and virtual depiction of Plant Pixel generated with Revit and dynamo plug-in (right-hand side). (Source: Author)*

4.3.2 (SQ1) How much do recycled materials reduce the embodied carbon of MLWS?

Based on the LCA, incorporating recycled materials in the *Plant Pixel* prototype significantly decreased embodied carbon to 66.7 $kgCO_2e/m^2$, in contrast to 229.3 $kgCO_2e/m^2$ with non-recycled materials (See Appendix A). This highlights the importance of material selection in reducing embodied carbon in MLWS. Similar systems range from 141 $kgCO_2e/m^2$ to 147 $kgCO_2e/m^2$ in the material stage. As a result, incorporating recycled materials led to a 50% reduction in embodied carbon. The results are consistent with previous research showing that the embodied carbon of MLWS prototypes could be lowered by using recycled materials and industrial waste (Manso et al., 2013; Bianco et al., 2017; Serra et al, 2017; Kio & Ali, 2021).

The LCA index (Figure 4-12) showed that the substrate with the lowest embodied carbon (0.4 $kgCO_2e/kg$) was recycled textile fiber (acrylic, cotton, wool mix) transformed into high-grade raw materials (Figure 4-12). This was followed by recycled synthetic fiber (polyester), recycled non-woven geotextile fiber, and the combination of recycled non-woven geotextile fiber with coconut coir. The weight of materials played an equally significant role in reducing embodied carbon: the lightweight substrate (37.58 kg/m^2) reduced the dimensions of the secondary 15-degree aluminum structural layer (2mm to 1.5mm thickness). This is in line with previous research showing that lightweight materials can reduce embodied carbon by decreasing structural loads (e.g., Manso and Castro-Gomes, 2015). The evaluation process was based on combined material properties to identify the most suitable substrate (Pacheco-Torgal et al., 2015) at an early stage. As a result, it has been concluded that additional hydrological testing is necessary to determine the most suitable substrate.

Recycled PVCU performed the best for use in the external layer regarding embodied carbon: low-embodied carbon (1.4 $kgCO_2e/kg$), recyclable, resistant to weather, fire and UV, and durability (up to 50 years). This echoes previous research showing that MLWS constructed with felt layers have a lifespan of

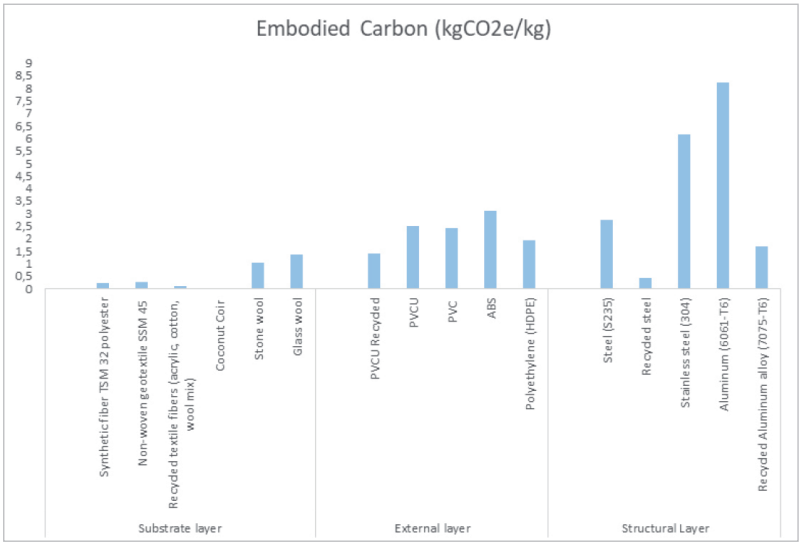

Figure 4-12. *Results of the comparison of the embodied carbon of the materials selected for Plant Pixel. (Source: Author)*

10 years, while planter boxes can last for over 50 years (Perini & Ottelé, 2014). Recycled aluminum was the material performing the best for the structural layer and fastening, given its inherent stability to support the structural load of a whole MLWS. Despite recycled steel having a slightly lower embodied carbon, recycled aluminum profiles were chosen for their cost-effectiveness.

4.3.3 (SQ2) How much do recycled substrates influence the hydrological performance of MLWS?

The test on water retention capacity revealed that the best-performing substrate was the recycled textile fiber (acrylic, cotton, wool mix), followed by geotextile fibers with coconut. The trial mock-up showed a maximum average capacity of water retention (61.02 l/m^2) for modules between 210mm and 310mm depth (Figure 4-13). The recycled textile fibers (61.02 l/m^2) showed a water retention capacity 5.31% higher than geotextile fibers with coconut (57.93 l/m^2), storing a large volume of water and reducing irrigation needs.

The values for water retention in the Plant Pixel (61.02 l/m^2) are higher than in other MLWS. For example, Kew et al. (2014) conducted a study for a similar MLWS, which retained an average of 4.8 l/m^2. Similarly, an experiment conducted on MLWS with expanded cork showed an average water retention of 4.1 l/m^2 (Cortes et al., 2019). The higher water-holding capacity of Plant Pixel is likely due to its substrate (recycled textile fiber), which has a high-water holding capacity. Likewise, Serra et al. (2017) found that incorporating 50% recycled textile in MLWS substrate enhances root development and water retention. In comparison, CLWS with felt layers have a low-water holding capacity

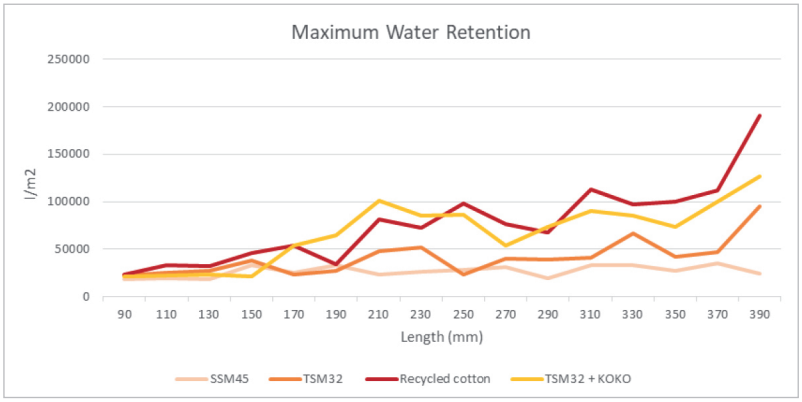

Figure 4-13. *Maximum water retention values of the four different substrates used in the Plant Pixel trial mock-up. (Source: Author)*

(1.35 l/m^2), which results in frequent irrigation needs (Pérez-Urrestarazu & Urrestarazu, 2018a) and high environmental impact due to the energy used to operate its water irrigation pumps (Manso et al., 2021; Oquendo-Di Cosola et al., 2020; Pérez-Urrestarazu et al., 2014). Higher water holding capacity reduces the cost of irrigation, increases the plants' access to water and, thus, the probability of plants to thrive.

Beyond the substrate, module length and inclination angle also play a role in the water-holding capacity of the trial mock-up. The 15-degree angle of the modules provides a suitable inclination for an even water distribution. This is relevant because substrates with uniform water distribution can lead to higher root growth and frequencies (Jørgensen et al., 2014). The module lengths between 90mm and 310mm enabled a proportional water distribution to all plants. Water distribution was found to be limited in reaching the outermost layer of the modules in lengths over 310mm, hence the modules of these lengths were excluded from the Plant Pixel prototype.

The water-tightness results proved that the extruded PVCU square profile and plug-in connections were watertight. There was no water infiltration towards the back of the square profile module towards the frame. However, the results show the need for quality control during production. Attention must be given to the water tightness. If a gap is left in any of the parts of the square profile modules water will be lost through a leakage. Similarly, as suggested by Ottelé et al. (2011) the details of windows, doors and corners should be considered to prevent water damage.

4.3.4 (SQ3) How do lightweight materials influence the structural performance of MLWS?

The full-scale mock-up withstood the maximum saturated weight (98.61 kg/m^2) transferring the water load and water pressure amongst the components without failure or undergoing large deformations. The weight of the dry trial-scale mock-up is 37.58 kg/m^2 and when completely saturated with water it is 98.61 kg/m^2 (Figure 4-14, 4-15). The selected material (UPVC) and thickness (2.5mm) for the trial mock-up generated a sturdy and lightweight structure. Therefore, the full-scale mock-up withstood the maximum saturated weight, validating the use of UPVC material and its thickness for structural stability.

Similar MLWS in the market weigh between 40 kg/m^2 and 150 kg/m^2 (ANS Global 72 kg/m^2; Modulo Green; Growall 80 kg/m2; Gsky 147 kg/m^2). Plant Pixel can be found in the middle range (98.61 kg/m^2), mostly due to the recycled textile substrate. The exclusion of module lengths over 310mm also contributed to reducing structural loads. This is of relevance because reducing weight and materials decreases the demand on the structural load. However, additional reinforcement may be necessary, depending on the height of the MLWS and the structural capacity of the building.

Nevertheless, structural stresses were identified at some points of the MLWS full-scale mock-up. Modules with an overhang of 80mm or more exerted greater force on the front of the profile module. The solution was to place a smaller square profile module above the cantilevered module, to create a counterweight. The modules were positioned to avoid stress zones and ensure stability without additional fastenings. This arrangement of the modules provided stability by relying on module weight and load distribution.

As a result of the structural analysis, the dimensions for the primary U-aluminum profile (50mm x 50mm x 2mm) and secondary 15-degree aluminum profile (60mm x 1.5mm) structures were chosen. The primary and secondary structures play a crucial role in load redistribution and ensuring stability within the MLWS system. It is worth noting that the reduction in the thickness of the secondary 15-degree aluminum profile (from 2mm to 1.5mm) was analysed with SkyCiv software (Appendix B). These dimensions consider factors, such as the dead load and the weight-bearing capacity to support the module. This is relevant because ensuring structural stability during the design phase is critical.

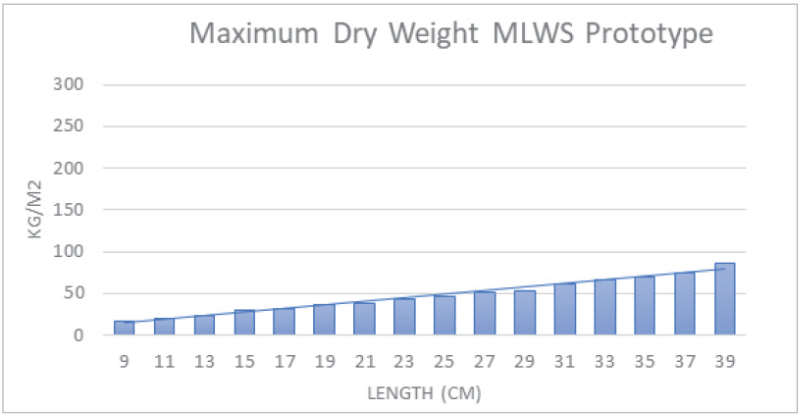

Figure 4-14. *Maximum dry weight of the MLWS full-scale mock-up. (Source: Author)*

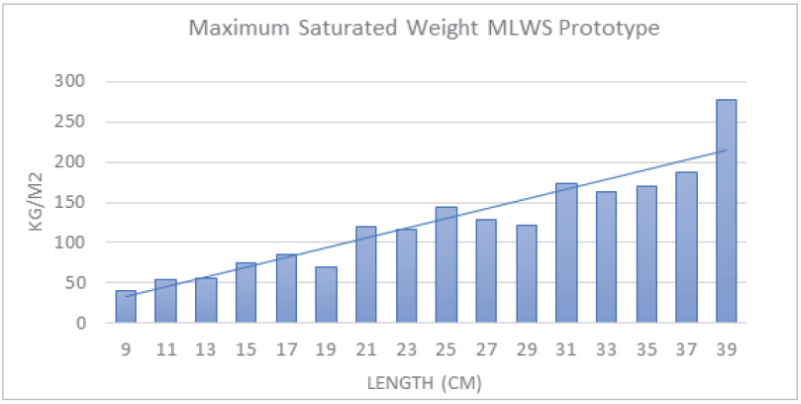

Figure 4-15. *Maximum weight of the MLWS full-scale mock-up when fully saturated. (Source: Author)*

4.3.5 (SQ4) How do low-maintenance plant species perform regarding survival rates in a bio-inspired MLWS?

Out of the twenty-two plant species selected, twenty had a high survival rate, showing good visual quality, extensive coverage and long-lasting blooms. *Aguja reptans* and *Ameria maritima* survival rates were lower. The plant performance quality remained constant between PP1 and PP2, for both orientations during summer and autumn. In winter, the west-facing Facade performed better than the south-facing Facade. The best-performing species in summer were *Allium x Millenium*, *Centranthus ruber*, *Geranium macrorrhizum*, *Hemerocallis*, *Sesleria caerulea*, *Veronica spicata*. The best-performing species in winter were *Allium x Millenium*, *Antennaria dioica*, *Geranium macrorrhizum*, *Thymus serpyllum*, *Fragaria x anassa*, *Hemerocallis*, *Artemisia schmidtiana* and *Centranthus ruber*. These results indicate that the plants included in the MLWS full-scale mock-up were successfully established and survived in southern Germany's climate during dry summers and heat waves.

Unlike other MLWS in the market, *Plant Pixel* (Figure 4-16) ensured the healthy growth of plants by avoiding root competition. Existing MLWS typically maintain a density of around 30 plants per square meter (Manso & Castro-Gomes, 2015). In contrast, *Plant Pixel* comprises a higher density of plants (70/m^2), which enables a wider range of plant species to be accommodated.



Figure 4-16. *Full-scale mock-up installed in a container in Germany. (Source: Author)*

During summer and autumn, plant species positioned at the top, middle and lower sections of the full-scale mock-up exhibited optimal interseasonal performance (Figure 4-17). The substrate's high-water retention capacity provided sufficient water for the plants during the summer and autumn months. This echoes the notion that MLWS plant design must consider moisture variation in the vertical direction (Fernández-Cañero et al., 2018). During winter (when the irrigation system was inactive), plant species positioned at the top sections of the full-scale mock-up performed better, benefiting from more exposure to rainwater.

As a result, it was observed that PP1 and PP2 exhibited similar percentages of vegetation cover (Figure 4-17). Throughout the experiment, there was a variation in the depth of vegetation as the plants became more established. In July 2022, an initial visual inspection showed that the wall was approximately 70% covered. However, by September 2022, the coverage increased to 96% and remained consistent until December 2023. In the latter stages of the study, noticeable dried brown stems were observed, juxtaposed with the emergence of sprouts. It is worth noting that Stuttgart experienced a mild winter with only a few frost days, which helped protect the plants from extreme cold temperatures. The dense coverage lasted until January, because of the mild winter weather. The dense plant coverage observed in Plant Pixel highlights the critical role of selecting the proper rooting substrate to facilitate root system development in plants (Figure 4-18).

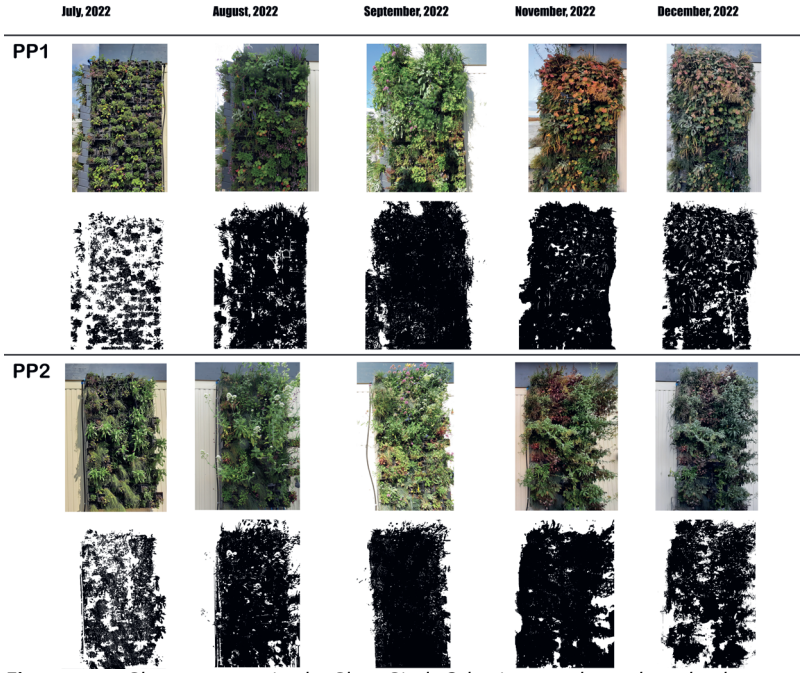

Figure 4-17. *Plant coverage in the Plant Pixel: Color images show plant development, contrasted with black and white binary representations for comparison. (Source: Author)*

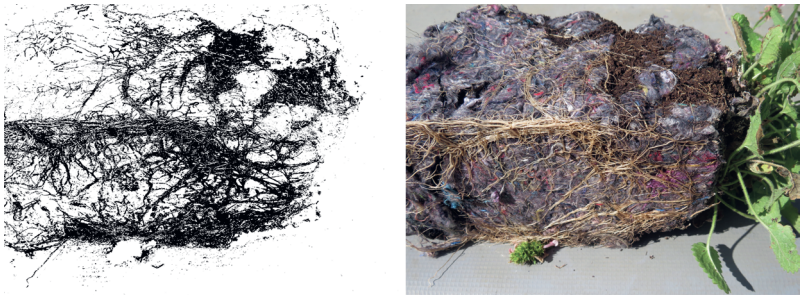

Figure 4-18. *Representation of the root growth in the substrate of the Plant Pixel: Binary image (left) isolates roots; original image (right). (Source: Author)*

4.3.6 (SQ5) How do the materials selected and the design for simple assembly-disassembly influence the cost of a bio-inspired MLWS throughout the production, installation and maintenance stages?

The total cost of the full-scale mock-up (Figure 4-15) amounted to 680.9 €/m^2. This cost is lower compared to MLWS, which range from 750-1,200 €/m^2 depending on the system type and material used (Huang et al., 2019; Manso et al., 2021; Perini & Rosasco, 2013; Rosasco, 2018; Rosasco & Perini, 2018). The costs of the full-scale mock-up were influenced the most by the materials chosen, followed by the plants selected. The gross material cost was 256.1 €/m^2, while the plant cost was 105 €/m^2 (Figure 4-19, 4-20).

The low cost of PVCU and the decreased use of aluminum contributed to the reduction of acquisition costs of raw materials. The high cost associated with plants in this system can be attributed to the high plant density of 70/m^2. The species included in the full-scale mock-up had costs spanning from 1.1–1.9 €/m^2. It was found that opting for plant species within the lower cost range (1.1-1.3 €/m^2) can lower plant cost down to 84.7 €/m^2 and, thus, lowering the total costs of Plant Pixel to 660 €/m^2. These results indicate the cost-effectiveness of Plant Pixel compared to other MLWS in the market.

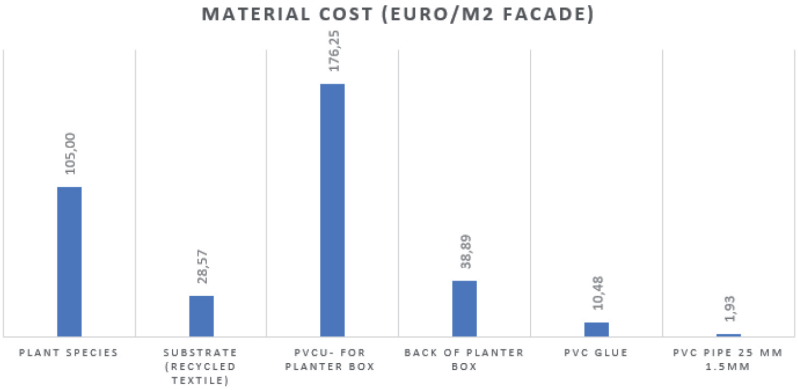

Figure 4-19. *Results and comparison of material costs of the modules of the full-scale mock-up. (Source: Author)*

3.7.1. Production Stage

The manufacturing process of the square profile modules aims to streamline the on-site assembly process. For example, all the connections were prefabricated to minimize the on-site assembly process.

Manually building the full-scale mock-up was time-consuming and labor-intensive due to the precision required for modules to fit the plug-in connection accurately. Cutting the 500 profile modules into eight lengths and drilling two openings were the most time-consuming steps. Next to this, testing each module's water tightness was time-intensive. An industrial process such as thermoforming (1 minute per item) can reduce manufacturing time by 90%, thus lowering production costs. For example, some MLWS have been built with 3D-printing machines, which could reduce manufacturing costs (He et al., 2020).

3.7.2. Installation Stage

MLWS with complex systems have high installation costs. Implementing easy assembly and disassembly processes in MLWS can mitigate installation costs (Bianco et al., 2017). Notably, the *Plant Pixel* addresses this challenge by incorporating a plug-in system, providing structural stability, construction ease and cost-efficiency. Unlike other MLWS in the market, *Plant Pixel*'s square profile

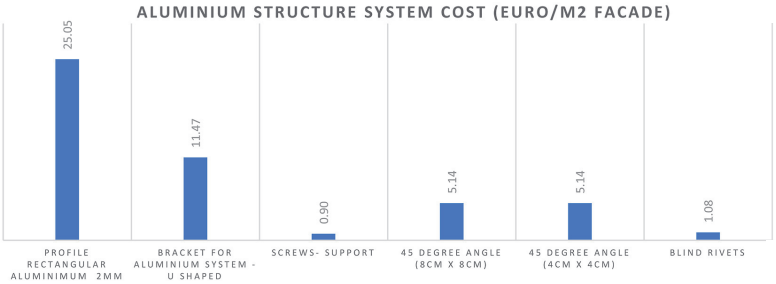

Figure 4-20. *Results and comparison of material costs of the aluminum structure of the full-scale mock-up. (Source: Author)*

modules are interlocked using a plug-in pipe instead of screws, creating a Lego-like configuration (Figure 4-21). The plug-in solution reduced labor costs by streamlining assembly and disassembly.

The installation process for the 500 square profile modules on the container was efficient, reducing on-site work. Square profile modules are mounted together through the plug-in connection. As a result, assembling and disassembling the full-scale mock-up is fast and simple. Assemblage simply requires placing the pipes every four rows at a 15-degree angle aluminum profile. Likewise,



Figure 4-21. *Process of installing the full-scale mock-up in a container in Germany. (Source: Author)*

disassembly is a straightforward process, where removing one module takes less than 10 seconds. To ensure reliable force transfer between modules, a fixed connection is assembled every four rows. Consequently, onsite labor costs are reduced by savings in construction time.

Lightweight modules were easy to transport, install, and disassemble. The process requires 1-2 people to assemble the full-scale mock-up. Overall, these characteristics enable 15 hours of work per 7.2m^2 of the installed wall, equivalent to the work of 2 installers per day (Figure 4-22). The use of square profile modules for the installation decreased the waste of material, hence the costs. The *Plant Pixel* assembly eliminates the need for heavy machinery, unlike other MLWS that require specialized machinery (Huang et al., 2019).

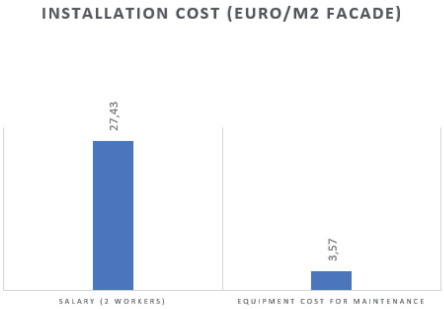

Figure 4-22. *Results and comparison of the installation stage costs of the Plant Pixel full-scale mock-up. (Source: Author)*

Afterward, the square profile modules were filled with the substrate and vegetation selected according to the plant criteria. Some activities, like inserting plants in modules, can only be done manually. Consequently, this activity required manpower, but the process was simple.

