Plant Microbial Fuel Cell Integrated Façade Living Wall System

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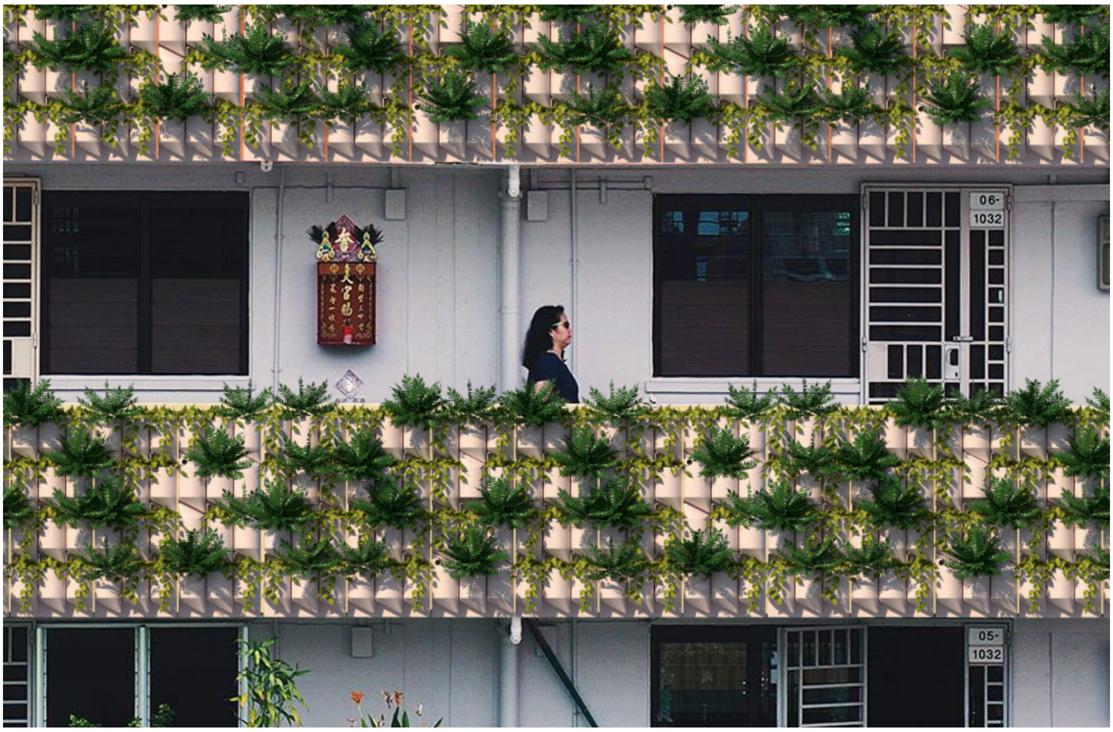

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Abstract

Rapid global urbanisation and climate change put significant pressure on centralised water and energy infrastructures. This thesis investigates regenerative design principles to transform building envelopes from passive resource consumers into active, ecologically functional habitats. The study presents the development of a multifunctional Plant Microbial Fuel Cell (PMFC) Integrated Façade Living Wall system intended to establish decentralised, circular water and energy flows. To assess practical feasibility, the design is applied to public housing blocks managed by Singapore's Housing and Development Board, taking advantage of the region's supportive sustainable building policies and tropical climate.

Experimental research was conducted to evaluate the performance of the proposed system. Designed prototypes were evaluated in terms of wastewater treatment efficiency (including oxidation rate, total suspended solids, and nutrient removal rates), energy generation capacity (including open and closed-circuit voltage, current, current density, power and power density), and overall plant health. The findings confirm that the integrated system functions effectively as an on-site biofilter, demonstrating reductions in suspended solids and nutrients in the supplied substrate. The energy-generation performance was successfully established, but the total power density remained low compared to conventional renewable energy technologies. Lastly, it was found that integrating PMFC technology benefits plant growth in both leaf and root growth.

Beyond the technical performance, this thesis highlights the broader environmental benefits of the system. The integration of the Plant Microbial Fuel Cell Integrated Façade Living Wall system contributes to urban heat island mitigation, improved air quality, noise reduction, and enhanced biodiversity, while also supporting human well-being. While further optimisation and evaluation are required, the system demonstrates potential as a circular, multifunctional strategy to improve environmental performance in dense urban contexts.

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1. Research Framework

1.1 Context

Since the rise of industrialisation, the human population has grown rapidly (Khan & Philadelphia Fed, 2008). According to the U.N., the total population is projected to reach 9.6 billion by 2050. Along with the growing population, pressure on resources is increasing. The demand for engineering goods and production leads to a surge in water and energy consumption (Sonawane et al., 2024). Estimates indicate that over 2 billion people lack access to drinking water (WHO & UNICEF, 2025) and around 1.1 billion people lack access to electricity (IEA, 2017).

Access to clean, potable water is getting constrained as water supplies are getting polluted by increased industrialisation (Shaikh et al., 2020). Because of this, pressure to improve the efficiency and ensure adequate sanitation of wastewater treatment technologies is rising. This increased pressure on water resources led to a shift in mindset toward treating and reusing wastewater (Vishwanathan, 2021). Apart from treated water, the conventional wastewater treatment process produces waste sludge, which needs to be disposed of (Kim et al., 2019). The handling of waste sludge is considered to contribute to up to 50% of wastewater treatment costs. A conventional wastewater treatment plant requires approximately 0.6 kWh/m^3 of energy to treat wastewater and several times more energy for transportation (You et al., 2021). Moreover, household wastewater contains organic energy content that is almost 10 times higher than is needed to treat it, though full energy recovery is not yet possible with current technologies (Pant et al., 2009). To facilitate treatment and further reuse of wastewater for purposes such as irrigation or toilet flushing, reliable and resource-efficient solutions are needed.

At present, most of the energy demand is met by burning fossil fuels (Vishwanathan, 2021). This causes depletion of the finite resources, air pollution and increased greenhouse gas emissions (Wang et al., 2022). Anthropogenic greenhouse gas emissions are causing Earth's temperature to rise above normal (IPCC, 2014). Such a temperature surge can cause more abrupt and intense weather events, like floods, droughts, or heatwaves. Researchers suggest that fossil fuel production will peak between 2015 and 2030, depending on the type of fuel (Chiari & Zecca, 2011), and that by 2100, most of the accessible fossil fuel resources will be depleted (Höök & Tang, 2012). Maintaining the present approach to energy production could lead to an energy crisis (Wang et al., 2022).

On the other hand, urbanisation has been rising in the developing countries since the Industrial Revolution. As our cities grow, we tend to replace greenery with buildings, paved squares or commuting infrastructure. Compared with neighbouring suburban areas, cities exhibit visible differences in local climate, namely humidity, precipitation, air quality, and surface and air temperatures (Guan & Yu, 2020). Increasing plant cover in cities is an important strategy to mitigate the negative environmental effects of climate change, such as the urban heat island effect. To positively regulate the urban climate, it is necessary to invest in green and blue infrastructure that can help to reduce pollution and regulate water.

In response to the climate emergency, a concept of regenerative design emerged. It recognises that traditional sustainable architecture is no longer sufficient to solve the ecological crisis. It states that it is necessary not only to be neutral but to leave a net-positive impact by restoring and revitalising natural systems. Regenerative architecture refers to buildings designed to give back more to their surroundings over their lifetime than they take during construction and operation (Armstrong, 2024). Regenerative design strategies recognise the need to facilitate co-evolution between the built environment and the living world (Craft et al., 2017). This methodology treats buildings as habitats that mimic the principles of biological ecosystems, such as maximising exergy efficiency and resource recovery (Hecht et al., 2024). It represents a transition from linear material flows to a more circular approach in which buildings serve as material banks of valuable resources intended for reuse (Fahmy et al., 2019).

Integrating Microbial Fuel Cell (MFC) technology into buildings can support regenerative design, as it embodies the core regenerative principle of co-evolution. MFC technology presents an opportunity to enable resource efficient wastewater treatment and simultaneously generate clean energy by taking advantage of naturally occurring microorganisms and their metabolic processes. When combined with green infrastructure, MFCs can support circular water management, renewable energy production and climate resilient urban design.

1.2 Research Objective

As a response, this research aims to develop a multifunctional, self-sustaining façade product system that integrates Microbial Fuel Cell technology with a green wall system to demonstrate the feasibility of using MFCs as façade components, which can enhance circular water and energy building flows. The presented integration transforms building wastewater into usable resources that can be returned to the building while simultaneously improving the indoor climate. The proposed Plant Microbial Fuel Cell Integrated Façade Living Wall system combines the biological conversion of wastewater into treated water and electrical energy of MFC technology with the climatic and psychological benefits of vegetation in Green Wall systems.

By taking advantage of the thermal properties of green wall systems, it lowers the building's energy demand needed for heating and cooling. By synchronous wastewater treatment and energy generation capabilities of the MFCs, it creates clean water for further reuse within the building and usable energy, ultimately reducing the water and energy bills. The proposed design is modular, scalable and adaptable to both existing and new buildings.

This thesis contributes to the field of sustainable building design by exploring how microbial technologies can transform façades from passive enclosures into active, resource-generating systems. It demonstrates that it is possible to create a sustainable building product that not only has a positive impact on the environment but is also highly aesthetic. This way, this thesis aims to explore new scenarios for the wider commercialisation of Microbial Fuel Cell technology.

1.2.1 Research Question

The main research question is formulated as follows:

> *How can Microbial Fuel Cell technology be implemented in a green wall system as a means for establishing circular water and energy flows in a building?*

The sub-research questions are formulated and grouped by category to support the main research question and guide the research process.

In terms of Microbial Fuel Cell technology:

- Which type of MFC is suitable for a Façade Living Wall integration?
- Which configuration of MFC components is suitable for a Plant Microbial Fuel Cell Integrated Façade Living Wall system?
- Which materials of MFC components are suitable for a Plant Microbial Fuel Cell Integrated Façade Living Wall system?

In terms of green wall systems:

- Which Green Wall system is the most suitable for MFC technology integration?
- Which design considerations are necessary for a Façade Living Wall system to successfully integrate Plant Microbial Fuel Cells?
- Which plant species are suitable for both Façade Living Wall and Plant Microbial Fuel Cells?

In terms of building adaptations required for a successful application of the Plant Microbial Fuel Cell Integrated Façade Living Wall:

- Which climate is the most suitable for the Plant Microbial Fuel Cell Integrated Façade Living Wall system?
- Which building infrastructure is necessary for a Plant Microbial Fuel Cell Integrated Façade Living Wall system?
- Which wastewater streams are suitable for a Plant Microbial Fuel Cell Integrated Façade Living Wall?
- How to effectively extract treated water and energy produced by a Plant Microbial Fuel Cell Integrated Façade Living Wall system?
- How to maintain a Plant Microbial Fuel Cell Integrated Façade Living Wall system to extend its service life?

In terms of the performance of the proposed system design:

— How does the Plant Microbial Fuel Cell Integrated Façade Living Wall perform in terms of wastewater treatment efficiency?

— How does the Plant Microbial Fuel Cell Integrated Façade Living Wall perform in terms of energy generation?

In terms of the influence of MFC technology integration on Façade Living Wall:

— How does MFC technology integration in Façade Living Wall influence plant growth?

— How does MFC technology integration in Façade Living Wall influence wastewater treatment efficiency?

1.3 Methodology

To answer the research question, this thesis is divided into three phases. The first phase is a literature study that helps to define the present state of the art of relevant aspects. It provides a necessary foundation for the following project phases. Phase two consists of the system design of the Plant Microbial Fuel Cell Integrated Façade Living Wall. It focuses on the reasoning behind the design decisions and explains in detail all the components of the design. In the third phase, the proposed Plant Microbial Fuel Cell Integrated Façade Living Wall system is evaluated in terms of performance. The prototype of the design is tested for the efficiency of wastewater treatment, energy generation, and plant growth. The thesis timeline is shown in Table 1.

Phase	Task	January	February	March	April	May
1	literature study					
2: system design	design PMFC reactors	6 weeks				
	design Living Wall modules		6 weeks			
	design Living Wall infrastructure			4 weeks		
	design Living Wall load bearing structure			2 weeks		
	design building adaptations			6 weeks		
3: system evaluation	set up PMFC reactors				2 weeks	
	prototype the Living Wall					4 weeks
	evaluate energy performance					5 weeks
	evaluate wastewater treatment efficiency					5 weeks
	evaluate plant growth					5 weeks

Table 1:
Thesis planning.

1.3.1 Phase 1: Theoretical Underpinning

The framework for this thesis is constructed through a literature study. For successful building integration of MFC technology, resource flows within a building are studied, with a focus on wastewater and electrical energy routing. Comparison with other on-site wastewater treatment and energy generation methods is made. Focus is put on Microbial Fuel Cell technology, its principles, components, designs, materials, benefits, limitations, practical applications and possible optimisation strategies. Different established or researched prototypes are studied in detail to gain insight and inspiration. Necessary building adaptation measures to successfully integrate MFC technology for wastewater treatment and energy generation are outlined. To enhance the performance and better combine Microbial Fuel Cells with Green Wall systems, different designs of the latter are explored. Case studies and experimental setups where Green Walls were used for on site wastewater treatment are analysed to identify key principles and design features necessary for these systems to function effectively.

1.3.2 Phase 2: System Design

In Phase 2, the knowledge from the literature study is applied to develop a prototype design. To design a Plant Microbial Fuel Cell Integrated Façade Living Wall system, it is necessary to consider the structural and operational aspects of both Plant Microbial Fuel Cells (PMFCs) and Living Walls. The proposed Living Wall system design must accommodate PMFC reactors, supply them with wastewater, harvest clean water and energy and route these resources back to the building. The design comprises PMFC reactors integrated in Living Wall modules, supported by a load-bearing structure, and electrical and hydraulic infrastructure connecting each module and the system to the building.

For successful prototype manufacturing and evaluation within the limited timeframe, MFC reactor design variables (type of MFC reactor, reactor's components size, materiality, architecture and composition of multiple reactors) are preselected based on literature findings and available fabrication capabilities. Since this study's primary objective is to identify effective integration strategies for Microbial Fuel Cell technology into Green Wall systems, evaluating alternative reactor designs falls outside the scope of this research.

Subsequent steps include form and material studies for the Living Wall modules, design of structural connections between modules and their load-bearing structure, selection of appropriate irrigation and water collection systems, and optimisation of electrical wiring across individual modules and the entire façade. Necessary adaptations to the building infrastructure are designed to supply the wastewater substrate to the Living Wall and integrate the treated water and generated energy back into the building.

Singapore's Housing and Development Board (HDB) public housing blocks are selected as a suitable case study for implementing the Plant Microbial Fuel Cell Integrated Façade Living Wall system due to Singapore's tropical climate, which enhances MFC performance, and legislation that supports building greening and on-site wastewater treatment initiatives. HDB housing, which accommodates 80% of Singapore's population, has a repetitive, modular typology that applies to both existing projects and new designs, making the integration of the Plant Microbial Fuel Cell Integrated Façade Living Wall system more seamless.

1.3.3 Phase 3: System Evaluation

Modules of the Plant Microbial Fuel Cell integrated Façade Living Wall are evaluated in terms of wastewater treatment efficiency (oxidation rate, total suspended solids and nutrient removal), energy output (voltage, current, current density, power and power density), and plant growth to assess their suitability for real-world integration. MFC reactors are established early, with their evaluation beginning as soon as they are complete. This approach captures microbiome startup dynamics, including colonisation time, voltage surges, and the development of nutrient removal efficiency. Off-the-shelf components in conventional planters are used to construct MFC reactors before they are transferred into designed Living Wall modules.

To assess MFC technology's specific contributions to this Green Wall integration, three control groups are established:

— Group 1: Plant Microbial Fuel Cell reactors fed on wastewater.

— Group 2: Plant Microbial Fuel Cell reactors fed with tap water.

— Group 3: Plants without Microbial Fuel Cell reactors fed with wastewater.

Groups 1 and 3 are compared to see how MFC technology influences the wastewater treatment efficiency of Green Wall systems. Groups 1 and 2 are used to measure the influence of substrate on energy-generation performance. All groups are compared to assess plant growth.

1.4 Societal and Scientific Relevance

Nowadays, conventional wastewater treatment plants and power stations cover large supply areas, resulting in long transmission infrastructure and thus in the case of an error, a large area can be affected. To mitigate reliance on centralised systems, there is an increased interest in turning towards more distributed energy generation and wastewater treatment on-site. Decentralised wastewater treatment solutions can help conserve energy used for the conveyance of wastewater and treated water, which is significantly higher than the energy required for the wastewater treatment process itself (Gholami et al., n.d.). Decentralised energy generation systems are more flexible in terms of location, storage and generation technologies (You et al., 2019). They can improve energy security, lower the environmental impact of energy generation and provide economic benefits by avoiding transmission and distribution costs (Hirsch et al., 2018).

Existing and future buildings can play a crucial role in the shift towards decentralised wastewater treatment and energy generation systems. They can mitigate the energy crisis, as buildings are large consumers in the energy sector. They account for over 20% of Singapore's total carbon emissions (Building and Construction Authority & Singapore Green Building Council, 2021). Singapore has set a target for 80% of new developments to achieve at least a 60% improvement in energy efficiency compared to 2005 baseline levels by 2030. By 2050, Singapore plans to achieve net-zero emissions. All buildings generate municipal wastewater, most of which is greywater originating from all sources that produce wastewater in a building, excluding toilets. Depending on the building's function, the amount of greywater produced varies. Since greywater contains fewer nutrients, pathogens, and organic matter, it can be treated on-site with simpler methods than those used in conventional wastewater treatment plants. Recycling greywater is a promising strategy for conserving water, yielding up to 50% savings in household water use (Gholami et al., n.d.).

The challenge to sustainably deliver enough potable water and electricity to buildings caused improved wastewater management and the development of alternative ways to generate energy (Shaikh et al., 2020; Sonawane et al., 2024). With the help of on-site wastewater treatment technologies and renewable energy sources, buildings can become active water and energy producers instead of passive consumers.

The development and optimisation of renewable energy technologies are growing due to the popularisation of environmentally safe practices and efforts to meet the global sustainable development goals (United Nations, 2025). Development of renewable, clean energy technologies can help combat climate change (Winfield et al., 2016) and achieve an energy-neutral future that supports the well-being of human and non-human ecosystems (Logan et al., 2006). Solar, wind, geothermal, nuclear, and other clean energy sources can help reduce pollution, but each has its own performance and use limitations (You et al., 2019; Solomon et al., 2021). To reduce the environmental impact of energy generation and ensure a smooth change to renewable energy sources, the development of green technologies must be compatible with existing energy infrastructure (Sonawane et al., 2024). To achieve sustainable development, it is necessary to further advance the clean energy sector, as it cannot fully replace current fossil fuel use (Wang et al., 2022). Focus must be shifted not only to improving existing technologies but also to developing new ones.

Renewable energy sources should deliver a continuous, uninterrupted supply of sustainable energy. Researchers outline the potential of microorganisms in the development of new, renewable, carbon-neutral energy production technology (Vishwanathan, 2021). Microbial Fuel Cell technology offers a promising approach to meet present and future energy demand sustainably and to support existing renewable energy sources (Wang et al., 2022). It shows promising results across various applications for reducing the environmental impact of energy generation (Rabiee et al., 2023). Simultaneous energy generation and wastewater treatment are unique characteristics of MFC technology (Solomon et al., 2021). Wastewater treatment is widely used to enhance circularity and resource recovery, but conventional methods consume significant energy. MFC technology offers an alternative approach to reducing the energy costs of wastewater treatment and to making the treatment process more self-sustaining. On-site wastewater treatment using MFC technology generates less waste than conventional plants. Beyond producing energy and clean water, MFCs create recoverable nutrients which can be used as fertilisers. Building integration also enables potential heat recovery from microbial reactions, further closing internal resource loops and transforming buildings into self-regulating ecosystems.

According to You et al. (2021), research on MFC technology integration into buildings has not been widely explored, particularly with building materials and components, though promising pilot projects exist. Implementing Microbial Fuel Cell technology into Green

Walls can offer dual benefits. MFCs will provide clean energy and water, while Green Walls mitigate urban climate impacts, enhance biodiversity, and provide thermal regulation. Green Walls in buildings can combat the urban heat island effect by providing natural shading and evaporative cooling (Ascione et al., 2020). These systems can also improve air quality by filtering pollutants through plant photosynthesis (Bhargava et al., 2024). Beyond environmental gains, green walls enhance mental well-being and social cohesion (Virtudes & Manso, 2012). In urban climates, where greenery is scarce, they support biodiversity by creating habitats for pollinators and birds. Integrating them with MFCs amplifies these benefits by making greening viable even in regions with less precipitation (Ascione et al., 2020).

2. Theoretical Underpinning

2.1 Regenerative Design

Ecosystem services are the direct and indirect benefits and contributions that healthy natural environments provide to human well-being and the economy. These include tangible resources like food and water, natural processes like climate regulation and water purification, and cultural benefits like recreation.

Regenerative design is defined as the reconnection of human activities to the evolution of natural systems to promote co-evolution between the built environment and the living world (Craft et al., 2017). It represents a shift toward an integrated approach to achieve a positive environmental impact. Unlike traditional sustainable architecture, which aims to create no negative emissions to minimise damage, regenerative design treats buildings as ecologically functional habitats or living entities that actively restore, renew, and revitalise their own sources of energy, water, and materials (Hecht et al., 2024). It aims to transform buildings into active participants that generate ecosystem services, such as clean air or water purification, for their surrounding environment. This approach emerged because traditional sustainability practices are no longer sufficient to address the global-scale climate emergency (Armstrong, 2024). While traditional sustainable design focuses on slowing the rate of depletion and degradation, regenerative design recognises that the planet's carrying capacity has been exhausted by industrialisation, and systems based on natural processes must now grow in proportion to increases in population and pollution. It answers the need to repair and rebuild resources rather than depleting them.