It is worth noting that the standardized elements of *Plant Pixel* created a resource-efficient MLWS design (*Plug and Play Skyscrapers - Designing Buildings*, n.d.). The plug-in solution promotes circularity and cost-effectiveness through the simple separation of components and their suitability for reuse, refurbishment and recycling. Therefore, extending the product's utilization phase and increasing its durability which is fundamental to circularity (Webster, 2007).

3.7.3. Maintenance Stage

The plant choices led to a cost-effective MLWS system due to decreased water intake and low- maintenance. For example, drought-resistant plants were instrumental in decreasing irrigation needs. Although plant selection focused on low-maintenance species, biannual trimming is necessary for aesthetic purposes. The selection of plant species that match the MLWS location is crucial for cost reduction (Huang et al., 2019).

The recycled textile substrate's high water-holding capacity and 15-degree angle further contributed to decreased water consumption. In the context of MLWS maintenance, costs are primarily linked to water consumption and pumps. Studies (Ottelé et al., 2011; Perini & Ottelé, 2014; Manso & Castro-Gomes, 2015) emphasize the significance of substrate selection in this regard. Substrates with high-water holding capacity led to reduced water consumption over the MLWS lifespan, consequently diminishing maintenance costs. Integrating an automatic irrigation system is crucial. During summer, irrigation frequency increases, with the full-scale mock-up watered three times a day for 5-10 minutes. During winter, no watering is required. Therefore, it is necessary to disable the irrigation system to protect it from frost damage.

For the full-size mock-up, a single drip line provided water, supplemented by a recirculating system. This method improves irrigation by redirecting and pumping recovered water into the system. Recirculation improves irrigation efficiency but raises water quality concerns (Pérez-Urrestarazu, 2021; Pérez-Urrestarazu & Urrestarazu, 2018a). It is worth noting that the application of liquid fertilizer every two weeks was necessary to encourage plant growth, accounting for 4% of the maintenance costs (Figure 4-23).

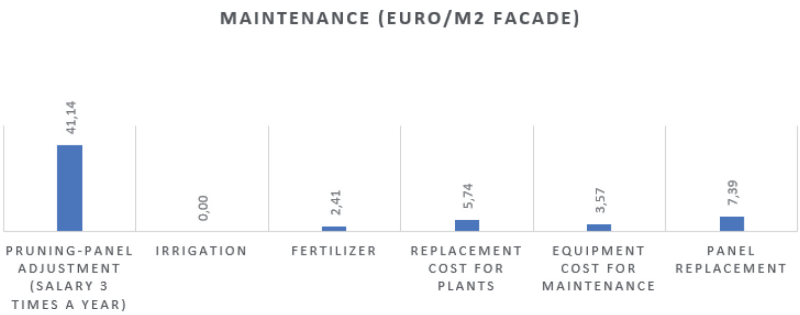

Figure 4-23. *Results and comparison of the maintenance stage costs of the Plant Pixel full-scale mock-up. (Source: Author)*

Research has found that inadequate maintenance of MLWS result in additional costs related to plant replacement (Huang et al., 2021). Unlike other modular systems that require removing front covers to replace vegetation (Manso & Castro-Gomes, 2015), the *Plant Pixel* prototype offers a simpler approach. Plants can be replaced by extraction, hence reducing maintenance costs by simplifying plant replacement. The *Plant Pixel* prototype's plug-in design enables easy disassembly for reuse, refurbishment, or recycling. This is relevant as designing for future reuse can substantially reduce costs (Bakker et al., 2019; Kio & Ali, 2021).

4.4 Limitations

Regarding the LCA index, it is difficult to obtain accurate data due to variations among suppliers, manufacturers and testing conditions used in the embodied carbon of the materials. To overcome this difficulty, various databases, such as ICE embodied energy and embodied carbon database, EPDs and H/B:ERT embodied carbon software were examined. This variability in terms of sources of data adds complexity to accurately estimating embodied carbon, which might have influenced the values presented above.

Gathering precise mechanical data is challenging due to variations among suppliers, manufacturers and testing conditions. These differences are influenced by factors such as raw material quality, type, grade and testing conditions. Additionally, recycled materials' mechanical properties vary based on their composition, quality and impurities in the recycling process. These data variations might have affected the accuracy of the measured mechanical properties.

Establishing a benchmark for MLWS comparison faces challenges due to limited performance data on the specified criteria. Confidentiality requirements prevent companies from disclosing detailed specifications and performance data. Therefore, it is difficult to obtain benchmarking data that allows for a comprehensive comparison between the *Plant Pixel* prototype and other MLWS in the market.

During the analysis of the maintenance stage of the full-scale mock-up, uncertainty and assumptions in Life LCCA were considered. This involved considering maintenance costs, including repairs to specific materials. LCCA uncertainties during the maintenance phase might have influenced the accuracy of cost for the *Plant Pixel* prototype. Nevertheless, factoring in variables such as maintenance costs and material repairs enhanced the comprehensiveness of the analysis.

During the numerical simulations conducted using SkyCiv, wind loads were not investigated because of the temporary nature and small area of the mock-up construction. Consequently, the numerical simulations of the prototype do not consider the influence of wind pressure on the stability of the *Plant Pixel* mock-up.

Finally, *Plant Pixel* is tailored for the size of the structure examined in this study. For example, for a multi-story construction, its structural performance could have been different due to increased complexity.

4.5 Conclusion

This paper addressed the question: *How to design a novel bio-inspired living wall system?* To answer this question, this paper presented a novel bio-inspired MLWS prototype developed with RTD that meets the criteria: of low-embodied carbon, hydrological and structural performance, plant performance, simple assembly-disassembly and cost-effectiveness. This process resulted in a bio-inspired, modular, low-embodied carbon and cost-effective MLWS prototype: *Plant Pixel* (Figure 4-24).



Figure 4-24. *Full-scale mock-up of the Plant Pixel prototype. (Source: Author)*

The results of this study show that the selected materials (recycled), plants (low-maintenance), substrate (with high-water holding capacity), and fixing system (plug-in, modular, lightweight structure) improved the mechanical performance, structural performance, lowered the embodied carbon and the costs of the *Plant Pixel* when compared to other MLWS products currently available in the market. In more detail:

- (SQ1) *How much do recycled materials reduce the embodied carbon of the Plant Pixel prototype?* The LCA index and mechanical properties indicate that the utilization of recycled PVCU, recycled textile, and recycled aluminum can decrease up to 50% the embodied carbon in MLWS products. The findings highlight the benefits of using recycled materials to lower embodied carbon in MLWS.
- (SQ2) *How much do recycled substrates influence the hydrological performance*

of the Plant Pixel prototype? The recycled textile fiber substrate selected has a maximum capacity of water retention (61.02 l/m^2) which minimized the irrigation requirements and provided optimal conditions for plants to grow.

- (SQ3) *How do lightweight materials influence the structural performance of the Plant Pixel prototype?* The selected structural materials (recycled PVCU and recycled aluminum) influence the performance of the *Plant Pixel* positively. Dimensions, thickness and design geometry ensured the structural robustness of the full-scale mock-up necessary to support the weight of plants and saturated substrate.
- (SQ4) *How do low-maintenance plant species perform regarding survival rates in the Plant Pixel prototype?* The *Plant Pixel* design enables a wider range of plant species to be accommodated. Twenty species out of twenty-two selected resulted in a high rate of plant survival. This plant species thrived in the *Plant Pixel* prototype and showed extensive vegetation coverage.
- (SQ5) *How do materials selected and the design for simple assembly-disassembly influence the cost of the Plant Pixel prototype throughout the production, installation and maintenance stages?* Plant Pixel maximized the use of recycled (PVCU) and reduced the use of aluminum, which resulted in reduced acquisition costs in terms of raw materials. The modular system comprising a simplified plug-in connection enabled ease of assembly and disassembly. Therefore, the design-for-assembly and disassembly approach reduced costs during installation and maintenance. Additionally, the maintenance of plants was reduced due to the high-water capacity substrate and low-maintenance plants. The final full-scale mock-up panels consisted of 500 modular square profiles, resulting in a cost of 256.1 €/m^2, while the cost of plants was 105 €/m^2.

Designing an optimized green wall system involves assessing materials, substrates, and fixing systems. Additionally, conducting an LCCA can help address economic constraints in MLWS. Cost and carbon reductions are achieved through features like fewer fasteners, recycled materials, a plug-in modular fixing system, and a lightweight structure. The *Plant Pixel* design offers modularity, low-embodied carbon, cost-effectiveness, and an innovative bio-inspired design for implementing living wall systems in dense urban areas.

Future research could develop the *Plant Pixel* prototype into a marketable product. Furthermore, *Plant Pixel* should also be tested for more complex structures, such as multi-story construction. The prototype's applicability to larger structures requires further research to find out its performance in diverse scenarios. It is also important to further investigate the performance of the connectors during extreme weights, to improve the plug-in connection system employed in *Plant Pixel* and utilize the full potential of the system. It is important that future research quantitatively measures the micrometeorological effects of the *Plant Pixel* to assess its actual contribution to reducing urban heat stress (Figure 4-24).

Acknowledgments

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5

Microclimatic Performance of a Novel Living Wall System



(Source: Author)

This chapter has been accepted for publication as: Microclimatic Performance of a Novel Living Wall, **Solera Jimenez, M.**, Nickayin, S., *Smart and Sustainable Building Environment*, (2026)

5

Abstract

This study investigates the microclimate performance of the *Plant Pixel*, an innovative Living Wall System (LWS). *Plant Pixel* is an optimized, low-embodied carbon, cost-effective, simple-to-assemble, and disassemble prototype. The research uses a *Plant Pixel* mock-up with 500 modules and plants. A long-term monitoring study was conducted from June 20, 2022, to January 1, 2023, in a temperate oceanic climate, comparing the *Plant Pixel* with a bare wall. Results indicate that the *Plant Pixel* achieved maximum temperature reductions of 5.5°C at 10cm and 3.3°C at 40cm from the LWS, exceeding reported cooling values for conventional LWS in temperate climates. While the LWS exhibited limited impact on outdoor air temperature during winter, it significantly reduced wind speed, highlighting its potential for thermal moderation year-round. These findings highlight the role of modular LWS in urban climate adaptation strategies, providing practical insights for policymakers, urban planners, and architects.

Keywords: Climate adaptation; design; living wall system; urban heat; urban microclimate

5.1 Introduction

Vertical Green Systems (VGS) have emerged as an effective strategy for mitigating the Urban Heat Island (UHI) effect and addressing heat stress in urban environments. These systems contribute to cooling urban areas by enhancing evapotranspiration and reducing the thermal mass effect of urban materials (Coma et al., 2014; Loh, 2008; Pérez et al., 2017; Pérez-Urrestarazu et al., 2015).The UHI phenomenon, driven by factors such as reduced vegetation and increased heat-retaining surfaces, poses significant challenges to public health and urban comfort (Prihatmanti & Taib, 2017; Susca et al., 2022; Zölch et al., 2016). In response, cities are increasingly incorporating VGS into urban design to improve microclimatic conditions and adapt to climate change (Beatley & Newman, 2013).

Vertical Green Systems are divided into two types: Green Facades (GF) and Living Wall Systems (LWS) (Loh, 2008; Manso & Castro-Gomes, 2015; Ottelé, 2011; Pérez et al., 2014). Green facades use climbing or hanging plants, either directly rooted in the ground or planted in planters, or indirectly, using structures like nets or trellises (Figure 5-1).

Living Wall Systems (LWS) use structures to support vegetation, enabling plant growth without ground-rooting (Manso & Castro-Gomes, 2015). Living wall systems are divided into two types: modular and continuous. Continuous living

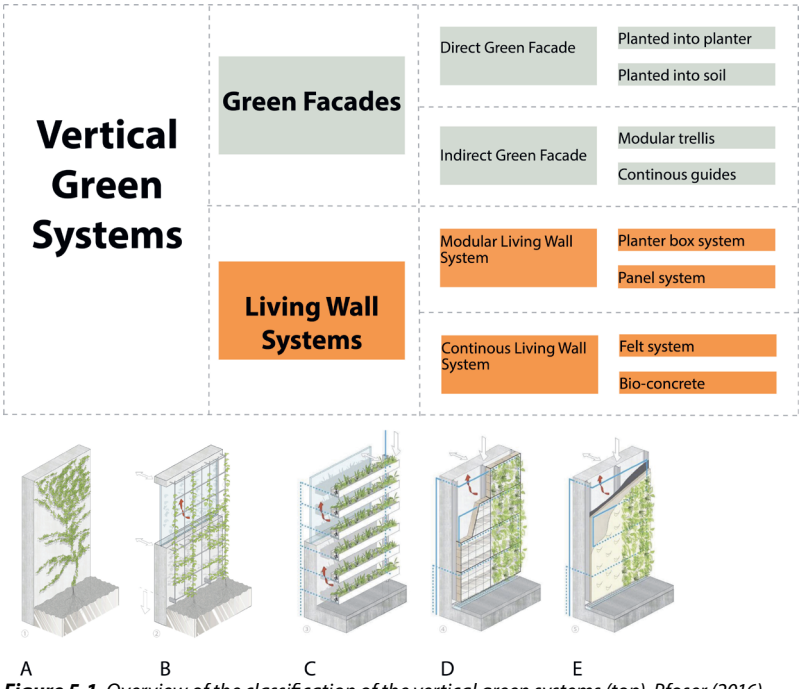

Figure 5-1. *Overview of the classification of the vertical green systems (top). Pfoser (2016) depicts different vertical green systems: (A) Direct green facade, (B) Indirect green facade, (C) Planter box system, (D) Panel system, and (E) Felt system. (Source: Author)*

wall systems, pioneered by Patrick Blanc, utilize synthetic felt layers with pockets for inserting the plants (Susorova, 2013). Modular living wall systems include a modular container system, growth substrate, waterproof layer, supporting frame, and an irrigation system (Loh, 2008; Manso & Castro-Gomes, 2015).

Studies have established a positive relationship between LWS and a reduction in outdoor temperature, improving thermal comfort for pedestrians (Alexandri & Jones, 2008; Susorova et al., 2014). For instance, a study conducted in France showed that implementing LWS resulted in a decrease of 4°C in mean radiant temperature (Djedjig et al., 2014). Tan et al. (2014) documented reductions of up to 11.5°C in mean radiant temperature at a distance of 0.5m. Moreover, reductions in mean radiant temperature were observed within 1m from the LWS.

In summer, LWS provide significant cooling benefits by absorbing solar energy and enhancing evaporative cooling, making them an effective strategy for mitigating urban heat stress (Di & Wang, 1999; Perini & Magliocco, 2014). For instance, LWS integrated with vegetation demonstrate 7.38 times higher cooling efficiency than soil evaporation alone, underscoring their significant thermal benefits (Kim et al., 2023). Additionally, foliage transpiration within LWS can absorb as much as 50% of incoming solar radiation, effectively lowering indoor and outdoor temperatures in temperate climates (Zhang et al., 2019). Furthermore, Chen et al. (2013) observed that implementing LWS decreased exterior surface temperatures by 20.8°C, leading to a 12% reduction in cooling energy consumption.

In winter, LWS act as thermal barriers by reducing wind speed near building surfaces and enhancing exterior thermal resistance (Perini, Ottelé, Haas, Raiteri, et al., 2011; Shafiee et al., 2025). Convertino et al. (2020) reported a 79% reduction in infrared radiation loss due to LWS. However, research on the microclimatic performance of LWS during colder seasons remains limited, underscoring the need for further investigation to optimize their winter performance (Susca et al., 2022).

Despite these benefits, research on LWS temperate oceanic microclimatic effects remains scarce (Table 5-1). Current research on Living Wall Systems (LWS) and their impact on outdoor near-wall air temperatures and solar radiation is limited. There are limited studies on LWS and ambient temperature in temperate climates (Pucher et al., 2022); most existing research predominantly addresses surface temperature (Ottelé & Perini, 2017; Perini, et al., 2011). This emphasizes the need for more LWS research on ambient temperature and solar radiation within temperate oceanic microclimates.

LWS allows for denser vegetation cover and controlled irrigation, leading to a more significant reduction in air temperature and solar radiation attenuation than GF (Morakinyo et al., 2019). Therefore, it is crucial to have accurate on-site measurements to assess the microclimatic performance of LWS. Previous

Table 5-1. *Outdoor Air Temperature and Surface Temperature Studies in Temperate Climates.*

Ambient Temperature Studies in Temperate Climates				
Season	**Study**	**Location**	**Finding**	**Vertical Green System Type**
Summer	Cameron et al., 2014	London, UK	Outdoor air temperature reduction up to 3°C	GF
Summer	Pucher et al., 2022	Austria	Outdoor air temperature difference of 3.4°C (well-irrigated LWS)	LWS
Summer and Autumn	Jesus et al., 2017	Madrid, Spain	Summer: Maximum reduction 2.5°C - 2.9°C. Autumn: Maximum reduction of 1.5°C	LWS
Surface Temperature Studies in Temperate Climates				
Summer	M.T. Hoelscher et al., 2016	Germany	Surface temperature reduction of 15.5°C.	GF
Summer	Perini et al., 2011	Netherlands	Surface temperature reduction of 2.7°C - 3.9°C	LWS
Winter	Bolton et al., 2014	Manchester, UK	Increased nighttime surface temperature by 3.5°C.	GF
Summer and Winter	Ottelé & Perini, 2017	Netherlands (Climate Chamber)	GF temperature difference of 1.7°C (summer and winter) Planter boxes LWS temperature difference 8.4°C (summer) and 10.6°C (winter) Mineral wool LWS temperature difference of 5.9°C (summer) and 10.6°C (winter)	GF, LWS

studies (Blanco et al., 2019; Jesus et al., 2017; Ottelé, 2011; Pérez-Urrestarazu & Urrestarazu, 2018; Wong et al., 2010) have used microclimatic measurements to evaluate the thermal performance of LWS in various climates. However, differences in methods, climates, materials, and orientations limit comparability, and research in temperate climates remains limited.

Uncertainties about the thermal properties of LWS make policy endorsement difficult, particularly in temperate oceanic climates (Kim et al., 2023). Despite extensive research on LWS, long-term microclimatic data in urban environments remain limited. Further investigation into LWS seasonal effects is required, focusing on winter performance and summer heat stress mitigation (Morakinyo et al., 2019; Perini & Ottelé, 2014; Santamouris, 2014; Susca et al., 2022).

To address these gaps, this study poses the following primary research question: To what extent do Living Wall Systems (LWS) influence microclimatic conditions in a temperate oceanic climate during summer and winter? Additionally, the study explores the following sub-questions:

- SQ1: How much do LWS influence outdoor air temperatures, humidity, solar radiation, and wind speed during summer in a temperate oceanic climate?
- SQ2: How effectively are LWS mitigating outdoor air temperatures, humidity and solar radiation during heat waves in a temperate oceanic climate?
- SQ3: How much do LWS influence outdoor air temperatures, humidity, solar radiation, and wind speed during winter in a temperate oceanic climate?

The study aims to contribute to a nuanced understanding of LWS seasonal performance by addressing these questions, focusing on the *Plant Pixel*, a novel modular LWS prototype. To address these questions, this study addresses the microclimatic performance of *Plant Pixel*, a novel living wall system developed within the SOLOCLIM project. *Plant Pixel* is a prototype featuring 500 modules and plants constructed in Germany (Jimenez et al., 2024). The *Plant Pixel*'s full-scale model underwent testing to assess its microclimatic performance. This research aims to investigate the thermal effect of the *Plant Pixel* on the microclimate in a temperate oceanic climate. Additionally, it aims to determine how effective the LWS is in reducing urban heat stress during summer and to identify its effect in winter. This investigation provides critical insights for urban planners, landscape architects and policymakers seeking to optimize LWS for urban climate adaptation.

5.3 Methods and Materials

5.3.1 Experimental Design

Long-term monitoring was conducted in Stuttgart from June 20, 2022, to January 1, 2023, to evaluate the impact of *Plant Pixel* LWS on microclimate. The experiment assessed the microclimatic performance of three LWS (*Plant Pixel*) positioned on a container during summer, autumn and winter. One LWS was placed on the west facade of a container and two on the south facade, with adjacent bare walls serving as reference points. Measurements focused on outdoor air temperature, solar radiation, humidity, and wind speed near the *Plant Pixel* and adjacent bare walls oriented south and west. Outdoor microclimatic data recorded variations in outdoor air temperature, humidity, wind speed, and solar radiation across seasons, which were then analyzed and compared with previous microclimatic studies (Appendix G).

To address SQ1, the summer microclimatic impact of the *Plant Pixel* was assessed compared to a bare wall by measuring air temperature, humidity, wind speed, and solar radiation. Microclimatic sensors were installed at heights of 10cm

and 40cm in the *Plant Pixel* and the adjacent bare wall. For SQ2, the *Plant Pixel*'s effectiveness during heat waves was assessed by analyzing periods with temperatures above 28°C for at least three consecutive days, focusing on reductions in air temperature, humidity, and solar radiation. To address SQ3, the *Plant Pixel*'s winter microclimatic impact was assessed by comparing air temperature, humidity, wind speed, and solar radiation near the LWS and an adjacent bare wall. The analysis focused on temperature fluctuations during cold days at or below 0°C to evaluate the system's performance under winter conditions. The following sections detail the LWS design and experimental setup.

5.3.2 Site Conditions

The experimental setup was on a 1:1 scale prototype of the *Plant Pixel* (Figure 5.2). Microclimatic measurements were taken on a container's south and west sides in Wolfschlugen (latitude 48.38°N and longitude 9.17°E), Stuttgart, Germany. The selection of the west and south facades aimed to evaluate the LWS' influence on microclimatic conditions, given the significant influence of solar radiation. South-facing facades receive direct sunlight throughout the day, while west-facing facades experience intense solar radiation in the afternoon and evening during summer.



Figure 5-2. *Full-scale mock-up installed in a container in Germany. (Source: Author)*

Stuttgart's climate is classified as temperate oceanic (Cfb) according to the Köppen climate classification. In 2022, Stuttgart experienced its warmest year on record, with an average temperature of 11.7°C, marking a 2.9°C increase from the long-term average (Stadtklima Stuttgart, 2024). During summer, temperatures ranged from 12°C to 38°C, with solar radiation exceeding 800 W/m^2. In autumn, temperatures fluctuated between 28°C and -3°C, with solar radiation levels averaging around 400 W/m^2. Winter temperatures averaged 3.8°C, surpassing the long-term average by 3.1°C. Rainfall slightly exceeded normal levels, reaching 717.4 l/m^2, while sunshine duration significantly surpassed the average, reaching 2,382.5 hours (Stadtklima Stuttgart, 2024)

Stuttgart's climate anomaly of increased rainfall and prolonged sunshine reflects broader climate trends, as projections show more frequent extreme weather events (WMO, 2023). NASA further reports that record-breaking heatwaves and prolonged droughts are intensifying (NASA, 2022). Given these trends, evaluating LWS microclimate performance is crucial for evaluating their potential to mitigate heat.

5.3.3 Design of the *Plant Pixel*

The *Plant Pixel* is an innovative bio-inspired LWS prototype developed to meet multiple criteria, including low-embodied carbon, hydrological and structural performance, plant performance and cost-effectiveness. It reduces carbon and costs by incorporating recycled materials, low-maintenance plants, a high-water retention substrate, and a plug-in installation (Jimenez et al., 2024).

The planter boxes are made from recycled PVCU modules filled with a recycled textile fiber substrate, requiring minimal irrigation. These modules are attached to the container using aluminum supports. These supports comprise vertical U-shaped profiles measuring 50mm x 50mm x 2mm and horizontal 15-degree profiles measuring 60mm x 2mm. A simplified plug-in connection system was integrated into the square profile modules to facilitate straightforward assembly and disassembly.