2.1.1 Regenerative Design Strategies

The foundational strategy of regenerative design is the place-based design approach, which emphasises context and co-evolution between built and natural systems (Craft et al., 2017). This strategy requires an understanding of local environmental conditions, resource flows, and spatial constraints, as well as the design's capacity to contribute positively to these systems. This ensures the building is not an isolated object but an active participant in its ecosystem, adding positive value to the whole network of interacting systems. To achieve this, designers employ ecosystem-level biomimicry, emulating the functional principles of natural systems rather than just their forms, to create buildings that serve as ecological habitats (Hecht et al., 2024).

A central technical strategy focuses on optimising system performance through a set of interrelated approaches. These include providing physical conditions that allow habitats to emerge through self-organisation, integrating living systems as biological sensing mechanisms, increasing the biomass of autotrophic communities for chemical energy storage, and enhancing biodiversity to support functional diversity (Hecht et al., 2024). In addition, regenerative systems prioritise multifunctionality, where individual components fulfil multiple ecological roles. They are also designed as dynamic, adaptive structures that exchange energy with their surroundings while incorporating reversible processes, such as bioelectrochemical systems, to support long-term system stability and resilience.

Regenerative strategies related to structural and material performance position buildings as long-term material systems designed for adaptability and circular use (Craft et al., 2017). This involves designing for reversibility and modularity, enabling components to be disassembled, replaced, or reused over time (Ajayabi et al., 2019). Material selection prioritises non-toxic, bio-based resources, as well as technical materials that can be reintegrated into industrial cycles. To support this, components can be documented and tracked with material passports and logged in BIM databases to track their residual value over time (Attia, 2018).

Another regenerative design strategy is net-positive resource management, as regenerative designs should extend beyond efficiency towards the active generation and regeneration of energy, water, and environmental qualities (Attia, 2018). This includes achieving positive energy balance through on-site renewable systems and managing water through circular flows, for example, by integrating nature-based treatment systems. In some approaches, additional functions such as food production are also incorporated, embedding productive landscapes within the built environment to reduce dependence on external resources (Gambato & Zerbi, 2019).

Finally, regenerative design emphasises occupant well-being by integrating natural elements into the built environment (Attia, 2018). This includes the use of daylight, vegetated systems, and adaptable environmental controls to improve comfort and health. These strategies are typically coordinated through integrative design processes that establish performance objectives across environmental, social, and technical domains from the early stages of design (Armstrong, 2024). In this way, building is understood as an active system that contributes to environmental quality and broader ecological processes.

2.1 Status Quo of Resource Flow in Buildings

2.1.1 Electrical Energy Flow

According to the UN's Global Status Report for Buildings and Construction 2024-2025, most buildings worldwide receive their electricity from centralised grids. Currently, electrical energy follows a predominantly unidirectional model in which power enters from the centralised grid and is distributed to end-use systems such as lighting, HVAC, and appliances in a building (Clark & Eisenberg, 2008). Reliance on centralised grids can make buildings vulnerable to price volatility, outages, or geopolitical disruptions.

Renewable energy sources such as solar panels, wind or water turbines, heat pumps or biomass can be integrated into buildings to limit dependence on centralised grids and tackle carbon emissions at the source. These technologies produce little or no greenhouse gas emissions during operation, which helps to reduce a building's carbon footprint. The locations of these energy sources can differ. It can be in a building's underground spaces or directly in the building fabric. Excess energy generated by these renewable energy sources can be stored in batteries, but a connection to the grid is often required to meet the building's energy demand (Hirsch et al., 2018). Some of these technologies are intermittent and variable, meaning output depends on weather, time of day, or season. Financially, although the initial capital cost is often high, renewable systems typically have low operating and maintenance expenses and can yield substantial long-term savings on energy bills.

To successfully implement renewable energy systems in buildings, several factors need to be considered. First, the site's physical and climatic conditions, such as available area, solar irradiation, wind exposure, shading, and local microclimate, must be assessed to determine which technology is most appropriate and how large the system can be. Second, the building's energy demand profile, including total electricity and heat consumption, peak loads, and seasonal variation, must be analysed to ensure the system is sized to meet on-site demand and to avoid significant under- or over-generation. In addition, regulatory and planning considerations, such as local building codes, zoning rules, permitted development limits, heritage or conservation area restrictions, and visual impact factors, also need to be taken into account (Hirsch et al., 2018).

One advantage of MFCs over conventional on site renewable energy sources, such as solar photovoltaics and wind turbines, is their low dependence on local weather conditions. MFCs can generate electricity continuously as long as an organic substrate is supplied, enabling relatively stable power output around the clock and year-round (Larrosa-Guerrero et al., 2010). From an environmental perspective, MFCs provide a carbon-neutral energy source because the carbon dioxide they emit is recycled from the atmosphere through the original photosynthesis of the biomass used as fuel (Du et al., 2007). Unlike some bioenergy processes, MFCs generally do not produce toxic residues or waste gases other than CO_2. The technology also offers substantial operational energy savings because MFCs are self-sustaining and require no external power supply for operation (Lu et al., 2020). Additionally, MFC systems are versatile enough to be modified for the building's customised needs. A comparison of the performance of renewable energy-generating technologies, including MFC technology, is shown in Table 2.

Table 2: Comparison of energy performance of different renewable energy sources, including Microbial Fuel Cells.

Renewable Energy Source	Power Density (mW/m^2)	Reference
Solar PV	1,500-19,600	Zalk and Behrens (2018)
Wind	Up to 4,200	Zalk and Behrens (2018)
Hydroelectric	8-870	Zalk and Behrens (2018)
Geothermal	80-14,940	Zalk and Behrens (2018)
Biomass	5-600	Zalk and Behrens (2018)
Microbial Fuel Cells	0.3-7,200	Van Limbergen et al. (2022)

2.1.2 Wastewater Flow

In a building, we can distinguish two types of wastewaters – greywater and blackwater. Greywater originates from showers, bathtubs, sinks, dishwashers and laundry machines. Blackwater originates from toilet flushing. The composition of both can vary depending on the building's function, its occupants, and its location (You et al., 2021). Greywater can account for up to 75% of total domestic wastewater production (Gholami et al., n.d.).

Chemical Oxygen Demand (COD) removal is the process of reducing the concentration of organic and inorganic pollutants in wastewater, measured by the amount of oxygen required for their chemical oxidation. It is a critical wastewater treatment step, to remove pollutants that, if discharged, would deplete oxygen in natural waters.

Most of the wastewater generated by the buildings is collected by a sewage system and transported to a centralised water treatment plant, where it is treated and can be further reused for purposes such as flushing toilets, irrigation, or cooling. On-site wastewater treatment methods exist, but not all of them facilitate the reuse of treated water (Diaz-Elsayed et al., 2017). The available technologies range from simple media filters, constructed wetlands, septic tanks, to more advanced aerobic treatment units (including membrane bioreactors and sequencing batch reactors), all designed to treat wastewater at or near the source rather than transporting it to a centralised plant. Currently, the status quo for most of these installations is a "lowest common denominator" approach that favours the simplest and least expensive methods, with many systems operating without performance monitoring or specific effluent limits (Bradley et al., 2002). Advanced on-site systems offer enhanced pollutant removal capabilities, which are often required in environmentally sensitive areas to protect human health and local ecosystems (Garcia et al., 2013).

Innovative nature-based methods are also emerging as sustainable alternatives for on-site wastewater management (Yadav et al., 2022). For example, Constructed Wetlands (CWs) utilise vegetation within a specific soil composition to passively remove pollutants (Oteng-Peprah et al., 2018). Another example is bioelectrochemical technologies, which represent an innovative approach to wastewater management that utilises microorganisms and their natural processes. These systems, most notably Microbial Fuel Cells, can significantly reduce energy consumption and sludge production while partially closing the energy loop through direct power recovery (Yadav et al., 2022). Table 3 compares the efficiency of wastewater treatment by selected on-site systems in terms of Chemical Oxygen Demand (COD) removal rate.

Table 3: Comparison of COD removal rate efficiency of different on-site wastewater treatment technologies including Microbial Fuel Cells.

On-site Wastewater Treatment System	COD Removal Rate (%)	Reference
Filtration	37–94%	Oteng-Peprah et al. (2018)
Constructed Wetland	81–82%	Oteng-Peprah et al. (2018)
Septic Tank	67%	Bradley et al. (2002)
Membrane Bioreactors	86–99%	Oteng-Peprah et al. (2018)
Sequencing Batch Reactors	90–98%	Oteng-Peprah et al. (2018)
Microbial Fuel Cells	80-96%	Roy et al. (2023)

2.2 Microbial Fuel Cells

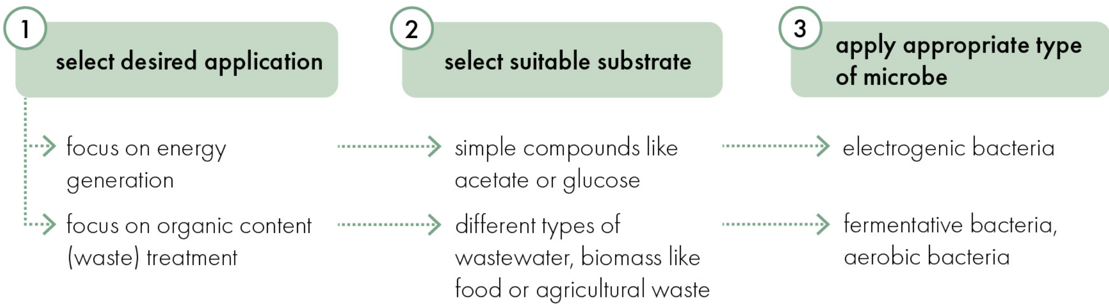
Microbial Fuel Cells were first described in 1911 by Potter. Since then, ongoing research has sought to develop this discovery into a feasible technology for present-day applications (Solomon et al., 2021). What makes MFCs so interesting for researchers is their ability to turn organic waste into electricity as part of their everyday metabolism (Ieropoulos et al., 2013). Imagine a system powered by the same kind of microbes that naturally reside in soil, ponds or compost heaps. Such a system could generate clean energy in an environmentally sustainable way while simultaneously treating different kinds of waste. This dual-utility aspect makes this technology excel among other renewable energy technologies (You et al., 2019). Because wastewater is rich in this type of organic waste, it has become a key area for exploring the potential of MFC technology. In recent years, there have been many promising efforts to use MFCs in wastewater treatment to offset the high costs of conventional wastewater treatment plants (Pant et al., 2009).

2.2.1 Working Principle

In a Microbial Fuel Cell, the "cell" refers to the fundamental bioelectrochemical unit that generates electricity.

Microbial Fuel Cells are bioelectrochemical devices that can generate energy without any additional power source (Lu et al., 2020). The chemical reactions occurring inside cells can be controlled to achieve desirable outputs (Shaikh et al., 2020). As biological systems, they can operate on different substrates depending on the required application. The substrate dictates not only the type of microbe applied inside the cell but also how well MFC performs in terms of energy-generating capabilities or organic content removal (Pant et al., 2009). A framework for designing Microbial Fuel Cells is depicted in Figure 1.

Figure 1: Framework for Microbial Fuel Cell design.



The microbes inside the MFC convert chemical energy from the breakdown of organic matter in wastewater into electrical energy (Wang et al., 2022). The rate at which these microbes generate electricity is directly linked to their metabolic rate, meaning microbes that treat (transform) the substrate more quickly and efficiently can, in theory, generate more power (Pant et al., 2009). Additionally, the higher the electricity generation, the faster the wastewater treatment process (Greenman et al., 2024). These dependencies are shown in Table 4.

Table 4: Dependence of bioelectrochemical performance metrics on the microbial metabolic rate.

Metabolic rate of microbes (rate at which microbes degrade organic content in the provided substrate)	**low**	**high**
Rate of substrate treatment	low	high
Amount of electrical power generated	low	high

2.2.2 Performance

Microbial metabolism encompasses processes microbes use to obtain energy and nutrients for growth and reproduction. Metabolic rate measures how quickly microbes perform these processes. Microbes break down chemical bonds of organic contents to release chemical energy that powers their cellular work. In special setups like MFCs, they redirect this process to convert that chemical energy into electrical energy.

The performance of Microbial Fuel Cells fed with wastewater is reflected in how effectively the system converts chemical energy in the wastewater into usable electrical energy. Chemical Oxygen Demand (COD) removal (substrate treatment efficiency) and power density (electricity-generation performance) are parameters used to evaluate MFC performance (Wang et al., 2022). The efficiency of wastewater treatment by MFCs can reach up to 96% (Wang et al., 2022) and is dependent on the amount of time that wastewater stays inside the MFC unit, the amount of organic matter to be treated, MFC design, type of microbial community applied, and operating conditions such as pH and temperature.

It is difficult to generalise the performance of MFCs because of the extreme diversity in their operating conditions, architectural designs, and biological components. This complexity stems from the fact that MFCs are interdisciplinary systems involving biology, chemistry, and physics, leading to a vast number of variants that lack a standardised framework for comparison. As shown in Table 1, MFCs can produce as much as 7,200 mW/m^2 and as little as 0.3 mW/m^2. The efficiency of MFC energy generation is relatively low because some energy is lost during microbial metabolic processes. The biofilm on the anode does not transfer all the energy from the substrate to the electrode – some is used by the microbes for biofilm growth and development (Li et al., 2018).

2.2.3 Microorganisms

The microbes used in MFCs are electrogenic bacteria that operate under oxygen-free conditions. These microbes can form a structured community called a biofilm, which adheres to a surface within an MFC and is enclosed in a self-produced protective matrix. The biofilm formation process is depicted in Figure 2. The biofilm can consist of mixed cultures or monocultures. The latter tend to be more beneficial in terms of performance (Sonawane et al., 2024), but they also impose higher requirements on substrate quality (Wang et al., 2022). This leaves room for customisation based on whether the priority is biofilm resilience or enhanced MFC performance.

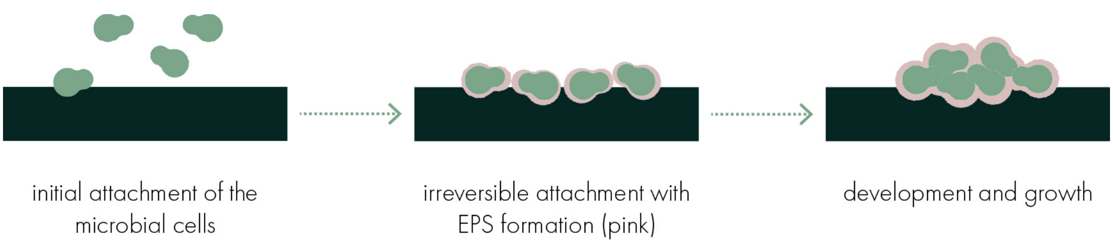


Figure 2: Biofilm formation process. Adapted from Stohl et al. (2023).

2.2.4 Substrates

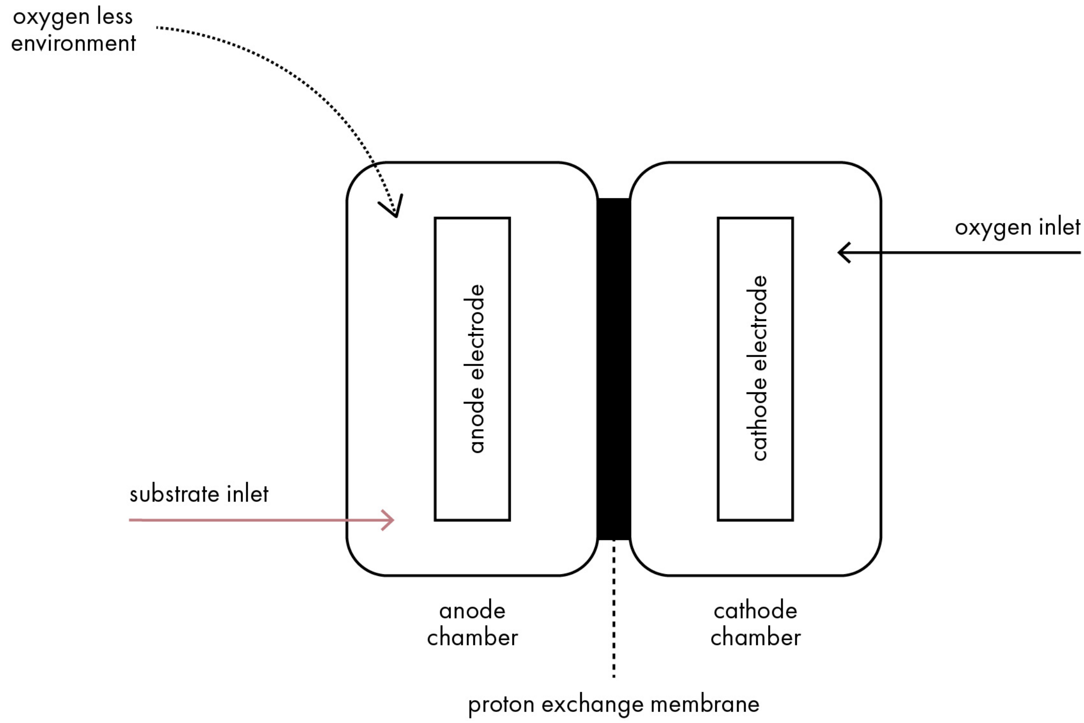
The energy-generating potential of the selected biofilm depends on the quality and quantity of organic content in the provided substrate. Organic content in the substrate serves as a nutrient and energy source for the microbes, acting as their "fuel" that can be directly converted into electricity. Different types of substrates can be used, including wastewater from municipal or industrial streams. Sonawane et al. (2024) compared different types of wastewater and their potential for electricity generation, as shown in Appendix 1. Generally, the more complex the substrate content, the less electricity MFC can generate (Pant et al., 2009). The level of substrate pollution fed into MFCs can be relatively high, as they are designed to treat contaminants.

2.2.5 Components

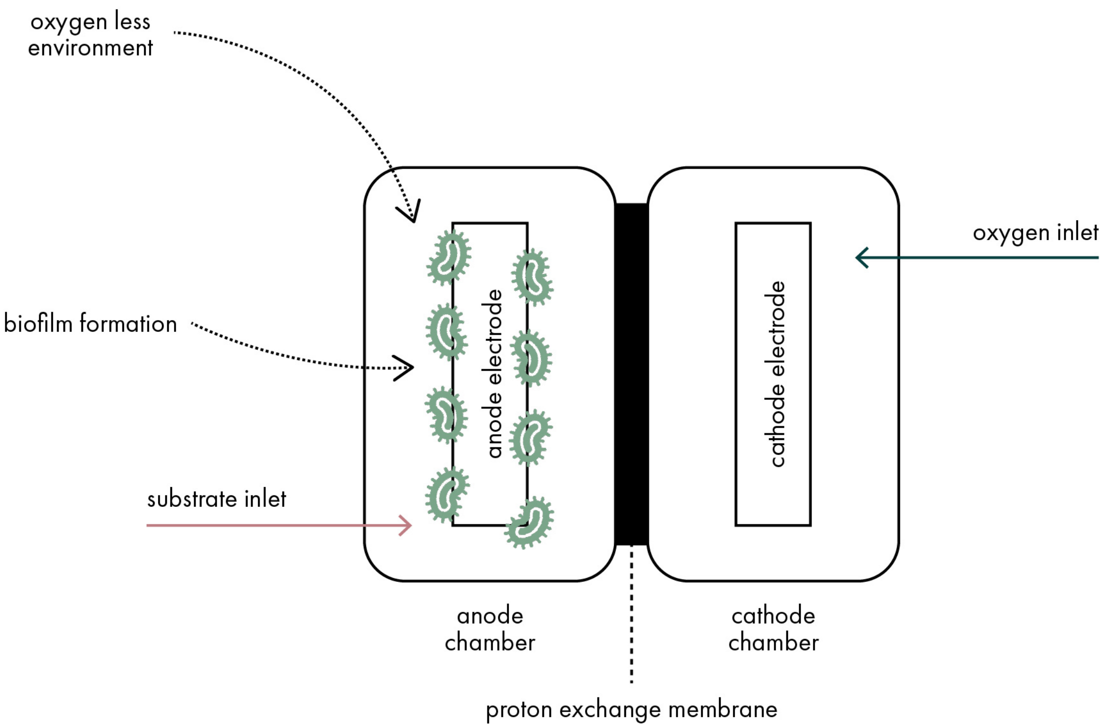
A typical Microbial Fuel Cell consists of anodic and cathodic chambers separated by a proton exchange membrane (Greenman et al., 2024). In the anodic chamber, there is an anode electrode, and in the cathodic chamber, there is a cathode electrode. Microbes use the surface of the anode electrode to form a biofilm. When the microbial community is established, it starts to digest the provided substrate. During digestion, protons and electrons are produced (Pant et al., 2009). Electrons can travel through an external circuit with a resistor connecting the anode electrode to the cathode electrode, from which they can be harvested to create usable energy (Vishwanathan, 2021). Protons travel through the proton exchange membrane located between the two chambers in the same direction as electrons. The membrane allows protons to pass but blocks oxygen from entering the anode chamber. This mechanism provides the oxygen-free conditions required by the microbes. In the cathode chamber, electrons and protons react with oxygen, which results in the generation of water (Wang et al., 2022). Because of that, it is preferable that the cathode chamber is exposed to atmospheric air or that an air supply is provided. The working principle and the bioelectrochemical processes occurring within an MFC are shown in Figure 3.

In addition to protons and electrons, microbes in MFCs can produce other usable products during substrate decomposition, such as biofuels, biopolymers, and volatile fatty acids. Biofuels (for example, biodiesel, biogas or bioethanol) can be used as renewable alternatives to fossil fuels. Biopolymers can replace conventional plastics, and volatile fatty acids (such as acetate and butyrate) can serve as feedstocks for further biofuel production (De Paula et al., 2018).