A full-scale prototype of the *Plant Pixel*, featuring 500 modules and 500 plants, was built in Wolfschlugen near Stuttgart, Germany (Figure 5-3). The full-scale mock-up was divided into *Plant Pixel* 1 (110mm to 210mm module lengths) and *Plant Pixel* 2 (150mm to 310mm module lengths). *Plant Pixel* 1 and 2 were installed on the container's south wall, each measuring 1200mm wide and 2400mm high. *Plant Pixel* 1 (110mm to 210mm module lengths) was installed on the west wall, measuring 600mm in width and 2400mm in height.

The *Plant Pixel* prototype used a drip irrigation system with a flow rate of 8 l/m^2. The South facade had 20 emitters on the drip line, while the west facade had 6 emitters on the drip line (Figure 5-4). A network of pipes ensured efficient water distribution, with a recirculation storage tank and an electronic scheduling timer. In summer, the system operated three times daily for 5 to 10 minutes, while in winter, it required no irrigation. Organic fertilizer was added to the water every two weeks to maintain plant health.

5.3.4 Plant Selection

The *Plant Pixel* mock-up featured 22 pre-grown plant species selected for suitability to specific microclimatic conditions. These plants were chosen for their drought tolerance, low maintenance requirements, ornamental appeal, dense foliage, hardiness, deep rooting and compatibility with the chosen substrate.

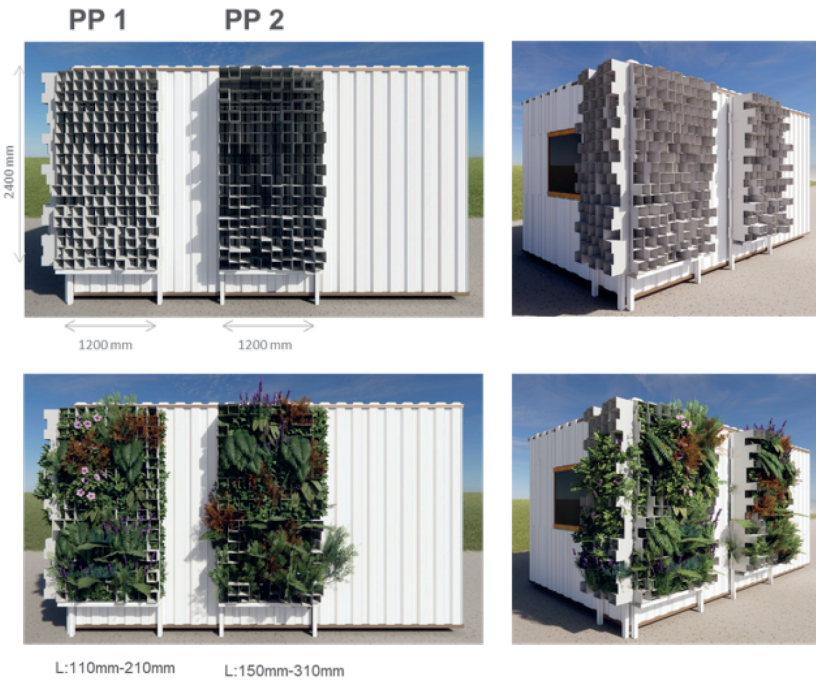

Figure 5-3. *Mock-up design (Source: Author)*

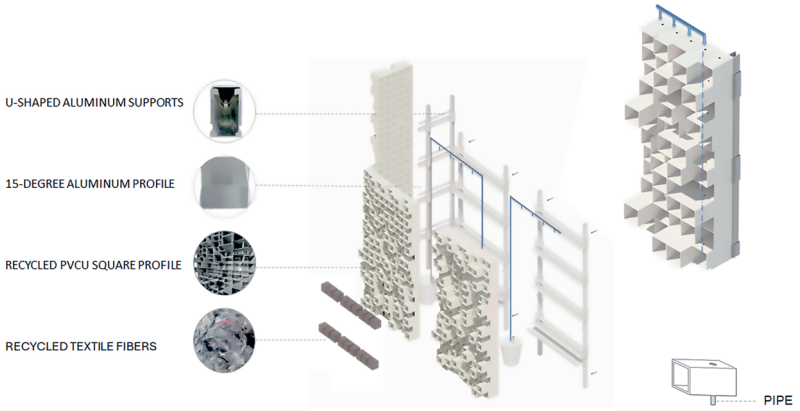

Figure 5-4. *Diagram of the different materials of the Plant Pixel. (Source: Author)*

The selection included 12 perennial herb species, 4 ornamental grasses, 2 perennial ground cover species, 2 perennial shrubs, 1 perennial bulb species, and 1 perennial fruit species (Table 5-2). Each plant was carefully assigned to one of the 500 modules within the full-scale mock-up to prevent root competition, considering the compatibility between root length and module dimensions. This distribution effectively covered the mock-up's upper, middle, and lower sections (Figure 5-5).

Table 5-2. *The 22 Plant Species Selected for the Full-Scale Mock-Up.*

Scientific name	Common name	Plant Type
Ajuga reptans	Bugleweed	Perennial ground cover
Alchemilla epipsila	Alpine lady's mantle	Perennial herb
Allium x Millenium	Millenium ornamental onion	Perennial bulb
Antennaria dioica	Mountain everlasting	Perennial herb
Armeria maritima 'White'	Sea thrift - White variety	Perennial herb
Artemisia schmidtiana 'Nana'	Dwarf silver wormwood	Perennial herb
Carex morrowii	Japanese sedge	Ornamental grass
Centranthus ruber	Jupiter's beard	Perennial herb
Ceratostigma plumbaginoides	Leadwort	Perennial shrub
Euphorbia cyparissias	Cypress spurge - Fens Ruby	Perennial herb
Festuca gautieri	Golden fescue	Ornamental grass
Festuca glauca	Blue fescue	Ornamental grass
Fragaria x ananassa	Strawberry	Perennial fruit-bearing plant
Geranium macrorrhizum	Bigroot geranium	Perennial herb
Hemerocallis	Stella de Oro	Perennial herb
Saponaria ocymoides	Rock soapwort	Perennial ground cover
Sesleria caerulea	Blue moor grass	Ornamental grass
Stachys byzantina	Lamb's ear	Perennial herb
Stachys officinalis	Betony - Saharian Pink	Perennial herb
Teucrium chamaedrys 'Nanum'	Dwarf germander	Perennial shrub
Thymus serpyllum	Creeping thyme	Perennial herb
Veronica spicata	Spike Speedwell	Perennial herb

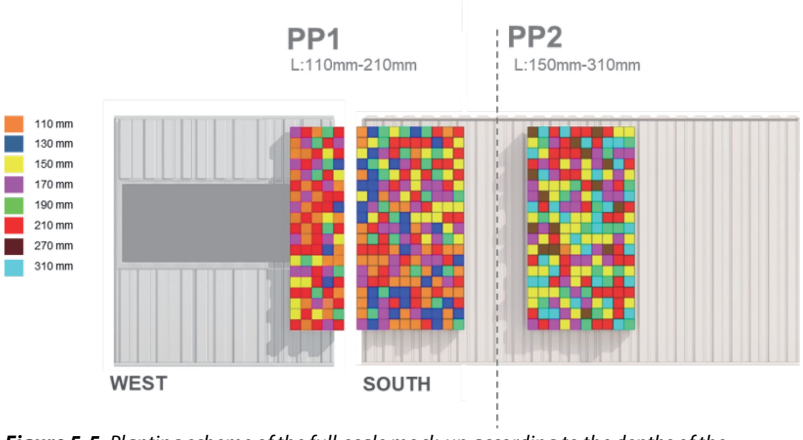

Figure 5-5. *Planting scheme of the full-scale mock-up according to the depths of the modules. (Source: Author)*

5.3.5 Microclimatic Measurements

Microclimatic measurements were conducted to evaluate the performance of the *Plant Pixel* Living Wall System (LWS) compared to an adjacent bare wall of a container. Key parameters assessed included outdoor air temperature, relative humidity, wind speed, and solar radiation (Table 5-3). The experimental setup divided the mock-up into two sections, referred to as PP1 and PP2, to facilitate comparative analysis (Figure 5-6). Microclimatic sensors were installed at 10cm and 40cm from the *Plant Pixel* and bare wall surfaces on the south and west facades. These distances were selected to capture immediate microclimatic effects (e.g., cooling and shading) at 10cm and to evaluate the extent of these effects at 40cm. This methodology aligns with prior research on LWS and ensures a comprehensive assessment of the *Plant Pixel*'s performance under diverse solar exposure and wind conditions. The detailed sensor distribution plan is depicted in Figure 5-6.

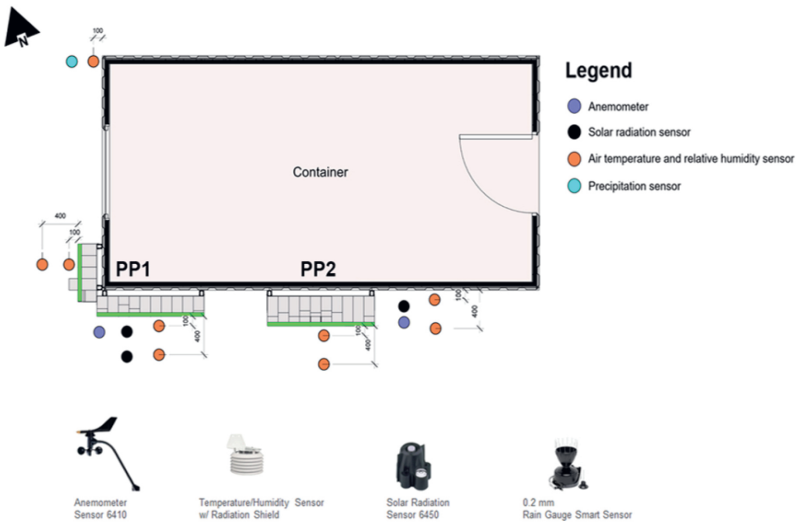

Figure 5-6. *Microclimatic devices distribution plan. (Source: Author)*

5.3.5.1 Outdoor Air Temperature and Relative Humidity

Nine microclimatic sensors were used to collect data on outdoor air temperatures and relative humidity levels. These sensors were positioned at 10cm and 40cm from the *Plant Pixel* and the adjacent bare wall to evaluate the near-wall air temperature. The sensors were all positioned 1.6m above the ground. Six microclimatic sensors were distributed at distances of 10cm and 40cm on the south facade, while three sensors were placed on the west facade. Temperature and humidity data were collected using the Davis 6830 Temperature-Humidity sensor, featuring a radiation shield to ensure accurate measurements. The sensors have a temperature accuracy of ±0.3°C and a humidity accuracy of ±2%. This setup enabled quantifying outdoor air temperature and relative humidity level changes induced by the LWS and their comparison with the bare wall.

Table 5-3. *Summary of the Sensors Used and Design of the Experiment.*

Sensor	Quantity	Model	Position	Height (cm)	Distance from Plant Pixel /Bare Wall (cm)	Accuracy
Outdoor air temperature, Relative humidity	9	Davis 6830 w/ Radiation Shield	South facade (6); West facade (3)	160	10 & 40	Temp: ±0.3°C; Humidity: ±2%
Solar Radiation Sensor	3	Davis Pyranometer 6450	South facade (3): Facing LWS, bare wall, and vertical	170	10 & 40	±5% of full scale
Wind Speed Sensor	2	Davis Anemometer 6410	15 cm in front of LWS; 5 cm beside LWS	180	15 & 5	±2% reading +0.2 m/s
Rain Gauge Sensor (precipitation)	1	Davis Rain Gauge Smart Sensor 6464M	Ground level	180	N/A	±4.0% (0.2 to 50.0 mm/hour) ±5.0% (50.0 to 100.0 mm/ hour)
Microclimatic Data Collection Nodes	4	EnviroMonitor Nodes 6810	Various locations near LWS and bare wall	N/A	50	5-min intervals

5.3.5.2 Solar Radiation

To assess the impact of the *Plant Pixel* on solar radiation, measurements of the reflected vertical solar radiation from the LWS and the bare wall were conducted. Three Davis pyranometer sensors were installed on the south facade to record solar energy input and output. Positioned at a height of 170cm, one sensor was directed towards the LWS, another towards the bare wall, while the third sensor measured vertical irradiance. The Davis Solar Radiation Sensor (SKU-6450) with a pyranometer accuracy of ±5% of the full scale was used for recording solar radiation data.

5.3.5.3 Wind Speed

Wind speed measurements were recorded to evaluate the impact of the LWS on wind speed reduction. Measurements were taken at a distance of 15cm in front of the LWS and 5cm next to the LWS, at a height of 180cm. The Davis Anemometer Sensor (Model 6410) was employed for these measurements, offering an accuracy of ±2% reading +0.2m/s. By capturing variations in wind speed at these distances, the study aimed to understand the role of the LWS in altering local airflow dynamics.

5.3.5.4 Precipitation

Precipitation data were collected using a Davis 0.2mm Rain Gauge Smart Sensor (Model 6464M). This sensor provides high accuracy (±1 count) with a margin of error of ±4.0% for rainfall rates up to 50mm/hour and ±5.0% for rates between 50 and 100mm/hour. While precipitation was not a primary focus of the study, these measurements ensured a comprehensive assessment of the microclimatic conditions during the monitoring period.

5.3.5.5 Data Collection

Data were recorded continuously during summer (June-August), autumn (September-November), and winter (December) to capture seasonal variations and microclimatic fluctuations. To address SQ1, data were collected during summer, focusing on outdoor air temperature, humidity, solar radiation, and wind speed. To assess SQ2, data were extracted for heatwave periods, defined as three consecutive days with temperatures exceeding 28°C. To evaluate SQ3, data were recorded during winter to assess *Plant Pixel*'s microclimate impact.

Microclimatic data were recorded at 5-minute intervals using solar-powered EnviroMonitor Nodes (SKU 6810). These nodes transmitted data wirelessly to a cloud-based storage platform, ensuring continuous monitoring (Figure 5-7). Sensors were placed at 10cm and 40cm from both the *Plant Pixel* and the bare wall to evaluate temperature gradients and airflow modifications. Measurements were taken across seasonal variations, peak solar radiation hours (10:00–19:00), and extreme weather conditions, ensuring a robust assessment of LWS performance.



Figure 5-7. *Microclimatic devices installed in the full-scale mock-up. (Source: Author)*

The microclimatic data collected from the Nodes was transferred to the Weatherlink platform through the IP Gateway for the EnviroMonitor. The Weatherlink platform facilitates data visualization and analysis. The simultaneous collection of data from the sensors enables accurate comparisons between the *Plant Pixel* and the reference bare wall.

5.3.5.6 Data Analysis

Seasonal variations in microclimatic conditions near the *Plant Pixel* and the bare wall were analyzed using a statistical approach. Key metrics were examined across summer, autumn and winter, including averages, maximums, minimums and temporal patterns. This analysis focused on identifying the LWS impact on local microclimate during typical seasonal conditions.

Summer conditions were analyzed to assess the impact of the *Plant Pixel* on outdoor air temperature, humidity, solar radiation, and wind speed, addressing SQ1. To answer SQ2, microclimatic performance was examined during heat waves exceeding 28°C to evaluate the system's effectiveness in mitigating air temperature, humidity, and solar radiation under extreme summer conditions. To address SQ3, winter data from days below 0°C were analyzed to assess the *Plant Pixel*'s microclimatic performance during winter.

By integrating these analyses, the study provided a detailed understanding of the *Plant Pixel*'s seasonal performance, offering insights into its potential as a tool for urban climate adaptation.

5.4 Results and Discussion

This section presents the results from the microclimatic measurements, including outdoor air temperature, relative humidity, wind speed, and solar radiation. The findings related to the research questions addressed in this study are discussed in the context of previous LWS microclimatic studies.

5.4.1 Results for SQ1: Summer Conditions

5.4.1.1 Outdoor air temperature

During the study, summer temperatures recorded on-site near the *Plant Pixel* and bare wall ranged from 15°C to 38°C, with afternoon peaks frequently exceeding 28°C (Figure 5-8, 5-9). The maximum recorded temperature was 39.2°C on August 4, 2022, measured at a distance of 10 cm from the bare wall. In contrast, the *Plant Pixel* prototypes (PP1 and PP2) demonstrated significant cooling effects. At 10cm, PP2 recorded a maximum temperature of 36.2°C, while PP1 registered 35.9°C. These values correspond to reductions of 3.0°C and 3.3°C, respectively, compared to the bare wall. At a distance of 40cm, temperature variations were 1.9°C, demonstrating the *Plant Pixel* prototype's cooling effect (Figure 5-9). These findings demonstrate *Plant Pixel*'s ability to lower summer outdoor air temperatures in PP1 and PP2 configurations.

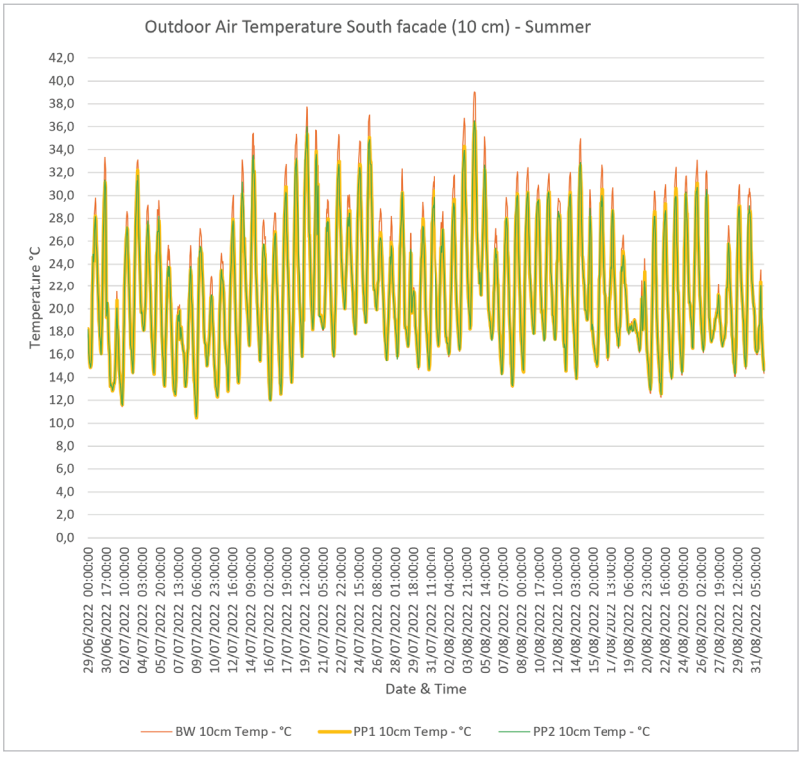

Figure 5-8. *Outdoor air temperature comparison between the Plant Pixel prototypes (PP1, PP2) and the bare wall (BW) at 10 cm distance from the south facade during the peak summer months (June–August 2022). PP1 cooled by 3.3°C at daily Tmax on 4 August. (Source: Author)*

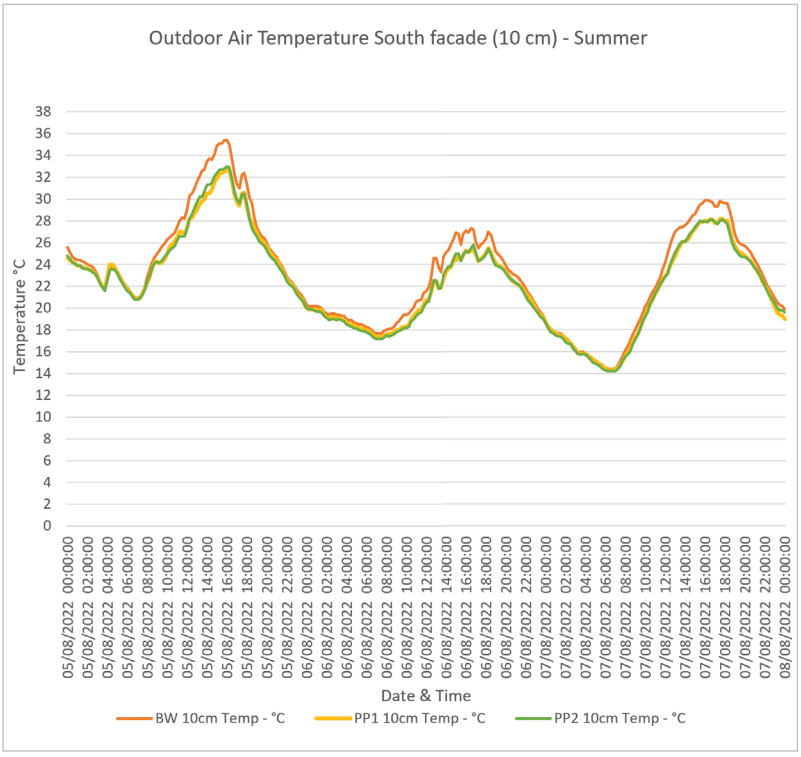

Figure 5-9. *South facade outdoor air temperature variation at 10cm from the Plant Pixel prototypes (PP1, PP2) and the bare wall (BW) in summer. PP1-PP2 cooled by an average of 2.62°C. (Source: Author)*

Consistently, during the peak hours of solar radiation (10:00 am to 7:00 pm), the *Plant Pixel* maintained lower temperatures than the adjacent bare wall (Table 5-4). On the south facade, the average temperature reductions at 10cm and 40cm were 2.62°C and 2.48°C, respectively (Figure 5-10, 5-11). These observations align with earlier studies. For instance, Cameron et al. (2013) reported a 3°C reduction in temperatures near a green facade in a temperate oceanic climate, specifically during peak afternoon hours. Similarly, Jesus (2017) found that a living wall system in Spain decreased temperatures by an average of 2.7°C.

Table 5. 4. *Temperature Profiles Comparing the Bare Wall (BW) and the Plant Pixel (PP1, PP2) on the South facade in Summer.*

Parameter	BW - 10cm	PP1 - 10cm	PP2 - 10cm	BW - 40cm	PP1- 40cm	PP2- 40cm
Average outdoor air temperature °C (Day and night summer)	22.2	21.3	21.4	22.0	21.6	21.5
Average outdoor air temperature °C average (8 am-8 pm)	25.9	24.4	24.4	25.8	25.0	24.5
Minimum air temperature (Day-Hour)	09/07/2022 06:00	09/07/2022 06:00	09/07/2022 06:00	09/07/2022 06:00	09/07/2022 06:00	09/07/2022 06:00
Minimum outdoor air temperature °C	10.3	10.4	10.5	10.3	10.3	10.3
Maximum outdoor air temperature °C (Day-hour)	04/08/2022 15:45	04/08/2022 15:45	04/08/2022 15:45	04/08/2022 15:45	04/08/2022 15:45	04/08/2022 15:45
Maximum outdoor air temperature °C	39.1	36.3	36.7	38.6	37	36.8
Maximum outdoor air temperature (Bare wall difference)	NA	5.5	5.3	NA	2	2.9

During summer, the west-facing bare wall reached a peak temperature of 38.2°C. In contrast, temperatures recorded at 10cm from PP2 and 40cm from PP1 were 37.8°C and 37°C, respectively (Figure 5-11). At 9:30 pm on August 4, 2022, the west facade displayed a marked temperature disparity, with the bare wall at 30.7°C and the LWS at 28.3°C, reflecting a 2.4°C difference at 10cm.

The *Plant Pixel* consistently maintained average temperatures approximately 2°C cooler than the adjacent bare wall throughout the day. However, the cooling performance of the west-facing LWS was slightly less pronounced compared

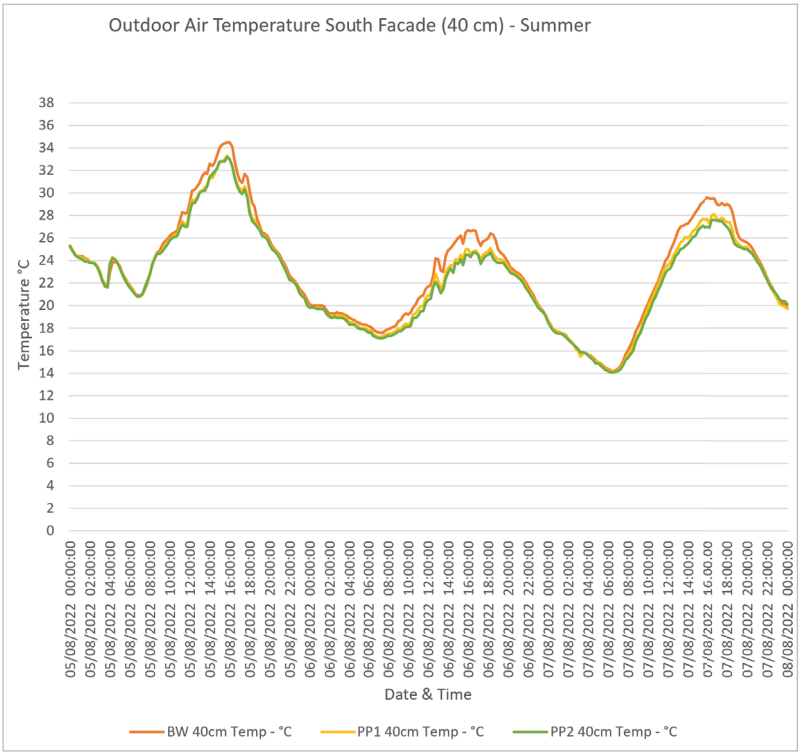

Figure 5-10. *South facade outdoor air temperature variation at 40cm from the Plant Pixel prototypes (PP1, PP2) and the bare wall (BW) in summer. PP1-PP2 cooled by an average of 2.48°C. S(ource: Author)*

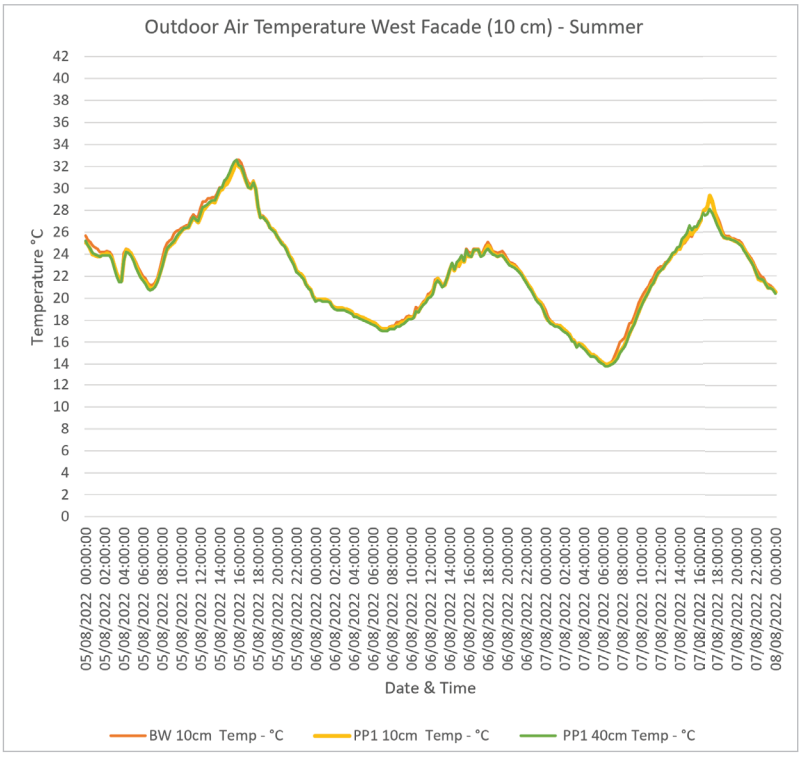

Figure 5-11. *West facade outdoor air temperature comparison at 10cm and 40cm from the Plant Pixel (PP1) and bare wall (BW) in summer. Cooling is less noticeable compared to the south-facing facade. (Source: Author)*

to the south-facing facade. This difference is attributed to the smaller surface area of the west-facing installation, which limited its capacity to regulate temperatures as effectively as the larger south-facing facade.

The temperature differences observed highlight the cooling potential of the west-facing *Plant Pixel*, particularly at a distance of 10cm. At night, the west-facing LWS continued to regulate temperatures, showing a maximum difference of 1°C compared to the bare wall.

Meteorological data for October and November 2022 revealed significantly elevated temperatures, exceeding the long-term average by 4.5°C and 3.0°C, respectively. This period also recorded above-average sunshine hours. For example, the first six weeks of autumn exhibited temperature patterns resembling those typically observed in summer.

On September 5th, temperatures near the bare wall peaked at 33.8°C, while at 10cm from the south facade, they amounted to 31.1°C (PP2) and 30.3°C (PP1). This trend continued until October 17th, with temperatures near the bare wall measuring 27.9°C at 10cm, 26.5°C (PP1), and 26.8°C (PP2) (Figure 5-12, 5-13). The south-facing LWS achieved a maximum temperature reduction of 3.8°C at 10cm. On the west facade, the maximum temperature reductions were 1.9°C at 10cm and 1.6°C at 40cm. These findings are consistent with a study conducted in Spain, which observed that LWS reduced 1.5°C in autumn temperatures ((Jesus et al., 2017)

These findings highlight the capacity of the *Plant Pixel* to moderate temperatures during transitional seasons, even under elevated heat conditions. Observed temperature reductions on the south facade highlight the importance of orientation and solar exposure in optimizing the thermal performance of LWS.

5.4.1.2 Solar Radiation Incidence

During summer, the study recorded maximum daily vertical solar radiation ranging from 735 to 1194 W/m^2 (Figure 5-14, 5-15). The *Plant Pixel* significantly reduced reflected solar radiation compared to the adjacent bare wall, contributing to lower outdoor air temperatures. For instance, on July 19 at 4:00 pm, the maximum difference in reflected radiation reached 336 W/m^2, with the bare wall reflecting 367 W/m^2 and the LWS reflecting only 31 W/m^2, while the vertical solar radiation was 1,086 W/m^2. This substantial reduction in reflected solar radiation highlights LWS's capacity to mitigate heat stress, particularly during peak solar radiation hours.

Research by Hoelscher et al. (2016) and Jim (2015) identifies solar radiation as the primary driver of the thermal performance of living wall systems. Consistent with these findings, the present study demonstrated a positive correlation (0.73) between outdoor air temperature and solar radiation at 10cm from the bare wall during summer. This correlation highlights the significant impact of solar

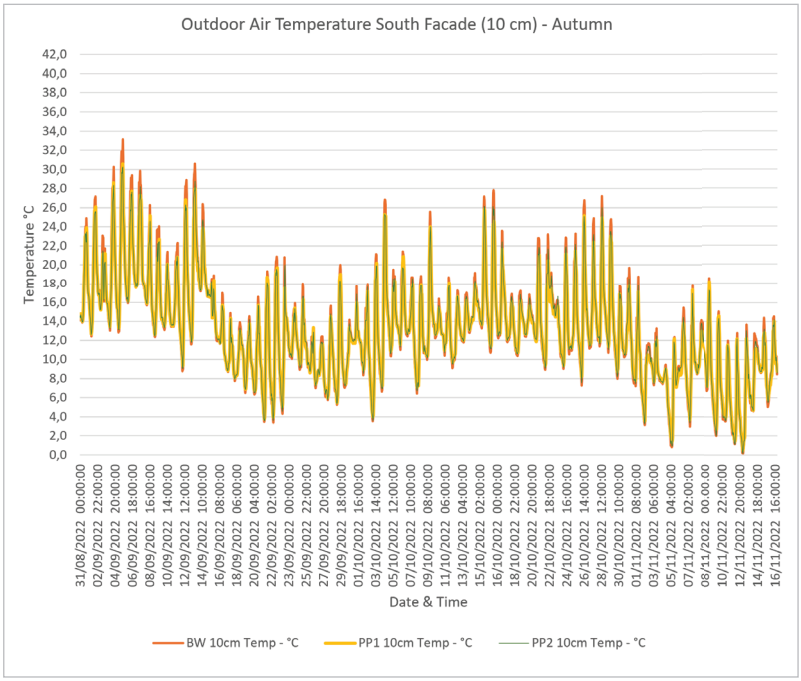

Figure 5-12. *Comparative outdoor air temperature between Plant Pixel (PP1, PP2) and bare wall at 10cm from the south facade during autumn. PP1-PP2 cooled by 3.8°C at Tmax. (Source: Author)*

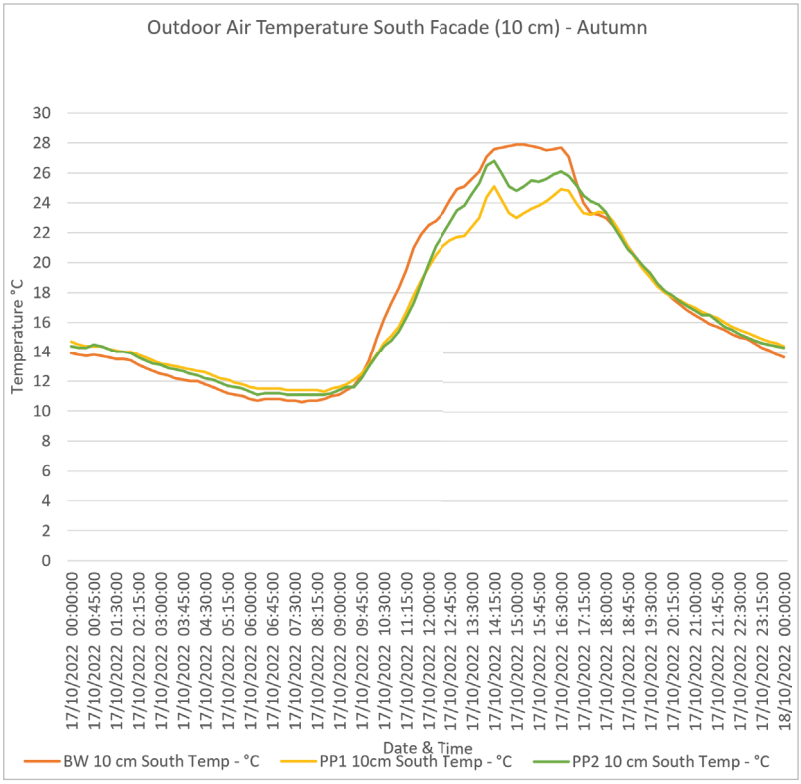

Figure 5-13. *Comparison of outdoor air temperatures at 10mm from the south facade (PP1, PP2, BW) during autumn (October 17, 2022). PP1 cooled by 1.4°C (day-avg). (Source: Author)*

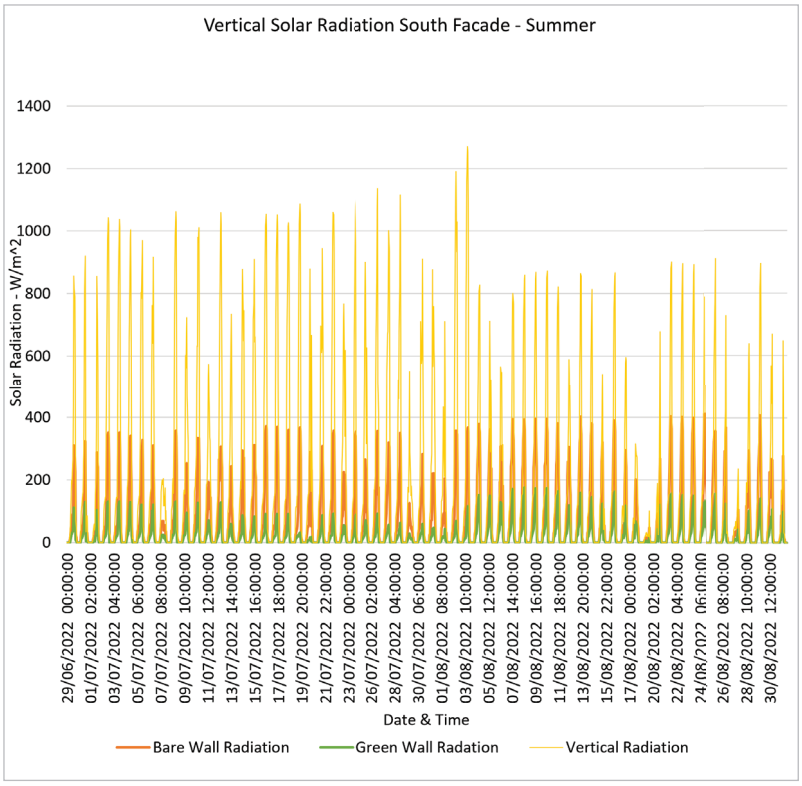

Figure 5-14. *Daily vertical solar radiation measured at the south facade during peak summer months (June–August 2022). Vertical Solar Radiation Ranges from 735–1194 W m^{-2}. (Source: Author)*

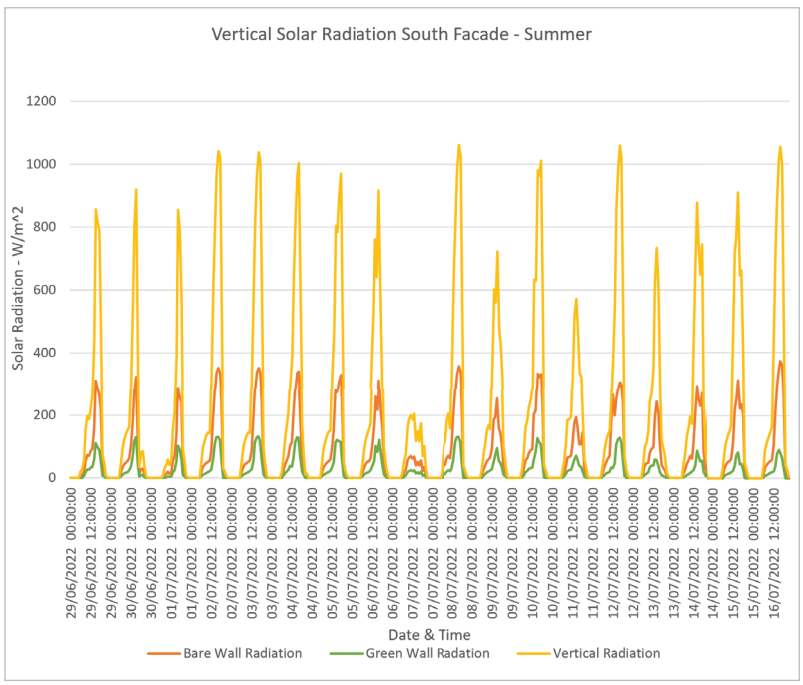

Figure 5-15. *Comparative solar radiation reflected from Plant Pixel and bare wall on the south facade over an 18-day summer period (June 29–July 16, 2022). Vegetation reduced reflection by 68%. (Source: Author)*

radiation on temperatures near the bare wall, which absorbs and radiates heat more directly under increased solar exposure (Figure 5-16, 5-17). In autumn, the correlation for the bare wall remains high at 0.66, indicating a continued pronounced response to solar radiation despite the seasonally reduced intensity (Figure 5-18 to 5-21)

Plant Pixel (PP2) exhibited a more moderate response to temperature changes influenced by solar radiation. The correlation between temperature and radiation for the green wall was 0.60 in summer, suggesting that the LWS buffers solar radiation's impact through mechanisms such as plant coverage and moisture retention (Figure 5-16 to 5-19). This buffering effect reduces the influence of solar radiation on local temperatures. In autumn, the correlation for the green wall was 0.61, showing consistent moderation across seasons. This stability highlights the *Plant Pixel*'s capacity to regulate temperatures, even during periods of fluctuating solar intensity.

Furthermore, the positive correlations observed between mean outdoor air temperature, solar radiation and relative humidity align with findings by Pan et al. (2018) illustrating consistent microclimatic interactions. These correlations highlight the distinct responses of different wall types to solar radiation: the bare wall (BW) has a pronounced response to radiation, especially in summer, while the green wall (PP2) buffers temperature fluctuations because of plant insulation and moisture retention.

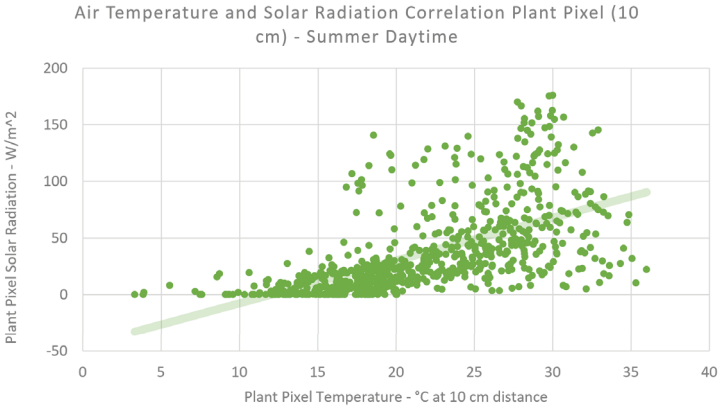

Figure 5-16. *Correlation between solar radiation and outdoor air temperature at 10cm from the Plant Pixel south facade during daytime summer conditions (July–August 2022). (Source: Author)*

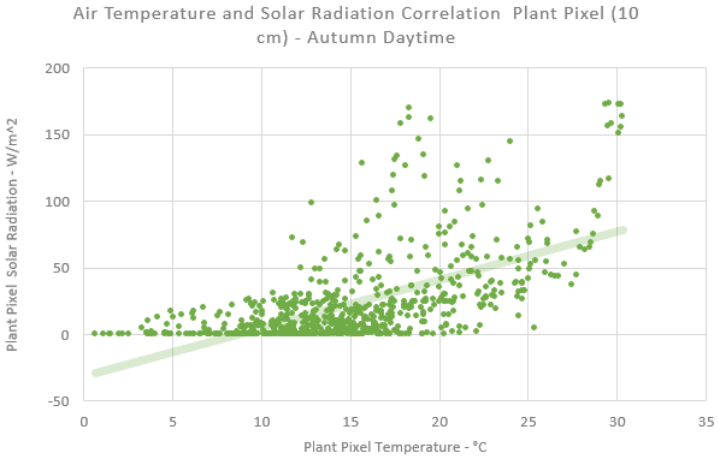

Figure 5-17. *Correlation between solar radiation (W/m²) and outdoor air temperature at 10cm from the Plant Pixel during autumn daytime conditions (September–November 2022). (Source: Author)*

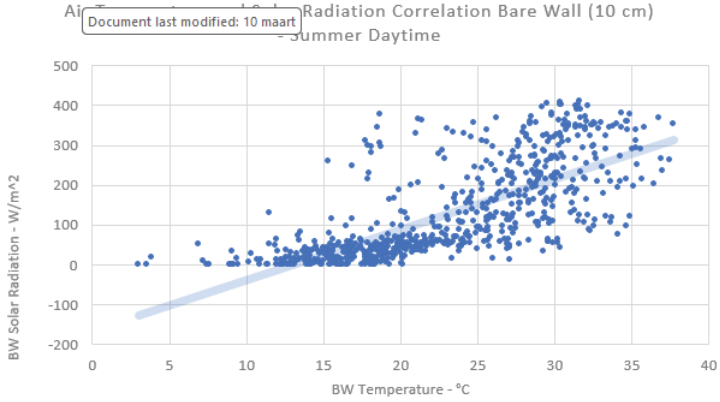

Figure 5-18. *Correlation between solar radiation and outdoor air temperature at 10cm from the bare wall (BW) south facade during summer daytime conditions (July–August 2022). (Source: Author)*

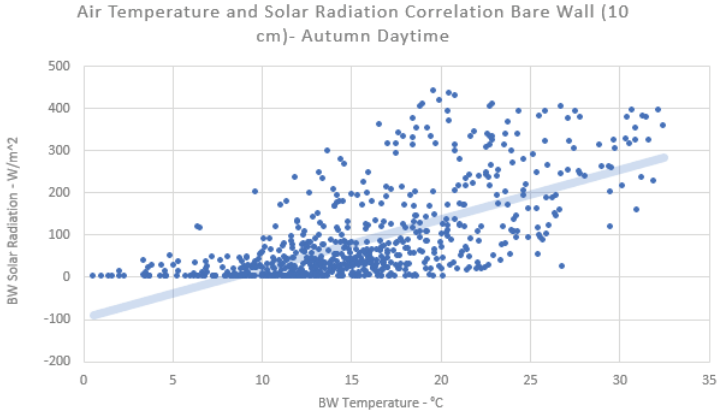

Figure 5-19. *Correlation between solar radiation and outdoor air temperature at 10cm from the bare wall (BW) south facade during autumn (September–November 2022). (Source: Author)*

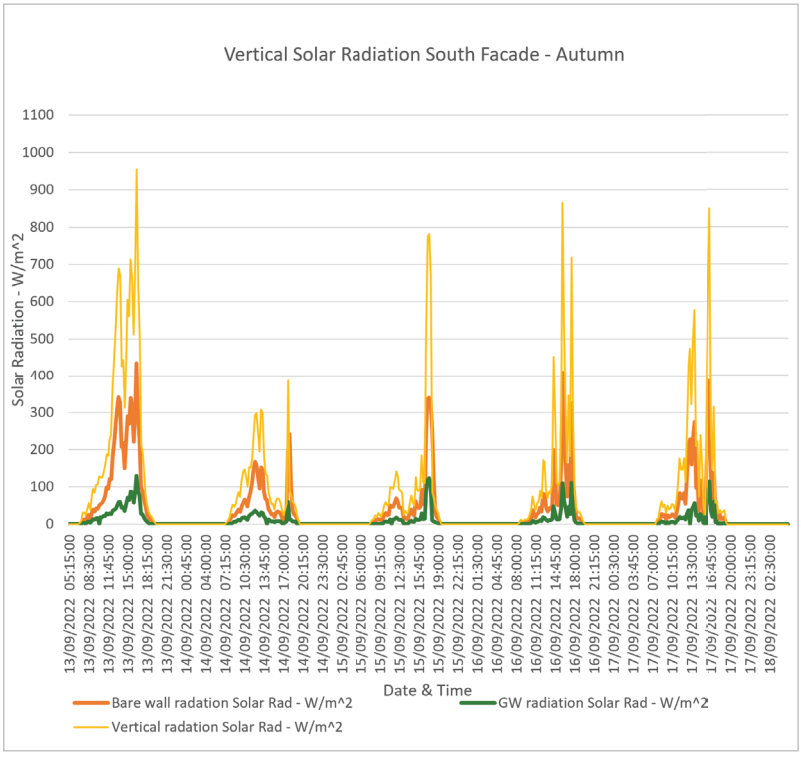

Figure 5-20. *Comparative solar radiation reflected from Plant Pixel (PP2) and bare wall on the south facade over a 6-day Autumn period (September 13–19, 2022). Vegetation cut peak reflection by 61%. (Source: Author)*

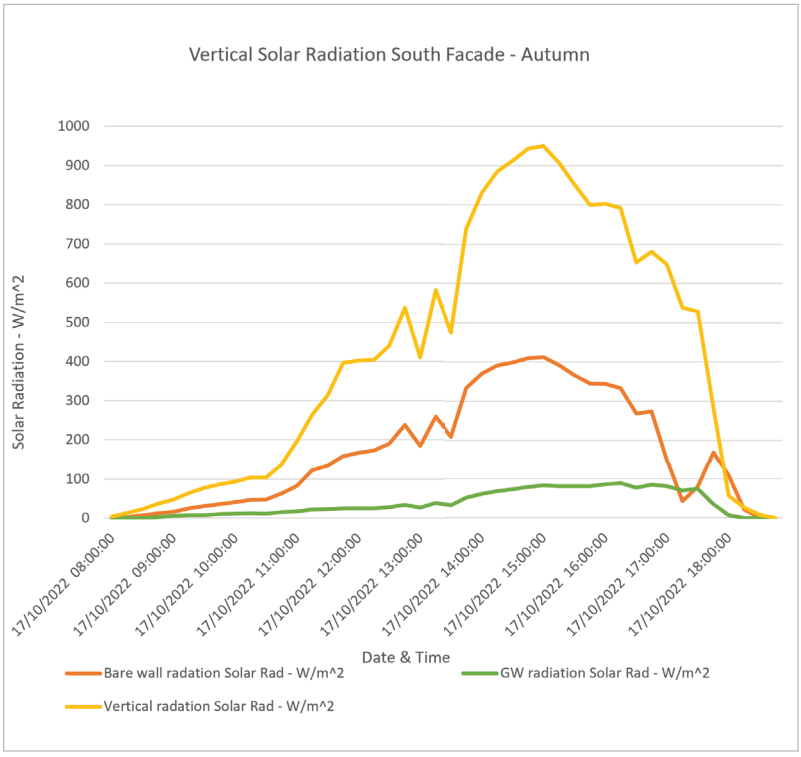

Figure 5-21. *Solar radiation reflected by the Plant Pixel and the bare wall on the south facade during autumn. (Source: Author)*

5.4.1.3 Humidity

Variations in humidity levels were observed near the bare wall and the *Plant Pixel* LWS, with notable differences based on proximity to the surfaces (Figure 5-22, 5-23). At 10cm from the bare wall, relative humidity ranged from a maximum of 98.5% to a minimum of 18.8%, with an average of 59.31%. At 40cm, the bare wall displayed similar humidity levels, with a maximum of 98.3%, a minimum of 17.9%, and an average of 59.2%.