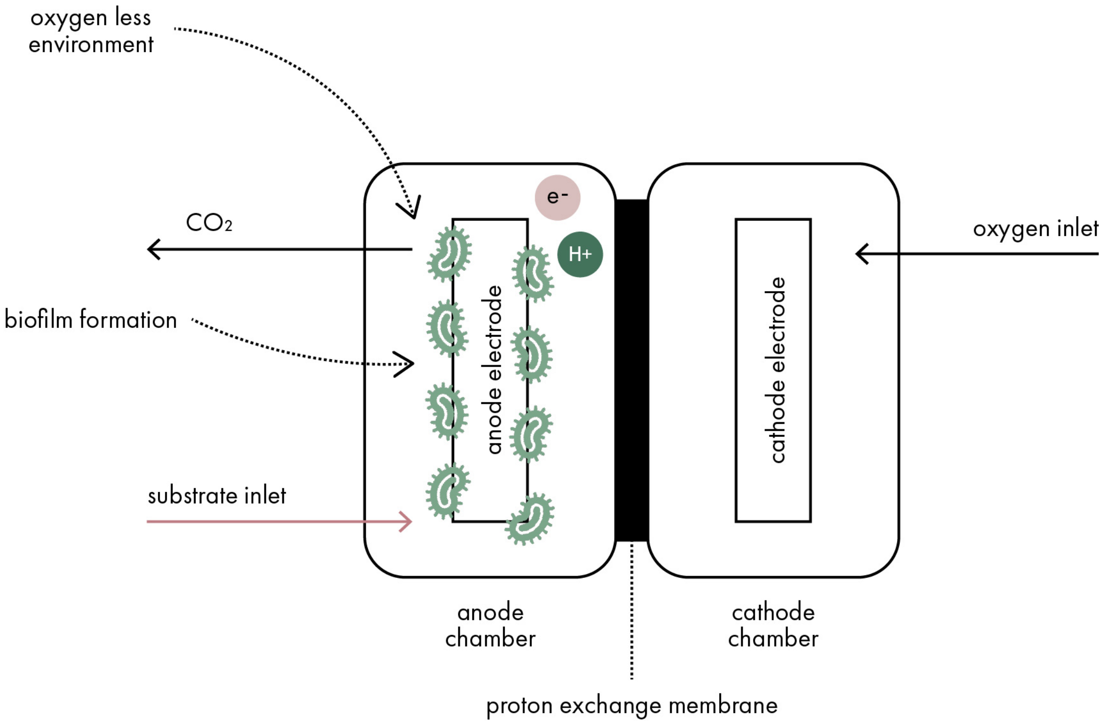
Figure 3: Working principle of Microbial Fuel Cell. Adapted from Moqsud et al. (2013).



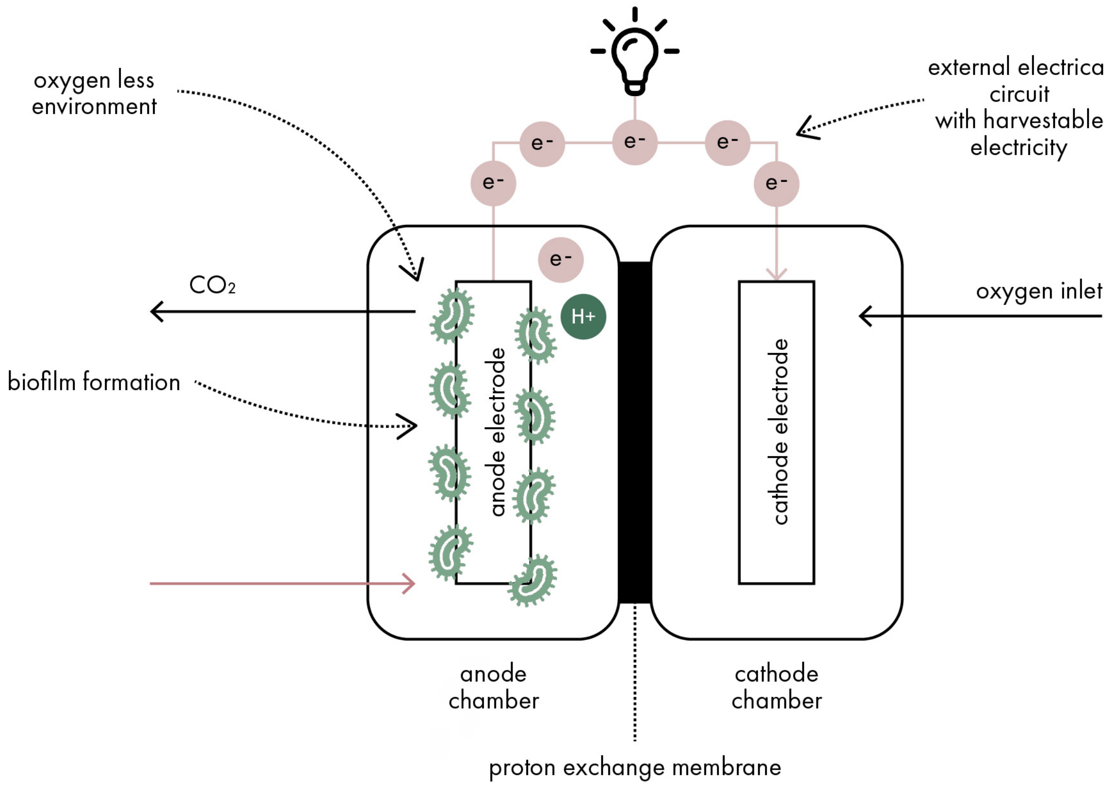
A typical Microbial Fuel Cell consists of anodic and cathodic chambers separated by a proton exchange membrane. These chambers can have different shapes, sizes and materials. Chambers host anode and cathode electrodes. The membrane has selective permeability, which means that it can block oxygen from entering the anode chamber to facilitate the required oxygen-less conditions for microbes.



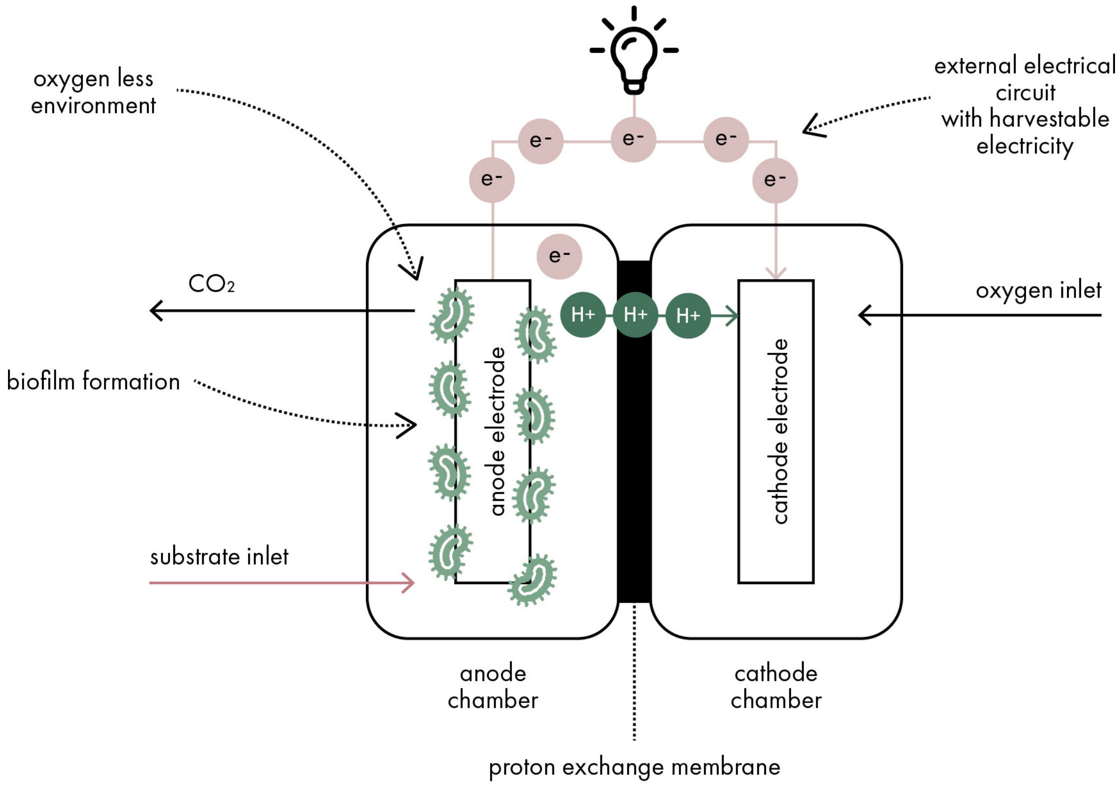
Microbes form a biofilm on the anode electrode in the anode chamber, where they digest the provided substrate.



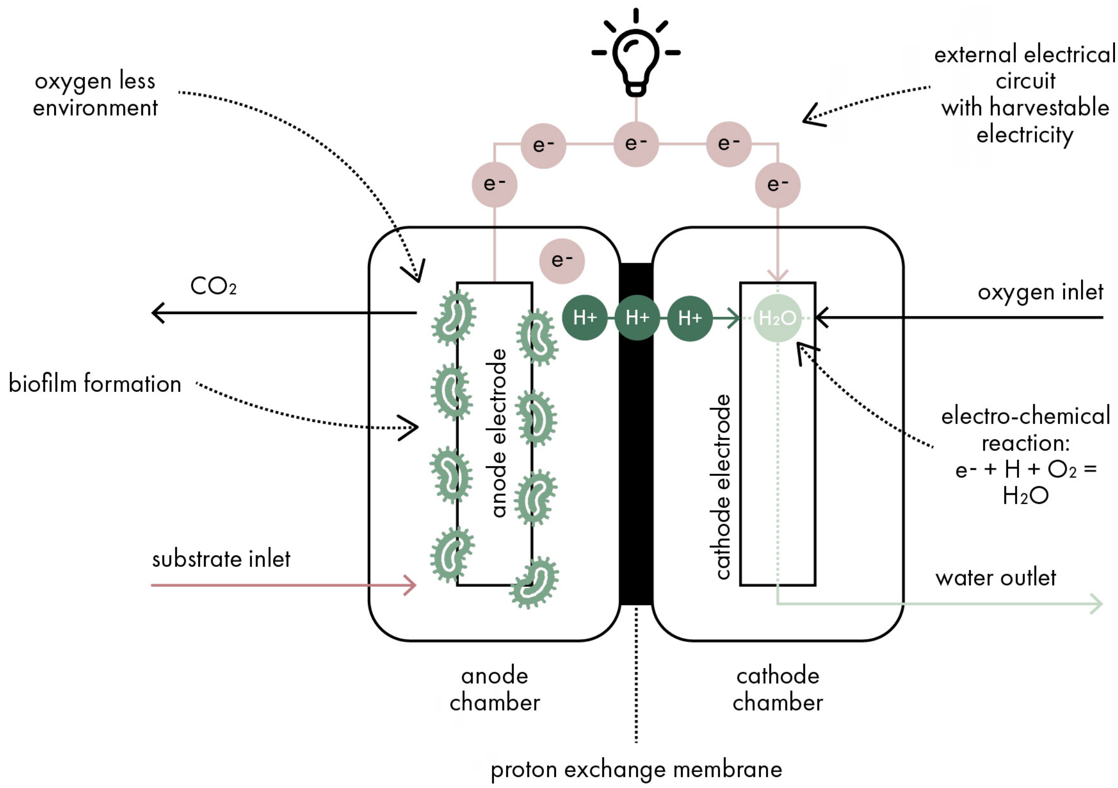
The digestion process produces positively charged protons and negatively charged electrons.