Proximity to PP2 resulted in higher relative humidity levels (Figure 5.22-23). At 10cm, humidity ranged from a maximum of 99.7% to a minimum of 23.8%, averaging 65.59%. At 40cm, the PP2 recorded humidity levels ranging from a maximum of 99% to a minimum of 19.5%, with an average of 60.8%. For the PP1, relative humidity at 10cm ranged from 99.7% to 25.4%, averaging 66.37%. At 40cm, PP1 created humidity levels between 100% and 21.5%, averaging 63.31%.

The *Plant Pixel* generated a 5–7% increase in relative humidity compared to the bare wall at 10cm and a 4% increase at 40cm. These findings align with studies conducted in Spain and the UK, which reported similar humidity increases of up to 7% near vegetated walls, offering a more stable microclimate than bare surfaces (Susca et al., 2022). The overall increase in humidity near the *Plant Pixel* in this study was moderate, reflecting its localized impact.

The observed cooling effect near the *Plant Pixel*, characterized by increased humidity and reduced outdoor air temperatures, is likely because of evapotranspiration, as Pan et al. (2018) suggested. Evapotranspiration enhances moisture levels in the surrounding air, particularly during periods of high solar radiation, contributing to localized cooling. These findings highlight the ability of LWS to regulate humidity and improve microclimatic conditions near the system.

5.4.1.4 Wind Speed

During summer, wind speed analysis revealed consistently lower velocities at 5cm from the *Plant Pixel* facade compared to measurements taken at 15cm (Figure 5-24). Wind speeds at 5cm ranged from 0.0m/s to a maximum of 3.0m/s, whereas at 15cm, speeds ranged from 0.0m/s to a maximum of 6.8m/s. The most significant recorded difference between these distances was 5.9m/s. On average, wind speed at 5cm from the *Plant Pixel* was 0.44m/s, compared to 0.77m/s at 15cm. This reduction is consistent with findings by Bakhshoodeh et al. (2022), who reported that living wall systems can reduce wind speed by more than 50%.

During autumn, wind speeds near *Plant Pixel* followed a similar trend. At 5cm, wind speeds ranged from 0.0m/s to 2.3m/s, while at 15cm, speeds reached a maximum of 5.4m/s. The most significant difference between these distances was 4.5m/s (Figure 5-25). The average wind speed at 5cm was 0.33m/s, increasing

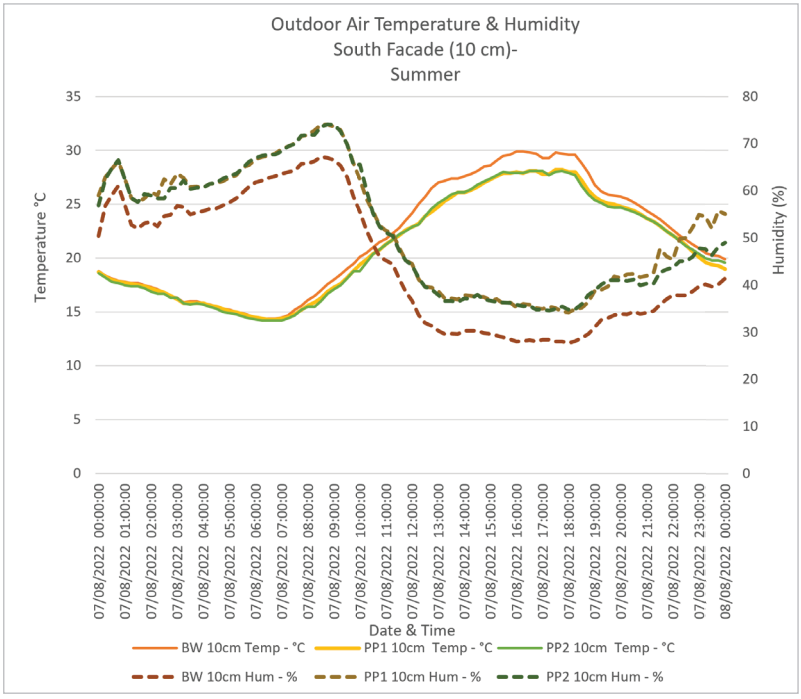

Figure 5-22. *Comparative temperature and relative humidity at 10cm from the south facade (Plant Pixel PP2 and bare wall BW) during summer. (Source: Author)*

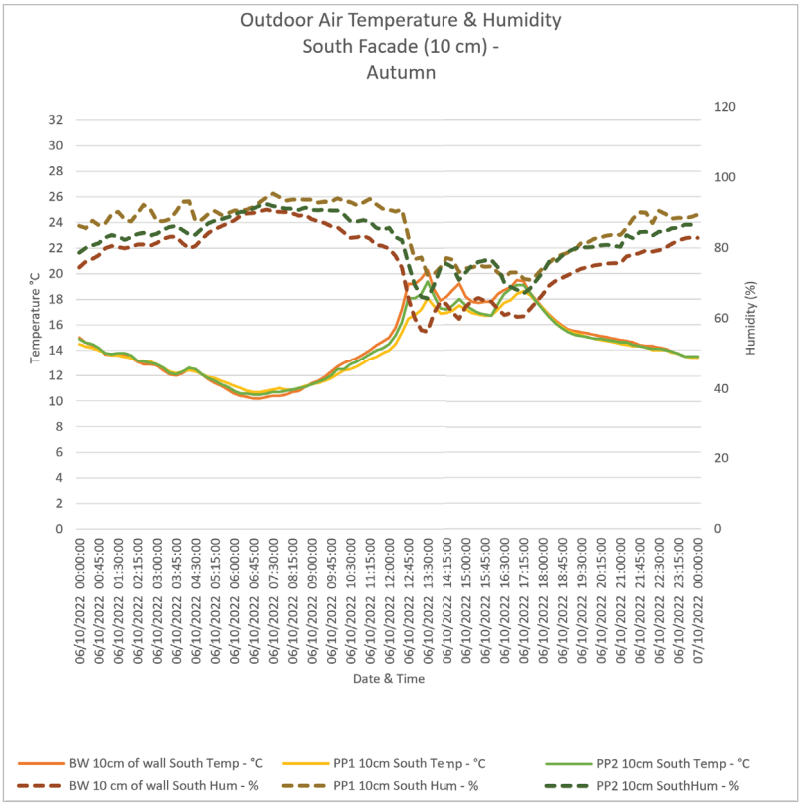

Figure 5-23. *Autumn outdoor air temperature and relative humidity comparison at 10cm from Plant Pixel (PP1, PP2) and the bare wall (BW) on the south facade. (Source: Author)*

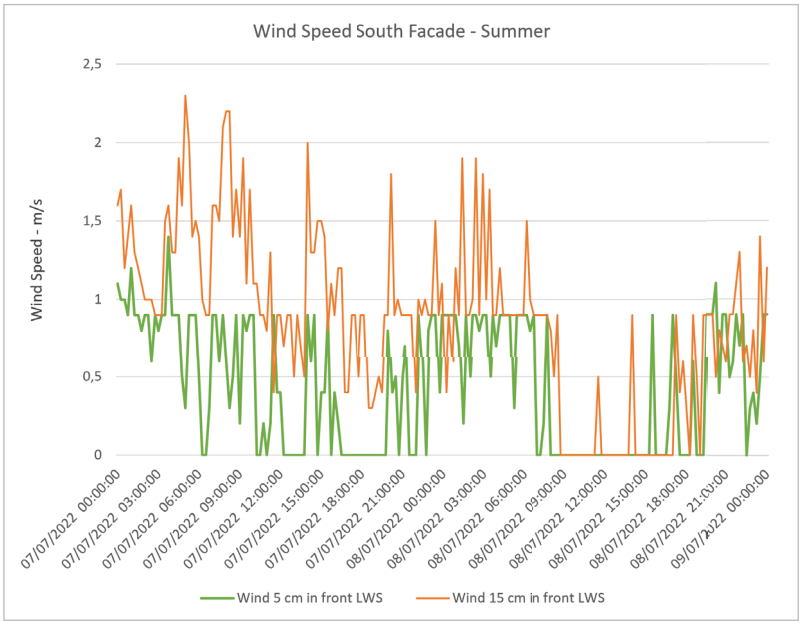

Figure 5-25. *Wind speed recorded at distances of 5cm and 15m from Plant Pixel from the south facade during autumn. (Source: Author)*

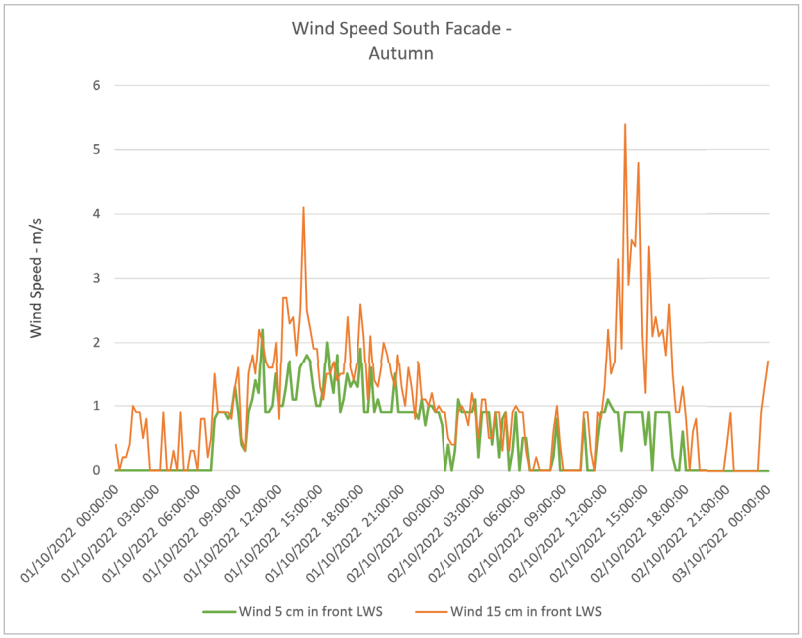

Figure 5-24. *Wind speed recorded at distances of 5 cm and 15cm from the Plant Pixel south facade during summer. Source: Authors own work.*

to 0.50m/s at 15cm. These results are aligned with the study by Ottelé and Perini (2017), which demonstrated the effectiveness of vegetated facades, such as planter boxes, in acting as wind barriers.

The observed reduction in wind speed near the *Plant Pixel* suggests the LWS modified micro-wind patterns, potentially creating a zone of reduced air movement near the wall surface. Therefore, localized wind velocity reduction may enhance indoor thermal comfort by minimizing convective heat loss and air infiltration through the building envelope (Pérez et al., 2011). The foliage of the LWS acts as a buffer, disrupting wind flow and potentially creating a more stable microclimate near the facade.

5.4.2 Results for SQ2: Mitigating Urban Heat Stress

During the heatwave from August 3 to August 6, 2022, the *Plant Pixel* prototypes (PP1 and PP2) demonstrated enhanced cooling capabilities. The data collected on August 4 at 1:00 pm indicates a 5.5°C temperature difference. The bare wall's temperature was 36.6°C, while the *Plant Pixel*, at a distance of 10cm, registered 31.1°C (Figure 5-26, 5-27). These results align with previous studies showing LWS altering surface energy balances by increasing latent heat release and reducing sensible heat release (Bakhshoodeh et al., 2022). Additionally, Cheng et al. (2010) suggest that denser vegetation on LWS improves temperature regulation to mitigate urban heat stress.

The *Plant Pixel* also exhibited a 55% reduction in reflected solar radiation compared to the bare wall, resulting in significantly lower outdoor air temperatures (Figure 5-27). For instance, at 5:00 pm on August 4, temperatures near the bare wall peaked at 39.1°C, while temperatures near the LWS remained lower at 35.8°C (Figure 5-27). Differences in solar reflectivity partly explain this discrepancy: the bare wall reflected 332 W/m^2 of solar radiation, whereas the LWS reflected only 147 W/m^2, despite surfaces receiving 809 W/m^2 of vertical solar radiation.

Furthermore, Di and Wang (1999) explain that the LWS cooling mechanism occurs through the conversion of absorbed heat to evaporation during photosynthetic evapotranspiration. Their findings indicate LWS reflects 15%, transmits 15%, and absorbs 71.5% of solar energy, with energy losses distributed as 40% through convection, 42% through transpiration, and 16% through long-wave radiation. Therefore, the transpiration process of LWS aids in cooling the surrounding air, countering the significant temperature increase caused by solar radiation near the bare walls (Di & Wang, 1999). Understanding these intricate heat exchange mechanisms in LWS is imperative for optimizing cooling processes and climate adaptation strategies (Hoelscher et al., 2015; Kim et al., 2023).

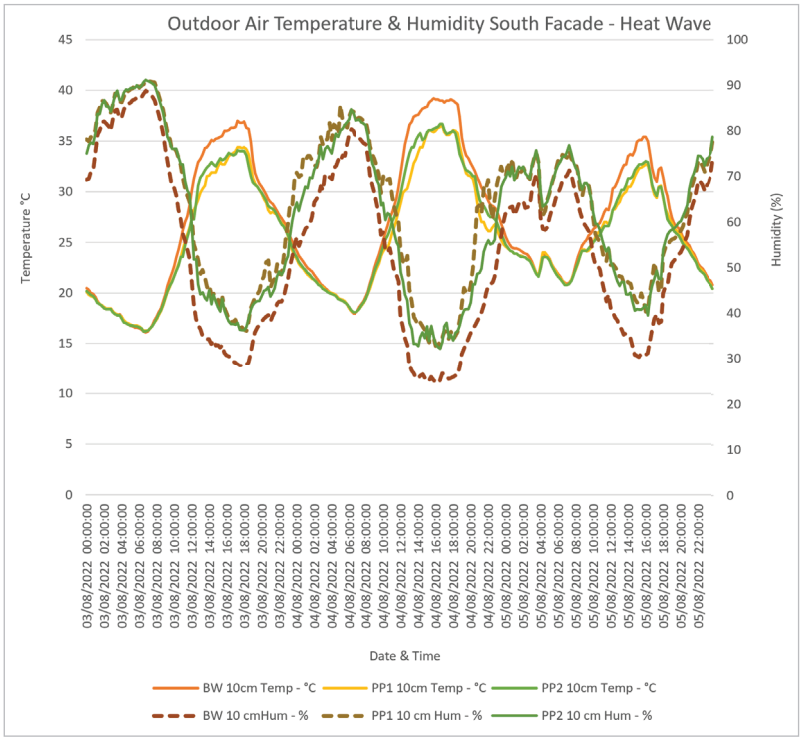

Figure 5-26. *Air temperature and relative humidity comparison at 10cm from the south facade during a heatwave (August 3–5, 2022). (Source: Author)*

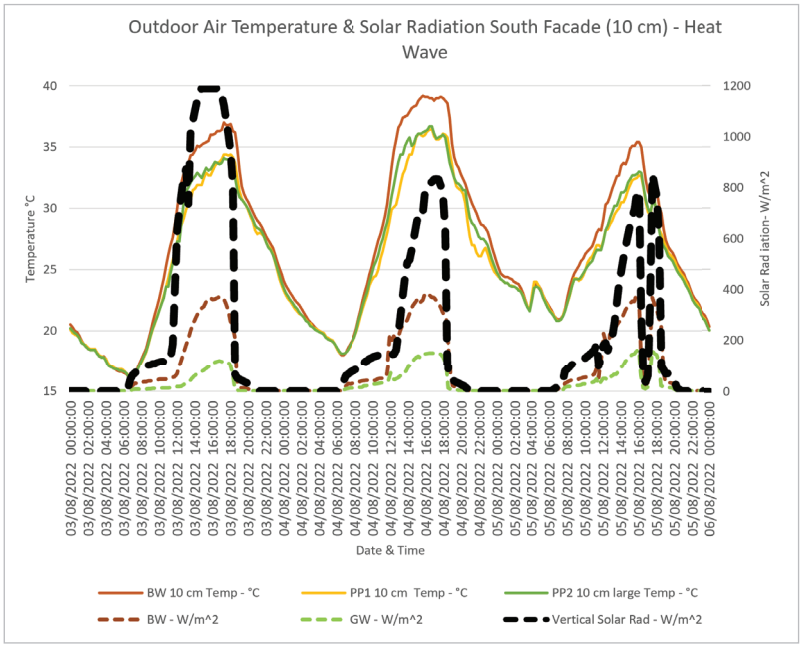

Figure 5-27. *Comparative air temperature and solar radiation during a heatwave on August 4, 2022, at 10cm from the south facade. (Source: Author)*

LWS are recognized for their capacity to modify urban surface thermal properties and mitigate heat stress by reducing solar reflection (Hoelscher et al., 2015). The present study identified a substantial reduction in reflected short-wave solar radiation, with the *Plant Pixel* reducing reflectivity by 213 W/m² compared to adjacent bare walls. These findings align with research by Kim et al. (2023), which showed that LWS reflect 180 W/m² less short-wave radiation than high-albedo walls. Vegetation on LWS effectively blocks and absorbs solar radiation, minimizing heat radiated back into the environment (Kim et al., 2023; Ottelé & Perini, 2017).

Furthermore, our investigation confirms that during heatwaves, *Plant Pixel* effectively reduces outdoor air temperatures through evapotranspiration and absorption of intense solar radiation. The higher plant density within the *Plant Pixel*, featuring 70 plants/m² compared to the typical 30 plants/m² in conventional living wall systems, underscores the crucial role of dense vegetation in optimizing cooling efficiency. These findings align with Zuckerman and Lensky (2023) indicating that temperatures exceeding 22°C, combined with direct sunlight and dense vegetation, promote cooling via enhanced evapotranspiration.

Adequate irrigation is critical for ensuring effective plant transpiration and maximizing the cooling potential of LWS (Cheng et al., 2010). Previous studies have demonstrated a direct relationship between irrigation levels and reductions in outdoor air temperatures. For instance, in Austria, the maximum temperature difference between a bare wall and a well-irrigated LWS reached 3.4°C (Cameron et al., 2014)(Figure 5-28).

Implementing LWS offers additional benefits by reducing urban outdoor air temperatures, which can lead to decreased reliance on mechanical cooling systems and improved energy efficiency (Susca et al., 2022; Feng & Hewage, 2014).

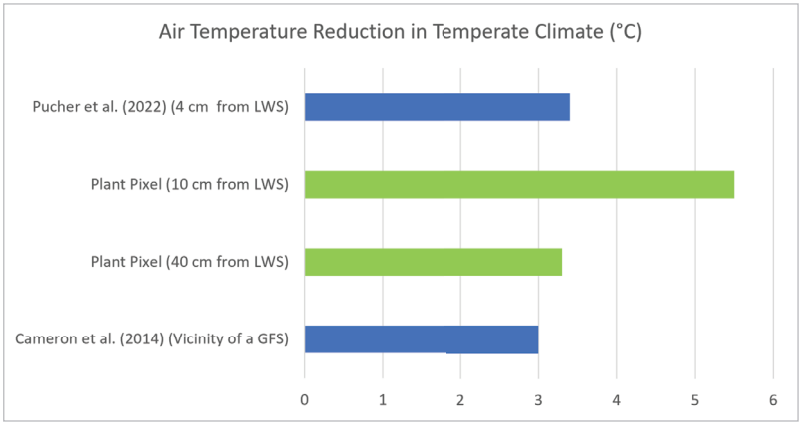

Figure 5-28. *Comparison of the Plant Pixel prototype with conventional LWS systems in temperate climates during summer. (Source: Author)*

5.4.3 Results for SQ3: Winter Conditions

5.4.3.1 Outdoor air temperature

In December 2022, winter meteorological data revealed daily outdoor air temperature fluctuations ranging from -3°C to 10°C. At a distance of 10cm from the bare wall, maximum temperatures were recorded as 14.5°C, while the corresponding values for PP2 and PP1 were 14.2°C and 14.0°C, respectively. At 40cm, the bare wall reached 14.4°C, whereas PP2 and PP1 registered 13.9°C and 13.9°C, respectively (Figure 5-29, 5-30).

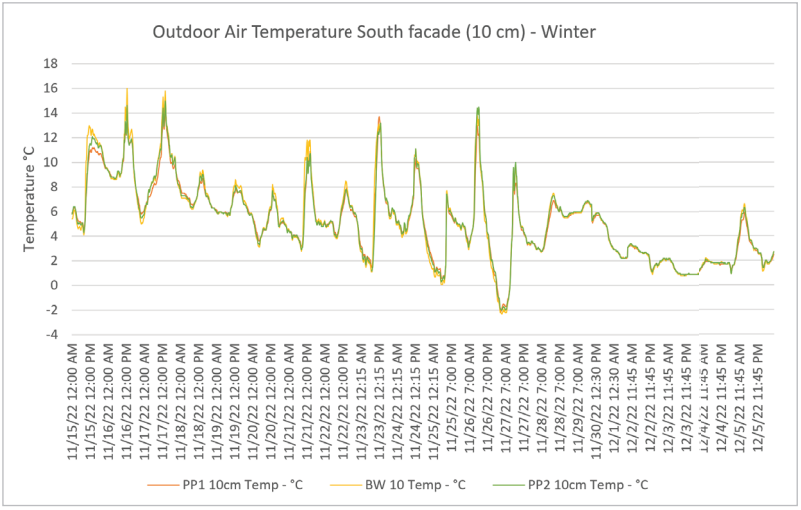

Figure 5-29. *Outdoor air temperature fluctuations measured at 10m distance from the south wall for Plant Pixel (PP1, PP2) and the bare wall (BW) in winter. (Source: Author)*

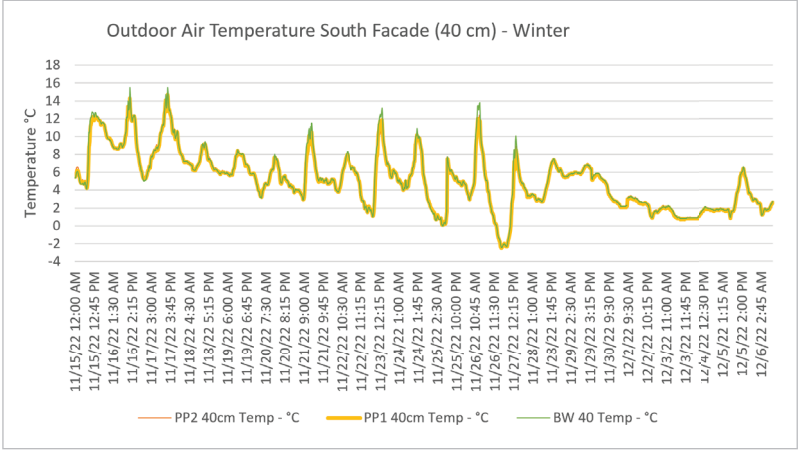

Figure 5-30. *Outdoor air temperature measured at 40cm distance from the south wall for Plant Pixel (PP1, PP2), and the bare wall (BW) in winter.(Source: Author)*

Plant Pixel contributed to a maximum outdoor air temperature reduction of 1.5°C at 10cm and 0.6°C at 40m, with an average reduction of 0.1°C (Table 5-5). Similar findings were reported in a Mediterranean climate study, where the south facade experienced a maximum outdoor air temperature reduction of 0.54°C in winter at a distance of 1m from the LWS in Spain (Oquendo-Di Cosola et al., 2020d). The similarity between the results underscores the consistent thermal moderation effect of LWS across varying climatic contexts, particularly in temperate and Mediterranean climates. Additionally, the west-facing side exhibited an average outdoor air temperature reduction of 0.1°C compared to the bare wall during winter.