Electrons can't penetrate the proton exchange membrane because of its selective permeability. But they can travel through an external circuit that can be routed between the anode electrode and the cathode electrode. Along this circuit the energy can be harvested.



Protons travel through the proton exchange membrane to the cathode chamber. They do that to maintain the balance with negatively charged electrons that already traveled to the cathode.



In the cathode chamber protons and electrons react with oxygen, which results in generation of clean water that can be harvested.

2.2.6 Materials

The anode and cathode electrode materials and surface areas determine the electron acceptance and water generation capabilities of an MFC. Currently, carbonaceous materials such as carbon cloth, carbon brush, carbon rod, activated carbon, coarse graphite, graphite plate, or graphite felt exhibit the best performance (Sonawane et al., 2024). The anode electrode surface is often enhanced by different chemical mediators. Cathode electrodes are often coated with a catalyst layer to enhance performance. In most cases, platinum is used, but with advances in materials science, composites made from various materials are being developed and explored (Wang et al., 2022). The most popular material for proton exchange membranes is Nafion-117, a costly polymer resembling PTFE. It is used primarily for its excellent conductivity (Sonawane et al., 2024). Most commonly used materials for MFC reactors are depicted in Figure 4.

Figure 4: Materials used to construct Microbial Fuel Cell reactors. Adapted from Amazon, n.d.

2.2.7 Designs

These three main components can be arranged and shaped in different ways, resulting in different MFC types and designs. Each of these designs can exhibit different performance characteristics in energy generation, wastewater treatment, and pollutant removal, and thus can be used in appropriate applications. The most common types are single-chamber and double-chamber MFCs, but other adaptations have also been explored as described by Du et al. (2007). Schematic diagrams of the single-chamber MFC and the double-chamber MFC are shown in Figures 5 and 6, respectively.

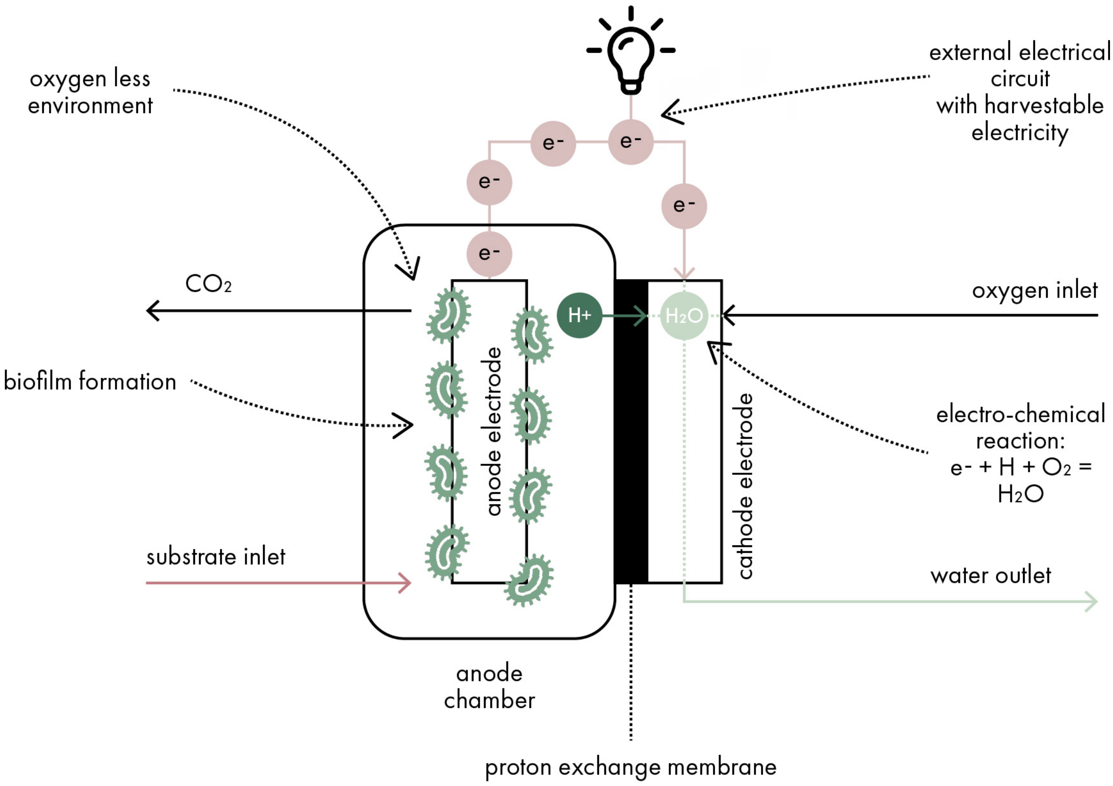


Figure 5:
Schematic diagram of a single chamber Microbial Fuel Cell. Adapted from from Roy et al. (2023).

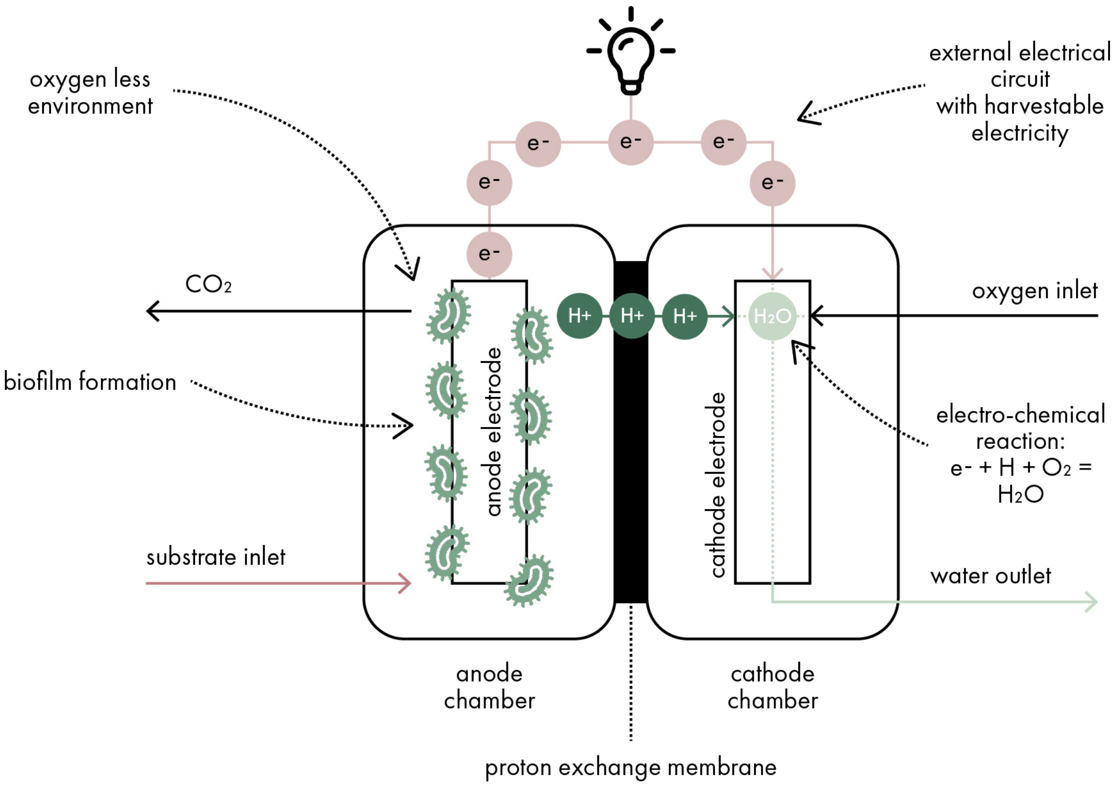


Figure 6:
Schematic diagram of a double chamber Microbial Fuel Cell. Adapted from from Ucar et al. (2017).

2.2.8 Applications

A microbiome is the ecological community of microorganisms (bacteria, fungi, viruses, and archaea) that share a particular space.

Practical applications of MFCs are restricted to certain environmental conditions that MFCs can tolerate. They function most efficiently at room temperature and an almost neutral pH (Sonawane et al., 2024), with stable temperature being the most influential factor on MFC performance (Wang et al., 2022). As with other parameters, the preferred environment for an MFC can vary depending on the types of microbes inside it. Sonawane et al. (2024) report a general temperature range of 15-45 degrees as optimal, and Solomon et al. (2021) state that raising the MFC environment temperature above 35 degrees can reduce the metabolic performance of the microbiome. Promising research is being conducted to adopt the MFC design to reduce operating temperatures without compromising performance. Maintaining high moisture levels and constant hydration is essential for optimal MFC performance, as a lack of moisture significantly increases electrical resistance, resulting in decreased power output (Pasternak et al., 2015).

In field applications, large temperature swings between day and night lead to unstable voltage output and decreased overall performance (Solomon et al., 2021). While MFCs are adaptable to diverse environments, stable and mild climates with high relative humidity are preferred. The most beneficial environmental conditions for MFCs are compared with the annual temperatures and relative humidity range of different climate zones in Table 5.

Table 5: Comparison of annual temperature and relative humidity ranges of different climate zones according to the Köppen climate classification (Köppen,1936).

Climate Zone	Annual Temperature Range	Annual Relative Humidity Range
Tropical climate	18–26 °C	60–85%
Dry climate	15–35 °C	10–40%
Temperate climate	5–15 °C	50–75%
Continental climate	−5–10 °C	40–70%
Polar climate	−20–0 °C	60–80%
Microbial Fuel Cells	15-35 °C	80-90%

Currently, MFC technology is primarily used for wastewater treatment, but it can also be used for biosensing or as a power source for small, low-energy electrical devices. It has been implemented in industrial wastewater treatment plants as both a treatment method and a wastewater toxicity monitoring system, since MFCs can detect toxicity early (Lu et al., 2020). For example, MFCs have been installed at a food processing plant, where they generated 330 kW/day of power from 7500 kg of organic waste at 30% efficiency, demonstrating their ability to effectively remove industrial waste (Logan et al., 2006). Apart from indoor applications, some specific types of MFCs can be used in urban greening or constructed wetlands to treat pollution (Guan & Yu, 2020). Detailed performance properties for different types of MFCs and their corresponding applications are compared in Table 6.

Table 6: Types of MFCs with their corresponding performance and possible practical real-life applications. Adapted from Wang et al. (2022).