Table 5-5. *Temperature Profiles Comparing the Bare Wall (BW) and the Plant Pixel (PP1, PP2) on the South and West facades in winter. (Source: Author)*

Parameter	SOUTH BW- 10 cm	SOUTH PP1 - 10cm	SOUTH PP2 - 10cm	SOUTH BW - 40cm	SOUTH PP1 - 40cm	SOUTH PP2 - 40cm	WEST BW - 10cm	WEST PP1 - 10cm	WEST PP1 - 40cm
Average outdoor air temp - °c	5.14	5.04	5.11	5.00	5.12	5.12	5.98	5.90	5.83
Maximum outdoor air temp - °c	14.55	14.09	14.20	13.98	14.40	13.98	13.5	13.7	14
Minimum outdoor air temp - °c	-2.23	-1.93	-1.93	-2.43	-2.30	-2.25	-2.38	-2.38	-2.6

The LWS have little to no effect on temperature regulation during winter, as the cooling impact is negligible. Instead, they contribute to a more stable microclimate near building facades, minimizing thermal fluctuations without significantly altering outdoor air temperatures (Figure 5-29, 5-30).

The *Plant Pixel* prototype showed minimal warming effect at night. Between 8:00 p.m. and 8:00 a.m., the *Plant Pixel* resulted in an average outdoor air temperature increase of 0.3°C, with a maximum recorded increase of 0.7°C at a distance of 10cm from the facade (Figure 5-31 to 5-33). This slight temperature increase can be attributed to the heat-retention capacity of the dense vegetation and substrate layer, which absorb heat during the day and release it at night, reducing thermal fluctuations near the facade. While the impact is minor, LWS contribute to stabilizing temperatures and enhancing thermal comfort in urban microclimates, moderating localized thermal conditions.

Previous studies have shown that the vegetation layers in LWS function as thermal barriers, influencing nighttime temperature dynamics. For instance, research conducted in the UK reported that green facades increased nighttime temperatures by an average of 0.5°C (Bolton et al., 2014). This highlights the insulating properties of plants in reducing heat loss during colder periods.

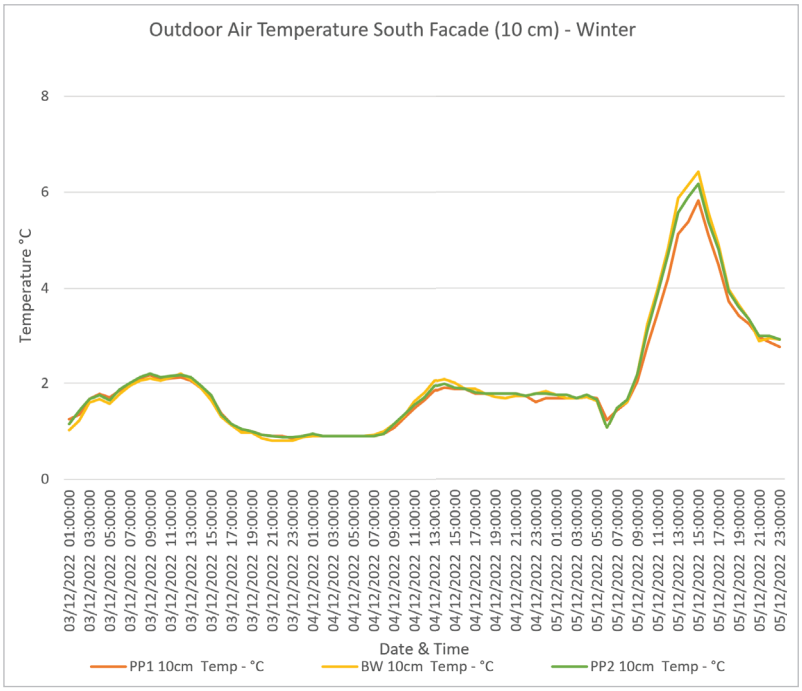

Figure 5-31. *Outdoor air temperature fluctuations measured at 10cm distance from the south wall for Plant Pixel 1 (PP1, PP2) and the bare wall (BW) during winter. (Source: Author)*

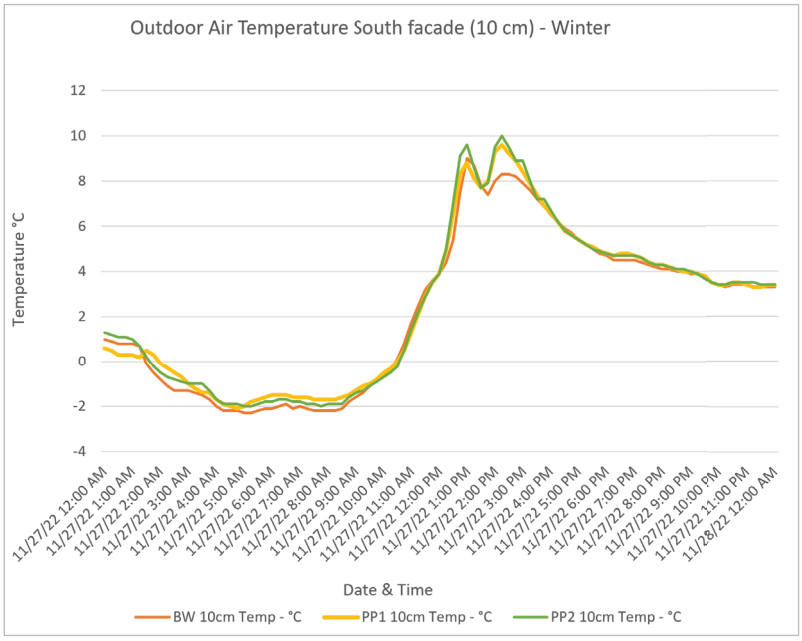

Figure 5-32. *Outdoor air temperature fluctuations measured at 10cm distance from the south wall for Plant Pixel (PP1, PP2) and the bare wall (BW) during the coldest winter day recorded (27 November 2022). (Source: Authors)*

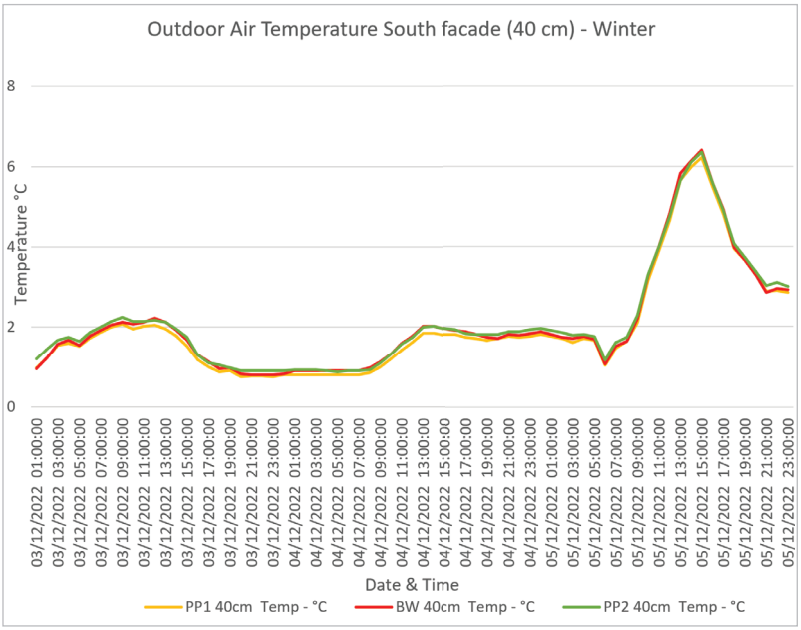

Figure 5-33. *Temperature fluctuations measured at 40m from the south wall for Plant Pixel (PP1, PP2) and the bare wall (BW) during winter. December nights; PP2 warmed by 0.2 °C. (Source: Author)*

5.4.3.2 Solar Radiation

During winter, the *Plant Pixel* reduced reflected solar radiation by an average of 63% compared to the adjacent bare wall (Figure 5-34, 5-35). The *Plant Pixel* and bare wall had daily average solar radiation values of 30.42 W/m^2 and 83.28 W/m^2, respectively. During the day, vertical solar radiation averaged 114.09 W/m^2. Vertical solar radiation during daytime hours – defined as periods when solar radiation exceeded zero – averaged 114.09 W/m^2. These measurements underscore the *Plant Pixel*'s ability to reduce solar radiation during winter, a characteristic that is not considered optimal in winter.

The winter weather recorded temperatures ranging from -3.3°C to 14°C, with a maximum vertical solar radiation at 480 W/m2, and an average of 8.5 hours of sunshine per day. During the winter, the *Plant Pixel* provides a reduced cooling effect during the day, averaging around 0.1°C. Conversely, at night, it tends to warm the air by an average of 0.3°C. Sternberg et al. (2011) found LWS increased external wall temperature by 0.5°C, minimizing temperature fluctuations on winter nights. However, the difference in outdoor air temperature between the LWS and the bare wall in winter is negligible.

While increased solar radiation typically enhances the cooling potential of LWS, such effects are diminished in winter because of lower solar intensity. Koyama et al. (2013) found that green facades require at least 300 W/m^2 of solar radiation to achieve effective cooling. In winter, the reduced solar input limits the cooling

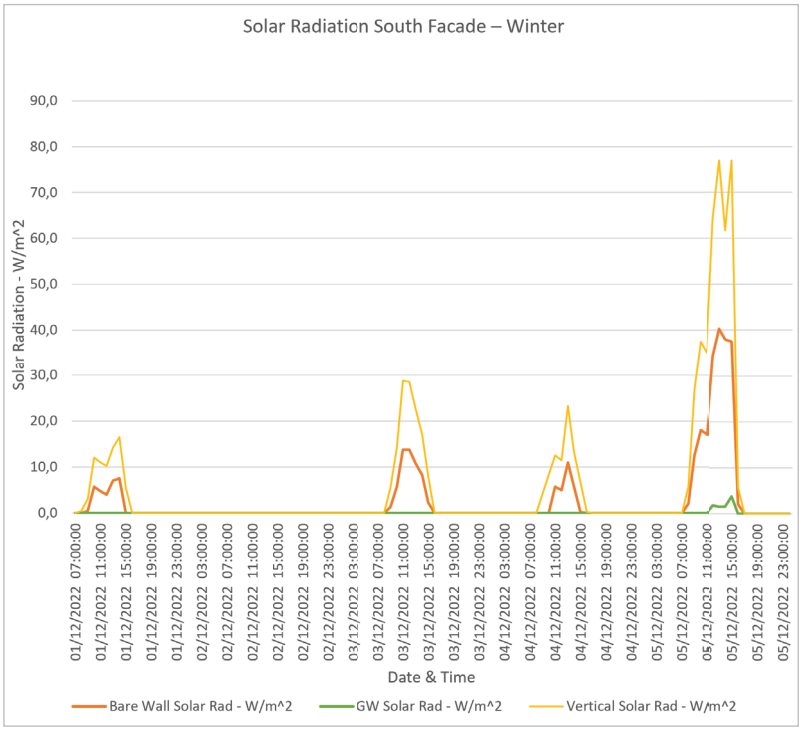

Figure 5-34. *Solar radiation comparison during winter at 10cm distance from the bare wall and Plant Pixel on the south facade. Plant Pixel reduced reflected solar radiation by an average of 63%. (Source: Author)*

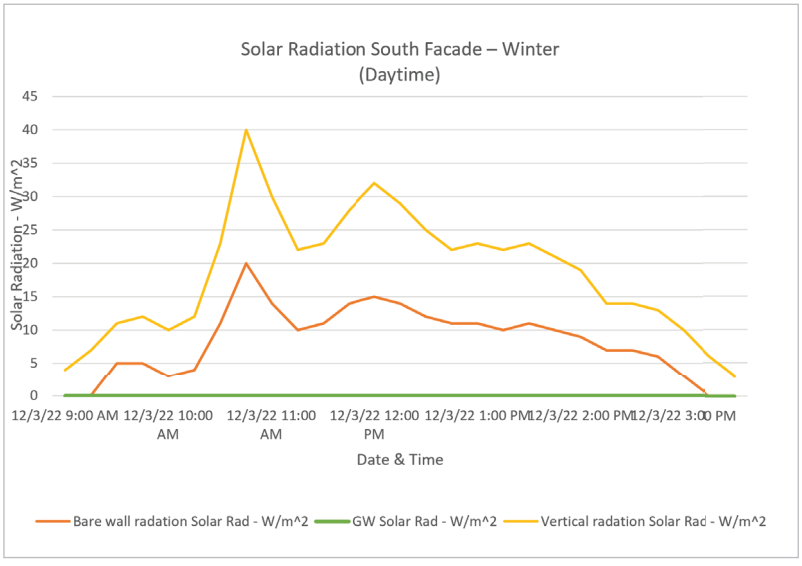

Figure 5-35. *Comparison of vertical solar radiation on the south facade during winter daytime hours (3rd December 2022). (Source: Author)*

capacity of LWS, resulting in minor temperature variations. However, the absorption of solar heat by the vegetation and substrate layers can improve the local microclimate by providing thermal stability during daytime hours.

These results highlight the significance of incorporating seasonal fluctuations in solar radiation when designing LWS for outdoor climate adaptation. The thermal behavior of LWS, including its interaction with shortwave radiation, varies throughout the day and is influenced by facade orientation (Kim et al., 2023). This emphasizes the necessity of adapting LWS to each specific site, maximizing their effectiveness throughout the year, offering cooling in summer and reducing wind speed in winter.

5.4.3.3 Humidity

During winter, the study revealed minor variations in humidity levels between the LWS and the bare wall. At a 10cm distance, LWS have slightly higher average humidity levels of 93.75% (PP1) and 90.83% (PP2) than bare walls, which have an average of 88.71%. Similarly, at 40cm, LWS have average humidity levels of 91.44% (PP1) and 89.59% (PP2), slightly higher than the bare wall's 89.19%. Despite these differences, the bare wall and the LWS achieve maximum humidity levels of 100%, while minimum levels are recorded at 48% (bare wall) and 57% (PP1, PP2).

According to the data, LWS have a modest impact on local humidity levels, with an average difference of 2% to 5% compared to bare walls, and a maximum difference of 9% observed at a 10cm distance during winter. LWS have slightly higher average humidity levels, especially at closer distances, but the overall humidity range is consistent. This demonstrates that, while LWS can influence humidity to some extent, their effect is less significant in the winter than in the summer. Similarly, a UK study discovered that in winter, ivy-covered walls had slightly higher mean daily relative humidity than bare walls, though the difference was insignificant (Sternberg et al., 2011).

5.4.3.4 Wind Speed

The *Plant Pixel* demonstrated a notable reduction in wind speed during winter, with decreases of up to 2.4m/s compared to measurements in front of the LWS. Maximum recorded wind speeds reached 3.5m/s at a distance of 15cm from the LWS and 3.0m/s directly adjacent to it (Figure 5-36). Average wind speeds next to the LWS were 0.38m/s, compared to 0.45m/s at 15cm, highlighting the LWS's capacity to reduce wind velocity and improve local microclimatic conditions in winter.

The findings align with Perini et al. (2011) who reported a gradual decrease in wind velocity from 0.56m/s to 0.10 m/s ($\Delta W = 0.46$m/s) when moving from 10cm from an LWS facade to its air cavity. In this study, the *Plant Pixel* decreased wind

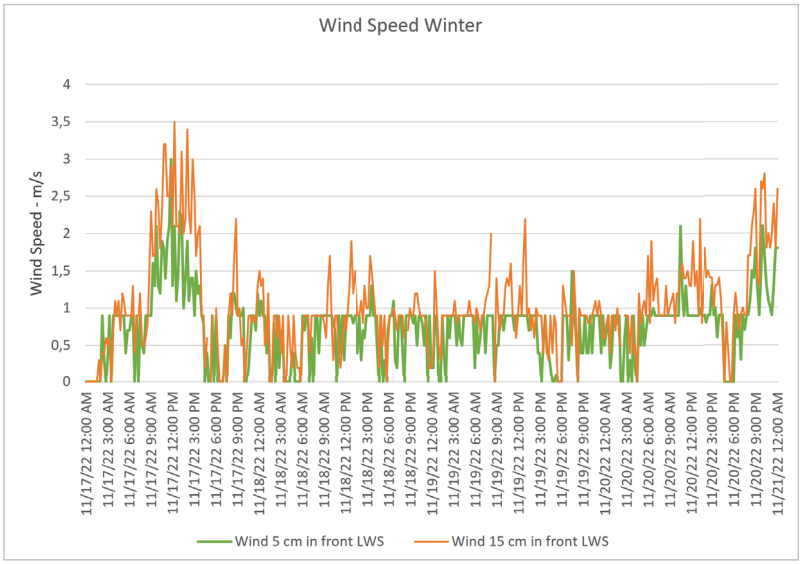

Figure 5-36. *Wind speed recorded at distances of 5cm and 15cm from the Plant Pixel south facade during winter. Vegetation reduced average speed by 15.5 %. (Source: Author)*

speed by an average of 15.5%, with some measurements approaching near-zero levels due to foliage obstruction. This reduction contributes to a more stable microclimate by minimizing convective heat loss from building surfaces.

Living Wall Systems act as effective wind barriers, reducing wind velocity along building facades and limiting heat loss during winter (Wong & Baldwin, 2016; N. Wong, Kwang Tan, et al., 2010). The dense foliage of the *Plant Pixel* plays a critical role in reducing wind speed near the facade, enhancing thermal performance. Feng & Hewage (2014) emphasize that foliage density significantly affects wind velocity modification and, by extension, a building's thermal behavior during colder months. By reducing wind speed, *Plant Pixel* contributes to creating a more stable and insulated microclimate near building facades, enhancing occupant comfort in urban environments.

Plant Pixel's dense foliage reduced wind speed by 15.5%, demonstrating its effectiveness as a wind barrier and enhancing winter microclimatic conditions. In temperate oceanic climates, optimizing LWS design to minimize wind exposure is crucial for maximizing their functionality. Therefore, understanding the interaction between wind dynamics and LWS is essential for improving their performance in urban environments.

5.5 Limitations

This research has various limitations and constraints. First, the focus is on the *Plant Pixel* system, which represents one type of LWS. Differences in design and vegetation may lead to varying outcomes. Results are based on an $8m^2$ mock-up size, which may differ from larger LWS areas. Scaling up the system would require significant additional construction and microclimatic monitoring resources, potentially introducing logistical and financial challenges.

Second, while the investigation evaluated microclimatic parameters, including outdoor air temperature, humidity, solar radiation, and wind speed, other variables, such as hydrology and soil moisture, were not incorporated. Including these factors could provide a more comprehensive understanding of LWS microclimatic performance. However, monitoring these additional variables would require specialized equipment and incur higher costs, posing practical challenges.

Third, the data collected during winter are limited due to technical issues with the sensors. While the available data still provides insights into the LWS microclimatic performance during this season. Furthermore, the study does not examine the microclimatic impact of the LWS during spring. As a result, the findings are limited to three seasons: summer, autumn, and winter. Future studies should address this limitation by incorporating more extended microclimatic monitoring.

Lastly, the research was conducted in a temperate oceanic climate, and the results may not be directly transferable to other climatic zones due to variations in weather patterns, solar exposure, and building orientations. Despite these limitations, this research provides valuable insights into the microclimatic performance of the *Plant Pixel* system in summer, autumn, and winter. These findings support LWS's potential to improve urban climate and adaptation strategies in temperate regions.

5.6 Conclusion

This study addresses the question: To what extent do Living Wall Systems (LWS) influence microclimatic conditions in a temperate oceanic climate during summer and winter? This paper quantifies the *Plant Pixel*'s microclimatic performance in a temperate oceanic climate by analyzing outdoor temperature, humidity, solar radiation and wind velocity parameters. Measurements were conducted during summer, autumn, and winter at distances of 10cm and 40cm from the LWS and adjacent bare walls.

- *SQ1: How much does the Plant Pixel prototype influence outdoor air temperatures, humidity, solar radiation, and wind speed during summer in a temperate oceanic climate?* The *Plant Pixel* prototype demonstrated a

significant capacity for mitigating heat stress during summer. Empirical evidence revealed a substantial reduction (68%) in average reflected solar radiation, contributing to decreased outdoor air temperatures by 2.5°C. This cooling effect, driven by mechanisms of transpiration and solar radiation absorption inherent to the LWS, created a measurably cooler microclimate, particularly during peak daytime hours (10:00 am to 7:00 pm). Additionally, the *Plant Pixel* increased relative humidity by 5–7% at a distance of 10 cm and reduced average wind speeds by 57%, further enhancing thermal comfort. This underscores *Plant Pixel*'s potential as a passive cooling strategy, offering an effective urban heat stress mitigation tool.

- *SQ2: How effective is the Plant Pixel prototype in mitigating air temperature, humidity, and solar radiation during heat waves in a temperate oceanic climate?* The *Plant Pixel* LWS demonstrated a significant capacity for mitigating urban heat stress during a summer heat wave. Observed reductions in peak outdoor air temperatures reached up to 5.5°C at 10cm and 2.9°C at 40cm from the *Plant Pixel* LWS facade. These findings demonstrate *Plant Pixel*'s effectiveness in creating a comfortable microclimate during extreme heat, even on facades with limited surface area.
- *SQ3: How much does the Plant Pixel prototype influence outdoor air temperatures, humidity, solar radiation, and wind speed in a temperate oceanic climate during winter?* While the *Plant Pixel* exhibited a pronounced cooling effect during summer, its impact on outdoor air temperature in winter was limited. Daytime measurements slightly reduced the mean outdoor air temperature (0.1°C), whereas nighttime measurements indicated a minor increase (0.3°C) at 10cm from the LWS. The *Plant Pixel* contributed to more stable microclimatic conditions despite these minimal temperature effects. It reduced wind speeds by up to 2.4m/s, effectively acting as a thermal barrier. This contributed to more stable microclimatic conditions near the LWS compared to the bare wall. These findings suggest that while the *Plant Pixel*'s direct impact on winter air temperature is limited, it may still contribute to improved thermal comfort by reducing wind chill.

Plant Pixel demonstrated effective microclimatic regulation, with air temperature reductions of up to 5.5°C in summer and 1.5°C in winter, while moderating temperature fluctuations. Reductions in solar radiation and wind exposure confirm its function as a passive climate adaptation measure for improving the microclimate in its vicinity.