MFC Type	Power Density (mW/m^2)	COD Removal Rate (%)	Application
Double Chamber	17–48	Up to 97	Laboratory-scale pollutant removal; used for powering sensors.
Single Chamber	140–280	Up to 98	Wastewater treatment in compact systems; power generator for low-voltage devices.
Plant Microbial Fuel Cell	88–240	Up to 86	Used in green roofs, constructed wetlands.

2.2.9 Benefits

The biggest advantage of MFCs is their dual capability to simultaneously treat wastewater and generate clean energy. Even though the energy output of the MFC is not significant, the development of more energy-efficient electronic devices suggests that this technology can be implemented in the future (Solomon et al., 2021). Additionally, because MFCs generate electricity themselves, it would theoretically be possible to create an autonomous, self-sustaining system (Lu et al., 2020) that could function without any interventions for a relatively long time, as microbes are self-renewable (Solomon et al., 2021). Compared with other green technologies, the maintenance cost of MFCs is much lower due to the system's longevity (Ieropoulos et al., 2013). This technology can treat a wide range of wastewater types in large quantities (Sonawane et al., 2024). It uses less energy than conventional aerobic wastewater treatment systems because operating an MFC for wastewater treatment is relatively simple (Wang et al., 2022).

Wider implementation of MFCs can enhance the well-being of our ecosystems, as this technology uses few chemicals and produces no pollution or greenhouse gas emissions (Sonawane et al., 2024). This technology also strongly aligns with the principles of the circular economy. The potential for practical implementation of MFCs is great as their design in terms of components' materials, size and configuration, supplied substrate, chosen microbiome and operating conditions is flexible and customisable.

2.2.10 Limitations

Even though MFCs show promise in wastewater treatment and renewable energy generation, their main issues are relatively low energy output compared to established power sources, high initial costs, and compromised stability (Ieropoulos et al., 2013; Sonawane et al., 2024). As a consequence, this technology is at present mostly explored in laboratory conditions. Present MFC technology doesn't meet the $1 kW/m^3$ threshold for feasible industrial energy recovery from organic matter (Pant et al., 2009). Achieving satisfactory energy output and COD removal from a single MFC unit may be problematic, and scaling-up solutions need further optimisation (You et al., 2019).

For an out-of-the-lab implementation, the cost of materials used to construct MFC reactors must be lowered (Winfield et al., 2016). Commonly used materials are not sustainable; for example, Nafion, used for proton exchange membranes, is not biodegradable, and platinum catalysts are very mining-intensive (Pant et al., 2009).

The environmental performance of MFCs is a major drawback to widespread energy generation applications, as real-world settings may not provide as stable habitats for microbes as laboratory conditions do. The start-up of this technology is complex, and it may take from a few days to a few weeks for microbes to develop on the anode electrode and begin producing stable electrical current (Pant et al., 2009; Lu et al., 2020). As it is a biological system, it can be prone to microbiome multiplying uncontrollably, which can affect the overall performance and require constant monitoring (Sonawane et al., 2024).

2.2.11 Optimisation Possibilities

To enable the commercialisation of MFC technology, it is necessary to overcome the current limitations of these systems.

> *To achieve this, it is necessary to develop and manufacture low-cost, efficient MFC components and materials, stabilise and optimise the operating environment and its adaptability, and improve harvesting (Gajda et al., 2015; Sonawane et al., 2024).*

Ongoing research shows promise that such obstacles could be overcome, and practical implementation of MFCs is possible.

The performance of an MFC can be optimised by modifying the reactor's materials, the composition of the components (mainly the distance between the electrodes), the environment, and the compatibility of the biofilm and substrate (Sonawane et al., 2024). Avoiding the use of a proton exchange membrane to lower costs is also possible by creating a membraneless reactor, but a physical barrier between the chambers is still necessary to prevent oxygen from penetrating the anode electrode and to provide adequate distance between the electrodes (Winfield et al., 2016). A tubular shape for MFCs seems beneficial for power output (Gajda et al., 2015). The development of genetic engineering and synthetic biology technologies can advance biofilm optimisation by enhancing the electrical performance of MFCs. To fit MFCs into more diverse environments and climatic conditions, it is possible to incorporate phase change materials into the reactor design, which will protect the biofilm from the negative influence of temperature (Solomon et al., 2021). Optimising the density of biofilm packing on the anode electrode relative to the volume of the MFC is another direction for achieving higher power yields (Walter et al., 2016). For this reason, it is more beneficial to create small units rather than large volumes (Ieropoulos et al., 2013).

To improve the performance and efficiency of MFCs, it is possible to stack them by connecting them electrically. Using multiple smaller units rather than enlarging a single unit's volume tends to be more beneficial (Winfield et al., 2016). The arrangement of single MFCs can be in parallel or in series, with parallel being more optimal for energy efficiency and series for COD removal (Ieropoulos et al., 2008; Winfield et al., 2016). Different possible designs scaling up MFC technology are shown in Figure 7. When scaling up, it is important to provide sufficient nutrient load and substrate flow rate to all modules of the MFC reactor (Walter et al., 2016). As substrate flows through a reactor, its quality gradually decreases as microbes digest the nutrients. Along with the scaled-up configuration, it may be necessary to bypass the underperforming units with a substrate of sufficient quality.

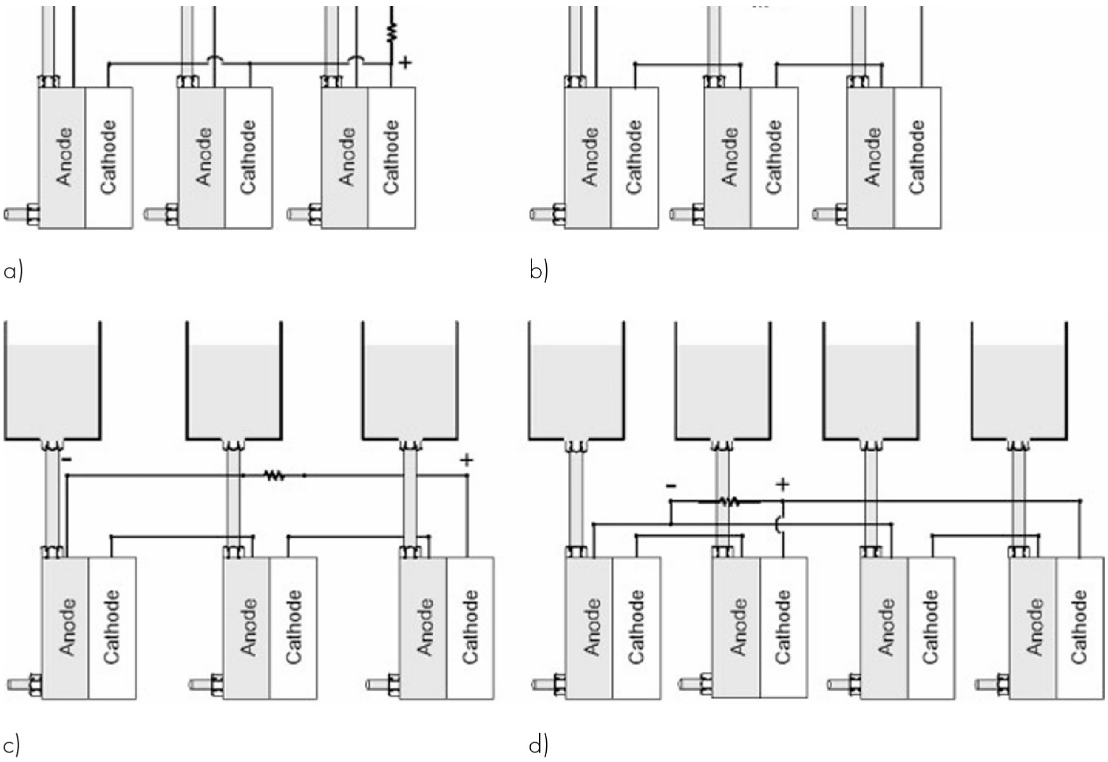


Figure 7: Designs for scaling up the MFC technology from Ieropoulos et al. (2008): (a) parallel electrical connection with a common feed line; (b) series electrical connection with a common feed line; (c) series electrical connection but with individual feed lines; and (d) series–parallel connections with individual feed lines and with an even number of MFCs.

Supplementing conventional materials for proton exchange membranes and electrodes with ceramics shows promise in terms of cost, sustainability, and even performance (Winfield et al., 2016). It can create a stable environment for the microbiome, enhancing energy efficiency. Additionally, ceramics can be modified in terms of porosity and density to fit a wide range of applications. Reports suggest it may be more stable and durable in the long term, but attention must be given to the possibility of pore clogging and a higher moisture evaporation rate. To optimise and simplify MFC manufacturing, it is possible to construct the entire unit in a single firing. Before firing, some factors that improve reactor performance can be incorporated. The cost of one square meter of a ceramic reactor can be as little as 4.78 € compared with 91.40 € per square meter when using conventional membrane materials (Pasternak et al., 2016). Using ceramics can limit the cost of a single MFC reactor to less than 1€ (Ieropoulos et al., 2013). Different types of ceramic materials can be used to adjust performance characteristics, and a thicker ceramic layer typically yields higher performance (Winfield et al., 2016).

Given that the initial 10 years of research on MFCs have resulted in a 10000-fold increase in their electricity production, further advancements in this technology are very probable, and achieving practical real-life applications is in reach (Pant et al., 2009; Gajda et al., 2015). With extensive material development and sufficient space, it is possible to construct scaled-up MFC reactors that can meet energy demands for commercial purposes (Greenman et al., 2024).

2.3 Microbial Fuel Cell Integration Possibilities within Buildings

As mentioned before, integrating MFC technology into buildings can bring several benefits. Using MFCs for on-site energy generation and wastewater treatment can lessen the load on centralised systems, increasing energy and water security (You et al., 2021). Such integrations are also in line with recent demand for sustainable and circular architecture, which aims to reduce the carbon footprint of buildings. Unfortunately, the electricity generated by the MFC system may not be sufficient to meet a building's total energy demand, but it is adequate to power the system's own infrastructure (You et al., 2021). Because of this, combining it with other renewable energy sources can provide a constant power supply to the building. Additionally, some restrictions and rules must be followed to integrate this technology successfully.

2.3.1 Requirements and Adaptation Measures

The first consideration is the required infrastructure to connect the MFC technology to a building and ensure efficient resource flow. Adequate connections must be established to provide the MFC with high-quality wastewater (Pant et al., 2009). For this purpose, some additional infrastructure for wastewater pretreatment and pumping may be necessary. To ensure that the quality of the supplied and treated wastewater is sufficient, sensors and meters are required. Moreover, additional piping may be required to route the treated wastewater back to the building, as its quality may limit its use to toilet flushing or irrigation only. To guarantee the right environmental conditions for MFCs, cooling or insulation may be necessary, depending on the MFC's location in the building and the building's location. As mentioned previously, MFCs can generate sufficient power for building implementation when scaled up. Wiring must be installed to connect individual modules to one another and later to the building's electrical infrastructure. Before the electrical current generated by MFCs can be utilised in the building, it must pass through a converter that transforms the low-voltage MFC output into usable energy.