The modular design offers a scalable solution for retrofits and new developments, particularly in dense urban areas. Its microclimatic performance supports green building standards (e.g., LEED, BREEAM) and urban climate adaptation goals. These findings position LWS as effective tools for improving livability in temperate oceanic cities. Therefore, urban policy integration through incentives and codes is essential for widespread adoption.

Future research should evaluate the scalability and operational performance of LWS across climatic zones, facade orientation, and urban morphologies to determine context-specific performance. Further investigation is needed into species selection, irrigation strategies, and evapotranspiration processes to optimize microclimatic impact. Integrating microclimatic data into urban planning frameworks can support evidence-based policy for climate-adaptive design. Additionally, incorporating subjective thermal comfort surveys can inform user-centered environmental performance criteria.

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Ethics statement: This study involved environmental monitoring of a living wall system; no human or animal subjects were involved. In line with journal policy, formal ethics approval was not required. *AI-use disclosure:* The authors used Grammarly for language refinement. No AI tools were used for data collection, analysis, or interpretation.

6

Conclusion



(Source: Author)

6

This thesis addressed the question: How can a bio-inspired, cost-effective, and low-embodied-carbon green facade system be designed to improve the urban microclimate? To answer this question, a bio-inspired MLWS was developed through a RTD methodology and evaluated against performance criteria: low embodied carbon, hydrological performance, structural performance, plant performance, ease of assembly-disassembly, cost-effectiveness, and microclimatic performance. This process resulted in a bio-inspired, modular, low-embodied-carbon, and cost-effective MLWS prototype: *Plant Pixel* (Table 6-1, Figure 6-1).

The initial design iterations focused on reducing embodied carbon and overall costs, informed by life cycle assessment and life cycle cost analysis. Hydrological and structural properties were first examined using a 3D-printed mock-up, which informed subsequent design refinements. The *Plant Pixel* prototype emerged in the fourth iteration, with its geometry derived from bio-inspired principles observed in natural rock formations. Trial-scale and full-scale mock-ups were subsequently used to evaluate embodied carbon, hydrological and structural performance, plant performance, ease of assembly and disassembly, and cost-effectiveness. Following design finalisation, a post-design evaluation phase involved long-term microclimatic monitoring, comparing the *Plant Pixel* system with a bare wall under a temperate oceanic climate. The results provided empirical evidence of the system's capacity to mitigate urban heat. The iterative process culminated in an optimised full-scale *Plant Pixel* prototype comprising 500 modules and plants. Variable module lengths introduced geometric irregularity, while targeted material selection – including recycled PVC-U, recycled textile fibres, and aluminium – improved mechanical, structural, and hydrological performance. The *Plant Pixel* achieved up to 50% reductions in embodied carbon compared with conventional MLWS, and the recycled textile fibre substrate enhanced water retention and reduced irrigation demand.

The results further show that the combined use of recycled materials, low-maintenance plant species, a high-water-holding capacity substrate, and a lightweight plug-in modular fixing system improves structural performance while reducing embodied carbon and lifecycle costs relative to commercially available MLWS. Assembly-disassembly trials confirmed the efficiency and reversibility of the modular system, while plant performance assessments indicated satisfactory survival and growth with limited maintenance. The following section addresses the sub-research questions in detail.

Table 6-1. *Research Through Design iterations and post-design evaluation in the development of the Plant Pixel prototype.*

Iteration	Main Objective	Activities
Iteration 1	Develop cost-effective, low-embodied carbon Green Facade Systems (GFS) prototypes.	Created early-stage GFS prototypes categorized by facade typology, establishing baseline designs.
Iteration 2	Reduce costs and embodied carbon of GFS through material selection.	Optimized prototypes with low-cost, low-carbon materials via Life Cycle Cost Analysis (LCCA).
Iteration 3	Assess hydrological and structural performance using 3D-printed GFS mock-up.	Enhanced water retention and structural stability, refining GFS design based on test results.
Iteration 4	Design MLWS inspired by steep rock walls.	Developed bio-inspired MLWS prototypes using recycled materials and improved water management.
Iteration 5	Optimize MLWS for plant performance, ease of assembly and disassembly, and cost-effectiveness.	Constructed full-scale MLWS mock-up (Plant Pixel) with modular plug-in connections and selected resilient plant species.
Post-design evaluation	Evaluate the microclimatic performance of the Plant Pixel in a temperate climate.	Demonstrated significant cooling effects, reducing air temperature by up to 5.5°C in summer.



Figure 6-1. *Plant Pixel mock-up. (Source: Author)*

6.1 Answers to the research questions

6.1.1 SQ1: How do different system types and material selections, including recycled materials, influence the embodied carbon of GFS and MLWS throughout their lifecycle?

We quantified how system typology and material selection affect embodied carbon in GFS and MLWS. In the *Plant Pixel* prototype, replacing conventional substrates with recycled textile fibre and integrating recycled PVCU profiles lowered production-stage embodied carbon from 229.3 to 66.7 kg CO_2e/m^{-2} (≈71% lower) while maintaining structural and hydrological performance.

From a materials perspective, recycled and lightweight components reduce the need for additional structural support and transport loads. Recycled textile fibres (≈0.4 kg CO_2e/kg^{-1}) and recycled PVCU (≈1.4 kg CO_2e/kg^{-1}) were selected for low embodied carbon, durability, and recyclability, aligning with the principles of a circular economy.

From a construction perspective, the modular design of *Plant Pixel* (and FP1) enables simplified assembly, disassembly, and clean material separation. This supports efficient end-of-life recovery, reduces material waste, and avoids emissions associated with landfill or incineration, while also facilitating refurbishment and component reuse. Maintenance is also simplified through the modular systems.

Overall, the integration of recycled materials and modular strategies in MLWS significantly reduces embodied carbon and enhances resource efficiency. These findings reinforce the potential of MLWS to contribute to circular construction and climate-responsive urban greening solutions.

6.1.2 SQ2: How do different materials, including recycled substrates, influence the hydrological performance of GFS and MLWS?

The hydrological performance of GFS and MLWS was evaluated by assessing water retention and distribution across different substrate types. Efficient water retention is critical for reducing irrigation demand and improving environmental sustainability.

In the FP1 prototype, organic substrates retained 86% of water, equivalent to 13.1 l/m^2, whereas felt-based substrates retained 1.35 $l/m^2$and required frequent irrigation. In the *Plant Pixel* prototype, recycled textile substrates retained 61.02 l/m^2, outperforming cork substrates (4.1 l/m^2). High water retention supports plant health during dry periods and reduces water consumption, critical for water conservation.

Substrate performance alone was insufficient. The modular design also played a key role in water distribution. *Plant Pixel* modules with depths between 90–310mm maintained even moisture profiles, while depths >310mm produced uneven flow and localized drying, elevating the risk of plant failure. The results emphasize the importance of substrate composition and module dimensions (depth) in enhancing hydrological performance.

Together, these results show that balancing water retention, durability, and system design improves the long-term performance and ecological value of GFS and MLWS.

6.1.3 SQ3: How do material properties, such as lightweight and recycled materials, influence the structural performance of GFS and MLWS?

We examined the impact of material properties, particularly lightweight and recycled materials, on the structural performance of GFS and MLWS. The FP1 system mass was 52.57 kg/m^{-2}, at the low end of the market range (40–150 kg/m^{-2}). Using a low-density organic substrate reduced system mass and embodied carbon while improving material efficiency. The long-term mechanical stability of this substrate (compression set, creep under saturation-drying cycles) remains to be verified.

The *Plant Pixel* employed recycled PVCU modules with aluminium primary and secondary members, balancing durability with lower embodied carbon. Structural tests showed that the full-scale mock-up supported a saturated load of 98.61 kg/m^2 without compromising stability, over twice its dry weight of 37.58 kg/m^2. Material thickness and composition are critical to load-bearing capacity, as demonstrated by the 50mm × 50mm × 2mm primary U-aluminium profile and the 60mm × 1.5mm secondary 15-degree profile.

A modular plug-in connection maintained frame stiffness while simplifying assembly/disassembly. This enabled reuse, refurbishment, and recycling, aligning with circular-economy objectives and reducing installation time, fastener waste, and end-of-life impacts. Lightweight substrates and recycled materials improved weight distribution and reduced embodied carbon without compromising structural integrity. The main design trade-off is balancing hydrological storage (for plant health) against added saturated weight (for structural demand).

6.1.4 SQ4: How do low-maintenance plant species perform regarding survival rates and growth in bio-inspired MLWS?

We investigated the survival rates and growth performance of low-maintenance plant species in the bio-inspired *Plant Pixel* MLWS prototypes (PP1 and PP2). Drawing from cliff vegetation patterns, the modular design introduced spatial irregularities to support diverse planting conditions. The system achieved a high planting density of 70 plants/m^2, more than double that of conventional MLWS (≈30 plants/m^2), enhancing species diversity and maintaining robust vegetation coverage.

During summer and autumn, 20 of 22 selected species exhibited high survival rates, with *Allium x Millennium* and *Geranium macrorrhizum* emerging as the strongest performers. At the same time, *Ajuga reptans* and *Armeria maritima* exhibited lower survival rates. These patterns were consistent across both prototypes and orientations. In winter, plant performance varied, with west-facing facades showing better health. *Allium x Millennium*, *Antennaria dioica*, and *Geranium macrorrhizum* remained the most resilient species, highlighting the importance of selecting seasonally adapted plants.

Vegetation coverage increased from approximately 70% in July 2022 to 96% by September 2022 and was maintained through December 2023. The high water-retention capacity of the substrate supported plant performance during summer and autumn droughts. In winter, inactive irrigation combined with natural rainfall improved conditions in the upper Facade sections. Moderate winter conditions in Stuttgart further contributed to sustained dense coverage. These results confirm the *Plant Pixel* system's effectiveness in maintaining year-round vegetation and supporting biodiversity.

6.5 SQ5: How do distinct system types and design strategies, including simple assembly and disassembly, influence the costs of GFS and MLWS across production, installation and maintenance?

We examined how design strategies, material selection, and assembly-disassembly methods influence costs across production, installation, and maintenance phases of the *Plant Pixel* MLWS.

Material costs were identified as a primary driver of production expenses, with the use of recycled PVCU reducing costs to 680.9 €/m^2, compared to the typical 750–1,200 €/m^2 for conventional modular systems. *Plant Pixel* exhibits a material cost of 256.1 €/m^2, lower than comparable MLWS products. This reduction was primarily achieved by minimizing reliance on high-cost materials such as aluminum.

During installation, the adoption of a design-for-assembly and disassembly approach, incorporating modular square profiles and plug-in connections, significantly reduced labor time and costs. The streamlined system improved operational efficiency, particularly in the assembly of 500 modules.

In the maintenance phase, practices such as high water-retention substrates and resilient, low-maintenance plants resulted in long-term cost savings. However, the high planting density of 70 plants/m^2 initially increased costs. Selecting lower-cost plant species (1.1–1.3 €/m^2) could reduce system costs to approximately 660 €/m^2. Despite these improvements, concerns remain regarding the long-term durability of plug-in connections in dense urban environments. Comprehensive lifecycle cost assessments are critical to evaluating the financial feasibility of MLWS.

6.1.6 SQ6: How do MLWS influence outdoor air temperature, humidity, solar radiation, and wind speed during summer and winter in a temperate oceanic climate?

We evaluated the *Plant Pixel* modular living wall system in a temperate oceanic (Cfb) climate. Measurements at 10cm and 40cm from the facade in summer, autumn, and winter show strong summer effects: peak reductions of 3.3°C (10cm) and 1.9°C (40cm) relative to a bare wall, with daytime (10:00–19:00) south-facade means -2.5°C. The system also reduced reflected short-wave radiation by up to 68%. During a heatwave, lowered near-wall air temperature by up to 5.5°C, indicating attenuation of short-wave input by foliage and substrate and enhanced cooling via evapotranspiration.

Winter effects were modest. Daytime cooling averaged -0.1°C, while night showed slight warming (+0.3°C at 10m). Reflected short-wave de by 63%, and near-facade wind speed decreased by 15.5% (instantaneous reductions up to 2.4 m/s^{-1}), which helped stabilize the facade microclimate by limiting diurnal fluctuations, convective heat loss, and wind chill. The limited cooling during winter corresponds to reduced solar input (often <300 W/m^{-2}), which limits evapotranspiration and supports more thermally stable conditions adjacent to the wall.

From a climate-adaptation standpoint, *Plant Pixel* shows the role of MLWS as passive cooling infrastructure. Performance depends on facade orientation, vegetated area, measurement distance, and planting density (70 plants m^{-2}). Properly designed and maintained, MLWS can reduce reliance on mechanical cooling, improve outdoor thermal comfort, and mitigate heat stress; in winter, reduced wind speed and mild nocturnal warming offer a secondary insulating benefit.

To optimize year-round performance, refinements should focus on (i) selecting plant species with higher transpiration capacity for warm seasons, (ii) modifying module and substrate design to enhance thermal insulation during cold periods, and (iii) implementing irrigation strategies according to seasonal moisture availability.

6.2 Critical reflection on the *Plant Pixel* MLWS Design Process

In this section I critically evaluate the iterative RTD process, considering the various test criteria examined throughout the RTD, and concludes with a general reflection on the challenges encountered during this process.

6.2.1 Embodied Carbon (SQ1)

The first design iteration prioritized reducing embodied carbon through innovative material selection and design optimization. This was supported by life cycle assessment of multiple recycled materials. However, reliance on specific recycled inputs limits scalability in regions where supply is scarce. Establishing local supply chains for recycled materials remains challenging, as the *Plant Pixel* prototype relied on regionally available recycled PVC-U profiles that are subject to regulatory certification and market availability. Although recycled PVC-U substantially reduced embodied carbon, its long-term durability in facade-integrated MLWS remains uncertain. While no material degradation was observed during the monitoring period, potential microplastic release under long-term weathering and UV exposure cannot be excluded.

6.2.2 Hydrological Performance (SQ2)

At this stage, a problem was identified in the MLWS design: the need to optimize hydrological performance to support water conservation and plant health. Building on the low embodied carbon achieved in the first iteration, the research shifted its focus to optimizing hydrological performance. This involved identifying and evaluating substrates that maximize water retention while ensuring compatibility with the overall system design. Chapters 3 and 4 examined the interrelationship between substrate properties, water retention capacity, and irrigation demands and their impact on long-term plant health.
However, the evaluation of hydrological performance was limited to initial testing periods, with no long-term data available to assess the system's performance under varying climate conditions. While the substrate's potential for water-scarce regions was promising, its long-term durability and hydrological

performance in diverse climates remain unverified. Further studies are needed to assess how these substrates perform under various environmental conditions, particularly in regions prone to extreme weather patterns.

6.2.3 Structural Performance (SQ3)

The design process identified key strengths and limitations of the *Plant Pixel* system. Using recycled materials and standardized modules lowered environmental impact while enhancing adaptability to varied architectural forms. Its modularity supports circularity, offering installation efficiency, design flexibility, and design for disassembly. These features position the system as a valuable model for future MLWS applications.

Although structural integrity improved, durability under extreme conditions is untested. The current evaluation addressed static load-bearing capacity but did not consider dynamic loads or stressors, such as wind, snow, or thermal fluctuations. Future research should incorporate long-term simulations and accelerated aging tests to assess performance under these conditions. Material resilience in high-humidity, high-wind, and freezing environments also requires investigation (Shen et al., 2019). Without these assessments, broader deployment of *Plant Pixel* in exposed or high-rise contexts will remain constrained.

6.2.4 Plant Performance (SQ4)

The system supported high plant density, with species selected for their sun tolerance, frost resistance, drought resilience, low maintenance requirements, ornamental appeal, dense foliage, hardiness, deep rooting, and compatibility with the chosen substrate. Implementation, however, revealed limits in species diversity. Prioritizing drought-tolerant species improved viability and reduced maintenance demands; however, this approach may not be suitable for all climates. This highlights a core design challenge in modular living wall systems: balancing plant survival with maintenance efficiency. Optimizing adaptability requires careful alignment of species traits, microclimatic conditions, and design parameters to ensure long-term performance in varied urban contexts.

6.2.5 Simple Assembly and Dis-Assembly (SQ5)

This design-for-assembly and disassembly approach contributed to reduced installation and maintenance costs. However, the plug-in system was specifically tailored to the scale of the prototype used in this study. In larger, multi-story building applications, structural demands would increase, potentially requiring

adjustments to the plug-in design to ensure stability under greater loads. Therefore, further investigation is needed to assess the long-term durability and maintenance performance of the plug-in design in multi-story applications.

6.2.6 Cost-Effectiveness (SQ5)

The main obstacles to creating a cost-effective modular living wall system were: (1) achieving cost reductions through innovative material use and design optimization and (2) ensuring that cost-effectiveness translates into practical application without compromising environmental performance.

While the initial cost reductions are promising, further research is necessary to assess the long-term economic performance of the system, particularly considering regional variations in labor and material costs. Conducting life-cycle cost assessments will be essential to address these uncertainties and ensure that the *Plant Pixel*'s cost-effectiveness remains robust under diverse urban conditions.

6.2.7 Microclimatic Performance (SQ6)

While the *Plant Pixel* demonstrated significant benefits in cooling, its effectiveness may vary depending on site-specific factors such as wind patterns, building orientation, and urban density. The localized cooling effect also raises questions about scalability and the cumulative impact of multiple installations in dense urban environments. In winter, the system had minimal influence on outdoor air temperature but reduced wind speeds by up to 2.4m/s, contributing to microclimatic stabilization.

We measured four microclimatic parameters: outdoor air temperature, humidity, solar radiation, and wind speed. However, it did not address hydrology, soil moisture, or the system's potential for insulation and energy savings during winter, despite their relevance for evapotranspiration, plant vitality, and thermal buffering. A thorough understanding of the interactions between MLWS and microclimatic factors such as wind patterns, thermal conditions, solar radiation, hydrology, and soil moisture is essential for optimizing year-round performance and enhancing its role in urban climate adaptation.

The study did not include spring conditions, limiting the analysis to summer, autumn, and winter. Conducted within a temperate oceanic climate, the findings may not be directly applicable to other climatic regions with different solar exposure and humidity profiles. Even so, the findings provide new evidence of the microclimatic seasonal performance of MLWS (*Plant Pixel*) and validates its contribution to urban climate adaptation in temperate cities.

6.2.8 Balancing Sustainability, Performance and Scalability

Sustainability encompasses environmental, social, and economic dimensions, requiring the responsible use of resources, preservation of biodiversity, reduction of carbon emissions, and equitable societal well-being (Purvis et al., 2019; Kremer et al., 2019; Aalborg Charter). Within this framework, a well-designed MLWS should deliver microclimatic and aesthetic benefits while minimizing costs, maintenance demands, and embodied and operational carbon. The *Plant Pixel* system was developed through a research through design process, in which each iteration refined overall performance and revealed necessary trade-offs and limitations. The RTD methodology was therefore central to the project, guiding iterative development and generating insights that provide a foundation for future research and system optimization.

This research highlights a core challenge in MLWS design: reducing embodied carbon without compromising structural integrity or cost-effectiveness. The resource-intensive nature of prototyping constrained the range of material trials and system variations, pointing to the need for further studies on material selection, plant diversity, and long-term durability, particularly as MLWS are scaled to different climatic and socioeconomic contexts.

6.3 Recommendations for future research: Enhancing the *Plant Pixel* MLWS

This study presents the *Plant Pixel* prototype, which was created using circular economy and bio-inspired design principles and guided by RTD. Integrating circular and bio-inspired principles, the system advances conventional MLWS through the use of low-embodied carbon materials, improved hydrological and structural performance, ease of assembly, high plant survival rates, cost-effectiveness, and microclimatic benefits. These features position the *Plant Pixel* as an innovative MLWS for climate-responsive building envelopes in dense urban environments. However, future research is needed to refine the prototype.

1. **Embodied carbon and materials.** Expanding life cycle assessments is critical to capture the system's full environmental impact. Further research should focus on substrates and materials to enable the development of bio-based, low-embodied-carbon solutions that are durable, and recyclable. Beyond carbon emissions, future studies should include resource depletion, toxicity, and waste generation. The release of microplastics from recycled PVCU remains a concern (Crawford & Quinn, 2020). Alternative low-carbon materials, such as bio-based polymers, should be tested, alongside closed-loop recycling strategies and local supply chains to secure material availability and reduce transport emissions (Shen et al., 2019).
2. **Hydrological performance.** Further research should test new substrates and refined design configurations to further improve moisture distribution and provide optimized MLWS in densely urbanized environments. Studies

should assess water retention under diverse climates, particularly during heavy rainfall and drought (Schmidt et al., 2014). Incorporating sensor-based irrigation could enable real-time monitoring, optimizing water use and improving plant health.

3. **Structural durability.** Research should investigate performance under wind, snow, and seismic loads (Bock & Linner, 2015). Accelerated aging tests can reveal vulnerabilities to UV exposure and temperature extremes. Bio-based composites could enhance strength while lowering embodied carbon. The plug-in connection system also requires testing for long-term durability without compromising modularity. Long-term fatigue and creep of the plug-in connection should be characterized under cyclic wetting to ensure the safe implementation of MLWS. Consistent monitoring of system performance and optimization of modular assembly will result in lower maintenance costs, promoting utilization in diverse socioeconomic contexts.
4. **Plant performance.** Broader trials of plant species are needed to improve adaptability across climates and seasons. Selecting species with improved transpiration capacity, drought resistance, and pollution tolerance would enhance cooling and support biodiversity. Emphasis should be placed on drought tolerance, temperature resilience, and ecological benefits, including pollinator support and biodiversity enhancement.
5. **Assembly and disassembly.** While the plug-in modular design reduced costs, its scalability to large facades and high-rise buildings requires validation. Research should test connection systems under repeated use and environmental stress, while exploring reinforced or alternative fasteners that maintain modularity and ease of maintenance.
6. **Economic feasibility.** Future cost-reduction strategies must consider all system components – materials, substrates, plant species, support panels, and fixings – emphasizing the importance of innovative, modular solutions to enhance economic viability for large-scale urban application. Regional differences in labor and material costs must also be assessed to ensure economic viability in diverse contexts (Bock & Linner, 2015). Finally, future studies should examine policy and financial mechanisms, such as subsidies, grants, carbon credits, and green finance tools, that could support GFS adoption
7. **Long-term monitoring and energy performance.** Extended studies are needed to evaluate seasonal microclimatic effects, including UHI mitigation and resilience to extreme weather. Particular attention should be given to winter insulation capacity and its impact on building energy demand. Coupling field data with dynamic simulation models will allow quantification of energy savings and integration into energy-efficient urban design (Oke et al., 2017). Finally, it is crucial that future research quantitatively assesses performance across facade orientations, building types, and urban morphology support evidence-based policy for climate-adaptive design.

The *Plant Pixel* demonstrates technical feasibility and provides a framework for aligning MLWS strategies with broader sustainability objectives. Additional research may yield improvements in MLWS's environmental performance, economic feasibility, and societal benefits. Further exploration of these research areas will enable the prototype to evolve from an experimental design to a scalable, climate-adaptive solution.

6.4 *Plant Pixel* Contribution to Innovation in MLWS

The *Plant Pixel* system integrates circular economy and bio-inspired design principles into a modular, cost-effective MLWS. It advances conventional systems through improved material efficiency, hydrological and structural performance, simplified assembly, high plant survival rates and measurable microclimatic benefits. The main contributions are:

- **Low-Embodied Carbon:** The use of recycled PVCU, textile, and aluminum reduces embodied carbon by up to 50% compared to non-recycled systems.
- **Hydrological Performance:** High water-retention substrates outperform conventional felt-based systems that require frequent irrigation.
- **Structural Performance:** *Plant Pixel* employs lightweight, durable materials that maintain structural integrity under full saturation. This avoids the need for additional structural support often required by heavier systems.
- **Plant Survival Rates:** The design supports higher plant density, enhancing biodiversity and ensuring robust vegetation coverage. Additionally, the research advances plant selection criteria that prioritize drought-tolerant, low-maintenance species, improving plant survival, visual appeal, and reducing operational costs.
- **Assembly and Disassembly**: A simplified plug-in modular design streamlines installation and maintenance. Unlike conventional systems with screw-based and complex assemblies, the plug-in mechanism enhances adaptability, optimizes the lifecycle, and promotes material circularity while reducing labor demands.
- **Cost-effectiveness:** Life cycle cost analysis demonstrates reduced production, installation, and maintenance costs, providing insights into the economic feasibility.
- **Microclimatic Impact:** Field monitoring confirms reduced solar radiation, lower near-wall air temperatures, increased humidity, and wind-speed attenuation. Cooling effects of up to 5.5°C were observed during heatwaves, demonstrating the system's effectiveness for urban heat mitigation and outdoor thermal comfort.

6.5 Professional relevance of *Plant Pixel*

This research delivers applied knowledge relevant to architectural, landscape architectural, urban design, and building engineering practice in the context of climate adaptation. This contribution is important because the limited availability of quantified performance data constrains the adoption of MLWS. The *Plant Pixel* prototype provides measured values for embodied carbon, structural load under fully saturated conditions, substrate water retention, and changes in near-facade air temperature during summer and heatwave periods. These measured values support decision-making under embodied carbon, structural, hydrological, and economic constraints and enable early-stage comparison between MLWS designs.

The modular plug-in system developed in this research addresses professional challenges related to installation, maintenance, and end-of-life management. The design's reversible assembly facilitates the reuse, refurbishment, and recycling of MLWS components, consistent with circular construction principles and policy goals as defined in the EU Green Deal and the Circular Economy Action Plan. This modular system allows for scalability and implementation in new construction and retrofitting projects within densely populated urban areas.

Furthermore, this research strengthens the relevance of MLWS for professional practice by linking microclimatic performance to urban design and policy agendas. In dense urban contexts where space constraints limit trees and ground-level green infrastructure, MLWS offer a facade-based means of integrating vegetation. Measured reductions in near-wall air temperature, solar radiation exposure, and wind speed indicate their potential as climate-adaptive measures, supporting their inclusion in sustainable building assessment frameworks such as LEED and BREEAM

Dissemination through publications, workshops, conferences, and industry exhibitions positions *Plant Pixel* as a validated MLWS prototype and a transferable design and evaluation framework. Beyond its current application, *Plant Pixel* demonstrates potential for further development. The modular system could be adapted for indoor applications to improve indoor air quality and thermal comfort and for vertical farming, where modular design and efficient water management are critical. This design enables scalability to larger units at neighborhood or district scale.

6.6 Societal relevance

This research addresses urban heat stress and the need for cost-effective climate adaptation measures in dense urban environments. As cities experience higher temperatures and more frequent heatwaves, vertical green systems are

increasingly used as building-integrated strategies to improve outdoor thermal conditions. In this context, the research contributes by developing and testing a bio-inspired, optimized modular living wall system prototype that addresses low-embodied carbon material selection, improved hydrological and structural performance, improved plant performance, simple assembly-disassembly, and cost-effectiveness. Additionally, the reduction in near-wall air temperatures under summer and heatwaves suggests these systems can reduce local thermal stress in urban settings.

This research is relevant in the context of social equity and environmental justice. Urban heat exposure is unevenly distributed and disproportionately affects vulnerable populations, including older adults, children, and lower-income communities, which often have limited access to green infrastructure. The *Plant Pixel* prioritizes cost-effectiveness, simple assembly-disassembly construction, and reduced maintenance, supporting the implementation of greenery where conventional MLWS are not feasible. In this way, the research contributes to more equitable access to climate-adaptive.

Beyond thermal mitigation, integrating vegetation into building envelopes contributes to public health and well-being by increasing access to greenery in dense urban neighborhoods. Vegetation supports psychological well-being, stress reduction, and improved perceived liveability. The modular plug-in system developed in this research reduces barriers related to installation, maintenance, and long-term management, enabling deployment across a wide range of urban contexts, including small-scale and non-iconic projects. This scalability is essential for reducing inequalities in environmental quality and ensuring that climate-adaptive infrastructure is not limited to high-profile developments.

At the same time, the *Plant Pixel* aligns with city-level and European objectives related to circular construction, climate-neutral buildings, and nature-inclusive design. The use of low-embodied carbon materials, reversible plug-in connections, and quantifiable performance indicators demonstrates how MLWS can contribute to integrated urban climate adaptation strategies while supporting circular construction principles and long-term resource efficiency.

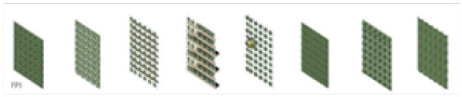
A

Appendix



(Source: Author)

7.1 Appendix A. (Chapter 3) General criteria assessment matrix



	FAÇADE-BASED TYPOLOGY	FP1	FP2	FP3	FP4	FP5	FP6	FP7	FP8
Low-embodied carbon	Low embodied carbon /Recycle/Recyclable	3	3	2	2	2	3	3	2
Cost-Effective	Low Cost Material/ Manufacture	3	3	3	3	3	3	3	3
	Low-Cost Maintenance	2	2	2	2	2	2	2	2
	Simple installation	4	4	4	4	3	4	3	4
Hydrological performance	Water distribution	4	2	1	2	1	3	2	4
Structural performance	System/ Structure feasibility (developed in 2 years)	4	4	3	3	3	4	2	2
	Light-weight/ Typology scale	4	4	4	2	3	4	4	4
Total		24.00	22.00	19.00	18.00	17.00	23.00	19.00	21.00



	BALCONY FOREST TYPOLOGY	BF1	BF2	BF3	BF4	BF5	BF6
Low-embodied carbon	Low embodied carbon /Recycle/Recyclable	3	2	3	3	3	3
Cost-Effective	Low Cost Material/ Manufacture	3	3	3	3	3	4
	Low-Cost Maintenance	3	3	3	3	3	4
	Simple installation	2	2	2	2	2	2
Hydrological performance	Water distribution	4	3	3	2	2	3
Structural performance	System/ Structure feasibility (developed in 2 years)	3	2	2	2	2	4
	Light-weight/ Typology scale	1	1	1	1	1	1
Total		19.00	16.00	17.00	16.00	16.00	21.00



	PATENT FAÇADE-REDESIGN TYPOLOGY	PR1	PR2	PR3	PR4	PR5	PR6	PR7	PR8	PR9
Low-embodied carbon	Low embodied carbon /Recycle/Recyclable	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Cost-Effective	Low Cost Material/ Manufacture	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	Low-Cost Maintenance	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Simple installation	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Hydrological performance	Water distribution	3.0	4.0	4.0	4.0	3.0	3.0	4.0	4.0	3.0
Structural performance	System/ Structure feasibility (developed in 2 years)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Light-weight/ Typology scale	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Total		22.00	23.00	23.00	23.00	22.00	24.00	23.00	23.00	22.00

Figure A1. *General criteria assessment matrix comparing the early-stage prototypes with a 5-point rating scale (1= worst; 5 = best).*

7.2 Appendix B. (Chapter 3) Cost calculations of early-stage prototypes

Table B1. *Comparison of material costs of 3 GFS typologies in the early-stage of the design.*

FP1	**Material: Name**	**Cost (€/m²)**
1. GFS external layer	PVC Recycled	28,2
2. Substrate Layer	Substrate	18,9
3.Fastening/Connection to the wall	Steel S235	13,3
4. Plants	Plants	26,7
Total		**87,1**
BF1	**Material: Name**	**Cost (€/m²)**
1. Roofing membrane	Single-ply membrane	2,5
2. Substrate	Substrate	13,7
3. Fastening /Connection to the wall	Steel S235	5,1
4. Structural layer/ Exterior	Wood - CLT	32,0
5. Plants	Small tree	40,0
Total		**93,3**
BF7	**Material: Name**	**Cost (€/m²)**
1. Roofing membrane	Single-ply membrane	2,5
2. Substrate	Substrate	16,6
3. Fastening /Connection to the wall	Steel S235	2,7
4. Structural layer/ Exterior	Wood - Glulam	65,3
5. Plants	Plants	6,0
Total		**92,5**

7.3 Appendix C. (Chapter 3) Embodied carbon calculations of the early-stage prototypes

Table C1. *LCA results and comparison of the embodied carbon of 3 GFS typologies in the early-stage of the designs*

FP1	**Material: Name**	**Material: Volume**	**Material: Density (kg/m³)**	**Material weight (kg)**	**Material: Waste rate (%)**	**Overall material weight (waste inc.) (kg)**	**Embodied Carbon ($kgCO_2$/kg)**	**Overall material EC ($kgCO_2e$)**	**Overall material EC ($kgCO_2e$)/m²**
1. GFS external layer	PVC Recycled	0.04 m³	1380	59,82	0,05	62,81	2,17	136,30	45,43
2. Substrate Layer	Soil	0.25 m³	1500	377,53	0,13	426,61	0,02	10,24	3,41
3.Fastening/ Connection to the wall	Steel S235	0.0035 m³	7800	26,56	0,15	30,55	2,73	83,39	27,80
Total		**0.30 m³**		**463,91**		**519,96**		**229,93**	**76,64**
BF1	**Material: Name**	**Material: Volume**	**Material: Density (kg/m³)**	**Material weight (kg)**	**Material: Waste rate (%)**	**Overall material weight (waste inc.) (kg)**	**Embodied Carbon ($kgCO_2$/kg)**	**Overall material EC ($kgCO_2e$)**	**Overall material EC ($kgCO_2e$)/m²**
1. Roofing membrane	Single-ply membrane	0.04 m³	1500	66,79	0,05	70,13	2,85	199,86	66,62
2. Substrate	Soil	0.18 m³	1500	273,50	0,13	309,06	0,02	7,42	2,47
3. Fastening /Connection to the wall	Steel S235	0.00 m³	7800	10,24	0,15	11,78	1,55	18,26	6,09
4. Structural layer	Wood - CLT	0.24 m³	500	121,84	0,1	134,02	0,44	58,57	19,52
5. Exterior	Wood - Glulam	0.02 m³	500	7,58	0,1	8,34	0,51	4,27	1,42
Total		**0.49 m³**		**479,95**		**533,33**		**288,37**	**96,12**
BF7	**Material: Name**	**Material: Volume**	**Material: Density (kg/m³)**	**Material weight (kg)**	**Material: Waste rate (%)**	**Overall material weight (waste inc.) (kg)**	**Embodied Carbon ($kgCO_2$/kg)**	**Overall material EC ($kgCO_2e$)**	**Overall material EC ($kgCO_2e$)/m²**
1. Roofing membrane	Single-ply membrane	0.05 m³	1380	63,51	0,05	66,68	3,1	206,71	68,90
2. Substrate	Soil	0.22 m³	1500	331,52	0,13	374,621	0,024	8,99	3,00
3. Fastening	Steel S235	0.000695 m³	7800	5,42	0,15	6,231	2,73	17,01	5,67
4. Structural layer	Wood - Glulam	0.49 m³	500	242,96	0,1	267,26	0,512	136,84	45,61
Total		**0.76 m³**		**643,41**		**714,79**		**369,55**	**123,18**

7.4 Appendix D. (Chapter 3) Embodied carbon calculations of the FP1 early-stage prototype

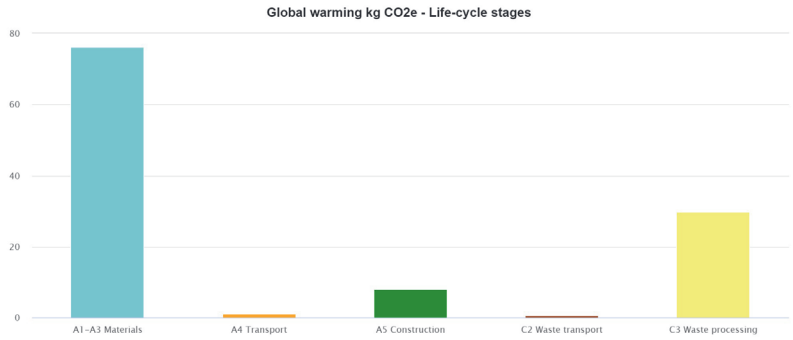


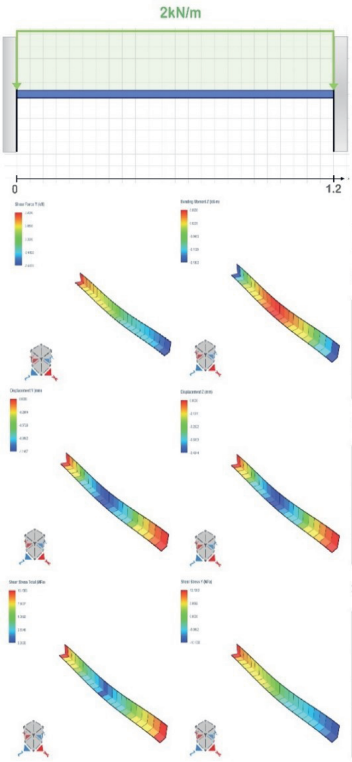
Figure D1. *Embodied carbon calculations of the FP1 prototype by life-cycle-stage*

7.5 Appendix E. (Chapter 4) Embodied carbon calculations of Plant Pixel prototype

Table E1. *LCA results and comparison of the embodied carbon of Plant Pixel prototype with recycled and non-recycled materials.*

Components	Material	Material Weight (kg)	Material Waste rate (%)	Overall material weight (waste inc.)(kg)	Material embodied carbon ($kgCO_2e$/kg)	Material EC ($kgCO_2e$)	Material Transport coefficient (%)	Overall transport EC ($kgCO_2e$)	Overall Material EC ($kgCO_2e$)
Scenario 1: Plant Pixel using recycled materials									
Planter boxes (Pixels)	Recycled PVCU	22,10	0,05	23,21	1,50	34,81	0,03	1,04	35,85
Substrate	Recycled clothing substrate	15,34	0,02	15,65	0,10	1,56	0,03	0,05	1,61
Bolts	Recycled Aluminum	0,20	0,05	0,21	1,69	0,35	0,03	0,01	0,37
Square tubes and horizontal bars	Recycled Aluminum	15,20	0,05	15,96	1,69	26,97	0,03	0,81	27,78
Watering system tubes	PVCU	0,20	0,05	0,21	2,50	0,53	0,03	0,02	0,54
Drip lines	PVCU	0,20	0,05	0,21	2,50	0,53	0,03	0,02	0,54
Total		**53,24**				**64,75**		**1,94**	**66,69**
Scenario 2: Plant Pixel using non-recycled materials									
Planter boxes (Pixels)	PVCU	22,10	0,05	23,21	3,10	71,94	0,03	2,16	74,09
Substrate	Stone Wool	15,34	0,02	15,65	1,05	16,43	0,03	0,49	16,92
Bolts	Aluminum	0,20	0,05	0,21	8,24	1,73	0,03	0,05	1,78
Square tubes and horizontal bars	Aluminum	15,20	0,05	15,96	8,24	131,51	0,03	3,95	135,46
Watering system tubes	PVCU	0,20	0,05	0,21	2,50	0,53	0,03	0,02	0,54
Drip lines	PVCU	0,20	0,05	0,21	2,50	0,53	0,03	0,02	0,54

7.6 Appendix F. (Chapter 4) Structural calculations of the secondary 15-degree aluminum profile for the Plant Pixel prototype



RESULT SUMMARY

Check	Status	Limit	Ratio	Max
Deflection	PASS	L/250	0.253	L/987
Custom Stress Limit	PASS	250 MPa	0.339	84.789 MPa
Material Yield	PASS	100 MPa	0.848	84.789 MPa
Material Strength	PASS	150 MPa	0.565	84.789 MPa

Reactions

Support at	X	Y	Mx
0	0 kN	0.9 kN	0.18 kN-m
1.2	0 kN	0.9 kN	-0.18 kN-m

Force Extremes

Result	Max	Min
Bending Moment	0.09 kN-m	-0.18 kN-m
Shear	0.9 kN	-0.9 kN
Displacement	0 mm	-1.146 mm

Stress Extremes

Result	Max	Min
Bending Stress	58.391 MPa	-84.789 MPa
Shear Stress Total	10.138 MPa	0 MPa
Max Combined Normal Stress	58.391 MPa	4.555 MPa
Min Combined Normal Stress	-3.137 MPa	-84.789 MPa

Figure F1. *Structural calculations of the secondary 15-degree aluminum profile.*

7.7 Appendix G (Chapter 5) Methodological Flowchart

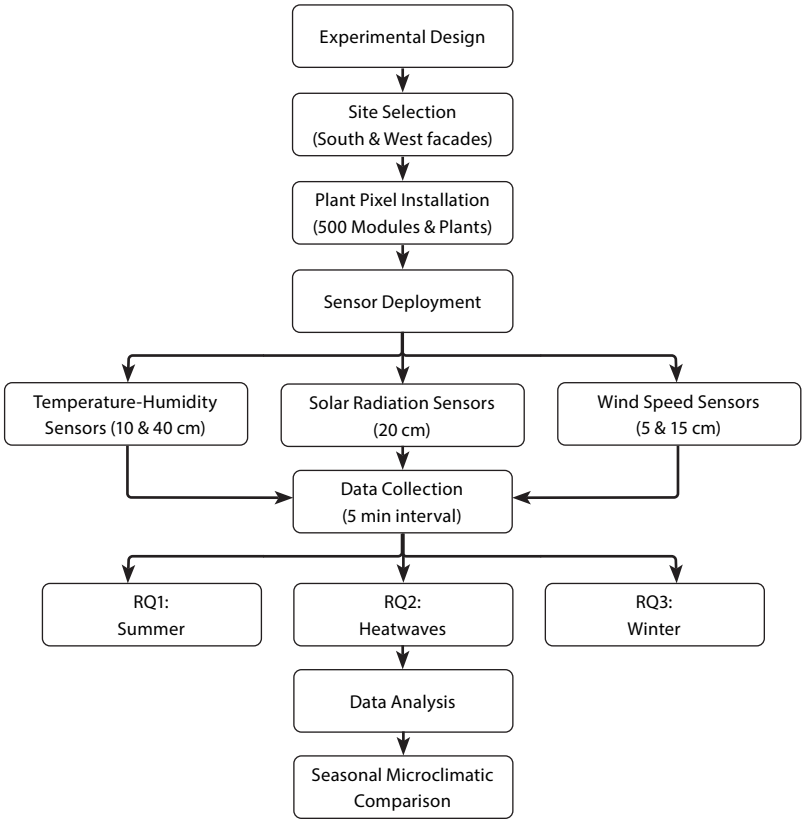


Figure G1. *Methodological flowchart illustrating the experimental design, sensor deployment strategy, and alignment with research questions (RQ1: Summer, RQ2: Heatwaves, RQ3: Winter). (Source: Author)*

7.8 Appendix H. Plant Pixel Image Process



Figure H1. *Chronological process of installing the Plant Pixel prototype on the container. (Source: Author)*

R

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About the author

Maricruz Solera Jimenez is a professional architect specializing in sustainable design and green infrastructure. She has extensive experience in research, design, and consultancy. She graduated with a Master of Science in Sustainable Architecture from Oxford Brookes University and later pursued a PhD in Landscape Architecture and Spatial Planning at Wageningen University in the Netherlands. Her academic and professional journey has been shaped by her commitment to addressing pressing environmental challenges through sustainable, innovative design and climate-responsive solutions.

Maricruz began her career designing energy-efficient buildings and large-scale residential projects in Costa Rica, where she developed master plans and passive design strategies that reduced embodied carbon. Motivated to further explore the intersection of architecture and sustainability, she moved to Europe, where she collaborated with renowned institutions and contributed to high-impact projects. Maricruz has combined her academic knowledge with practical design expertise throughout her career. She has worked on prominent projects in London and Costa Rica, applying her skills in sustainable design and project management. Her ability to engage with stakeholders and industry leaders has made her a respected voice in sustainable architecture.

During her doctoral research at Wageningen University, her work reached new heights, where she developed the *Plant Pixel* prototype, an innovative modular living wall system (MLWS). The system integrates low-embodied-carbon materials and advanced modularity to enhance urban microclimatic performance, achieving air temperature reductions of up to 4°C and reducing carbon emissions by 40%. This research received widespread recognition, including nominations for the Earthshot Prize 2024 and the Green Product Award 2023 and an honorable mention at the Design Intelligence Award (DIA).

Maricruz's expertise spans across sustainable urban planning, modular green facades, and nature-based solutions. Her work has been showcased at international events such as the Eco-design Award in Berlin and Dutch Design Week in Eindhoven, where she presented her innovative solutions to global audiences. She has published extensively in leading scientific journals, including the Journal of Developments in the Built Environment and Building and Engineering, disseminating cutting-edge research on low-embodied carbon and cost-effective green facade systems.

Parallel to her academic pursuits, Maricruz has contributed to education and industry through guest lectures, workshops, and collaborations. For instance, she conducted a masterclass on microclimatic green walls for Mobilane, a leading living wall system provider. She advocates for innovative, sustainable, and scalable solutions, bridging the research and practice gap.

Currently, Maricruz is advancing sustainable and human-centred system innovation through her research on circular materials for railway assets, bridging technology with environmental and social performance goals. She is involved in the European Flagship 2 project R2DATO (Railway Digital and Automated Transformation), which centers on Human-Centered risk-informed migration strategies for digital automation, and the European Flagship 4 Earth to Rail program on Sustainable and Rail assets and Rolling Stock within Europe's Rail Joint Undertaking. Her work showcases dedication to building resilient, inclusive, and environmentally conscious systems that address the interconnected issues of climate adaptation, technological transition, and design innovation.

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Wageningen, 10 September 2026

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The SENSE Research School declares that **Maricruz Solera Jimenez** has successfully fulfilled all requirements of the educational PhD programme of SENSE with a workload of 54.0 EC, including the following activities:

SENSE PhD Courses

- A1: Environmental Research in Context (2021)
- A2 Research in context activity: ' Creating a website and Video for Plant Pixel' (2024)

Other PhD and Advanced MSc Courses

- Time Management and Thesis Planning, Kent University (2020)
- Organizing the PhD, Kent University (2020)
- Advanced knowledge of Urban Climate and simulation, Wageningen University & Research (2020)
- Expert on Advanced Facades, Polytechnic University of Madrid (2021)
- Circular Building Products for a Sustainable Built Environment, TU Delft (2021)
- Scientific Writing (online course), Wageningen University & Research (2022)
- Design of lightweight Facades, Polytechnic University of Madrid (2022)
- One Click LCA Construction LCA Bootcamp 2023, One Click (2023)

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- SOLOCLIM symposium "Prototypes Ready!" (2022)
- SOLOCLIM Final symposium "Cooling Cities-Solutions for Urban Climate Adaption" (2023)

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- *Sustainability, Micro-climate and Thermal Comfort for the Design of Future Green Cities*. SOLOCLIM Midterm-symposium "Outdoor solutions for climate adaptation - from street to city-scale, 8-10 September 2021, Turin, Italy
- *Low-embodied carbon and cost-effective green façade system. Living skins" session. Advanced Building Skin conference, 20-21 November 2022, Bern, Switzerland*
- *Microclimate performance: A low-embodied carbon and cost-effective green façade* Nature-based Solution session. 11th International Conference on Urban Climate (ICUC) conference, 28-31 August 2023, Sydney, Australia
- Presented the 1:1 GFS mock-up. "Vegetation-based" session at SOLOCLIM Final symposium "Cooling Cities-Solutions for Urban Climate Adaption", 19 June 2023, Milan, Italy

Colophon

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