Municipal wastewater generated within the building can be used as a feedstock for on-site MFCs for potential treatment and energy generation (You et al., 2019). All types of municipal wastewater can be used as a substrate for MFCs. Greywater, especially that generated by sinks or dishwashers, can be a valuable substrate because it has high nutrient content and doesn't require complex pretreatment. Removing larger particles may be necessary to avoid clogging of the system (You et al., 2021). Additionally, research indicates that MFC technology and its biofilm can be resilient to cleaning products that greywater may contain. Moreover, some commonly used household products, such as dishwasher salt, can enhance the power output. On the other hand, the quality of municipal wastewater requires constant monitoring, as its organic content can change throughout the day depending on building use.

2.3.2 Presently Explored Real-life Applications

Several approaches can be taken to integrate MFC technology directly into a building. To this day, most of the explored practical building integrations involve connecting individual MFCs to plumbing fixtures, such as sink drains (Ye et al., 2016) or urinals (Walter et al., 2018). You et al. (2021) suggest that the most feasible building-integrated MFC systems for treating wastewater and generating substantial electricity would likely be stacked or cascading configurations of individual MFCs. Some experiments have been carried out to integrate MFC technology directly into building fabric. You et al. (2019) converted off-the-shelf bricks into a MFC reactor, Hogle et al. (2023) designed a modular bioreactor wall that used MFCs and Guan and Yu (2020) installed MFCs in a green roof. They have been analysed in Appendix 2 in terms of ease of integration, performance, requirements and components.

Another approach is to integrate MFC technology into green walls (You et al., 2021). This strategy synergises the benefits of MFCs for energy generation and wastewater treatment with those of green walls. It does not take much additional space inside the building, as the main reactors and infrastructure utilise unused wall space outside of the building. Design measures for such a strategy would be similar to MFC-integrated green roofs, but can offer more versatile use, as not all buildings can accommodate a green roof. Space on buildings that can accommodate green roofs may be limited by other rooftop infrastructure, such as ventilation units. In an urban context which comprises mostly mid- or high-rise buildings and where greenery is scarce, there is usually more wall space available for MFC integration than roof area. This available space can enable scaling up the system and thus improve the energy output of MFCs.

For successful integration that enhances the building's circularity, the sustainability of the MFC's components has to be improved. Conventional materials used in MFCs can be supplemented with ceramic materials, and the use of precious metals and harmful chemicals should be limited. The developed integration strategy must comply with building codes for structural compliance, fire safety, and health regulations.

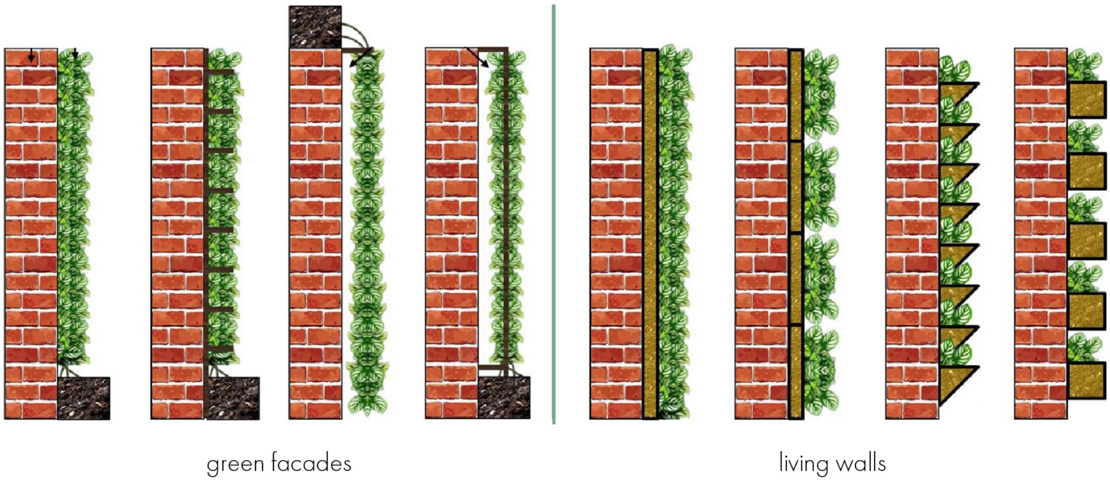
2.4 Green Walls

The concept of green walls encompasses all technological systems that enable the greening of vertical building surfaces (e.g., facades, walls, blind walls, partition walls, etc.) with various plant species, including all the solutions to grow plants on, up or within the wall of a building (Manso & Castro-Gomes, 2014; Yan et al., 2022).

2.4.1 Types

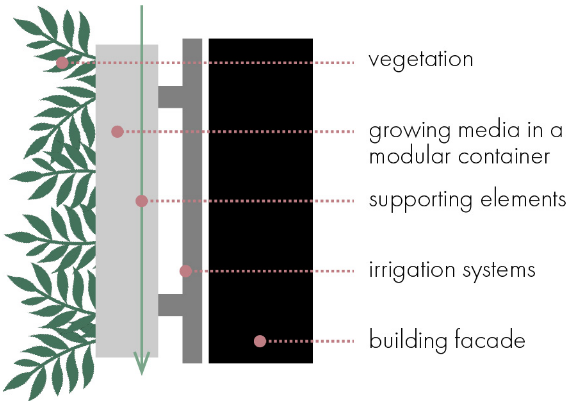
The green wall systems operate on fundamental structural principles consisting of five core functional elements: supporting elements, growing media (substrate), vegetation, drainage, and irrigation (Palermo & Turco, 2020). These systems can be subdivided into two categories: Green Facades and Living Walls, as depicted in Figure 8.

Figure 8: Different types of green walls from Yan et al. (2022).



Green façades utilise climbing plants that may attach directly to a building surface or grow along climbing aids such as stainless steel or wooden trellises, meshwork, grids, and tensile cables (Yan et al., 2022). Generally classified as "ground-based" greening methods, green facades usually feature plants rooted in the ground or in planter boxes at the base, although boxes can be placed at intermediate heights for taller structures (Manso & Castro-Gomes, 2014). These systems are characterised by low technology and light weight (Palermo & Turco, 2020). While they are cost-effective and easy to install, they often require several years to achieve full coverage and offer a more limited plant selection than living wall systems.

Figure 9: Living Wall System components. Adapted from Ottelé et al., 2011



In contrast, living wall systems are more technologically advanced, employing pre-vegetated modular panels, rigid trays, vessels, or continuous lightweight permeable screens and geotextile felts to support plant growth independent of ground-level soil (Palermo & Turco, 2020). An example of a Living Wall System based on planter boxes with materials layers is shown in Figure 9.

The growing media anchors plant roots and can consist of traditional soil or specialised soilless materials like coconut coir, perlite, vermiculite, rockwool, biochar, or lightweight expanded clay aggregate (LECA) (Wang et al., 2024). To prevent moisture damage to the building, these systems frequently include waterproofing membranes, root barriers, and a stagnant air cavity maintained between the building facade and the greenery (Ascione et al., 2020). Living wall systems rely on integrated and often self-automated irrigation networks to provide essential moisture and nutrients to plants (Ramadhan & Mahmoud, 2023). The delivery method is dictated by the system's design: continuous living walls typically feature a drip line installed at the top of the structure, utilizing a permeable geotextile layer to distribute moisture uniformly through gravity, while modular living walls often incorporate perforated pipes or drippers located at the top of each panel or tray recess to ensure that water reaches the growth substrate (Manso & Castro-Gomes, 2014). Modern walls utilise sensors and computer-controlled valves to regulate water delivery based on real-time soil moisture and weather conditions, frequently employing recirculating pumps to transport harvested rainwater to upper levels for reuse. Daily water consumption is highly dependent on the chosen technology and on the climate in which the wall is located (Prodanovic et al., 2019). To maintain efficiency, these systems may include filtration units to prevent nozzle blockage, although the network typically requires specialised maintenance every 7.5 years due to salt crystallisation from nutrient solutions (Ottelé et al., 2011).

2.4.2 Benefits

Green walls provide an array of environmental, social, and economic benefits by functioning as nature-based solutions that mitigate the negative impacts of urbanisation (Yan et al., 2022). One of the most significant advantages is thermal regulation and energy efficiency, achieved through shading provided by the leaf canopy, evapotranspiration, which cools the ambient air, and insulation provided by the substrate and air gaps (Ottelé et al., 2011; Ouldboukhitine et al., 2025). During hot periods, green walls can reduce external surface temperatures by up to 15°C to 20°C compared to bare walls, significantly decreasing the heat flux into the structure. This cooling effect translates into tangible indoor benefits, such as reducing internal air temperatures by 3°C to 4°C and lowering building cooling loads by approximately 64% to 75%. While summer performance is driven by cooling, the system serves as a thermal buffer in winter, with the air behind the wall remaining up to 2.1°C warmer than the ambient air, thereby mitigating heat loss (Lakho et al., 2021). The efficiency of these benefits is highly dependent on design variables such as the leaf area, the orientation of the façade, and the water-retention capacity of the substrate (Ascione et al., 2020).

Green wall systems serve as a passive noise control strategy by leveraging the natural ability of plants to reflect, diffract, and absorb sound waves, in addition to the acoustic insulation provided by their growth substrates (Yan et al., 2022). The overall acoustic performance is primarily influenced by vegetation morphology and the physical properties of the substrate, including its density, depth, and porosity. While leaves and branches are effective at scattering high-frequency noise, the porous growing media are responsible for significant attenuation in the low-to-middle frequency range. Living wall systems typically provide better absorption than green façades because their lightweight, highly permeable substrates can achieve performance levels similar to industrial sound-absorbing materials like fibreglass. Experimental data reported in the sources indicate that green walls can achieve a weighted sound reduction index of 15 dB, which may be further enhanced by increasing the structural mass and ensuring the system is properly sealed. The efficiency of these systems is also sensitive to moisture levels, as increasing substrate humidity has been found to improve acoustic insulation (transmission loss) while simultaneously reducing the absorption coefficient. In high-density urban areas, green walls mitigate noise pollution by reducing the reverberant field between building façades.

From an ecological perspective, green wall systems function as vital nature-based solutions that mitigate the detrimental environmental impacts of urbanisation. A primary benefit is the mitigation of the urban heat island effect (Ascione et al., 2020). Green walls significantly improve air quality by functioning as natural filters that capture particulate matter (PM10) while simultaneously sequestering carbon dioxide and restoring oxygen to the atmosphere through photosynthesis (Bhargava et al., 2024). These systems also play a critical role in stormwater management, as they reduce surface runoff (Wang et al., 2024). Furthermore, green walls promote urban biodiversity by providing essential habitats, food sources, and nesting resources for birds, insects, and pollinators, acting as ecological "stepping stones" or corridors that reconnect fragmented natural spaces within dense city environments (Ascione et al., 2020).

Besides thermal and acoustic benefits that positively influence human wellbeing, green walls facilitate a vital connection with nature that appeals to an innate human biological dependence known as biophilia, satisfying essential immaterial and non-consumptive human needs (Bradley et al., 2002). These systems provide profound therapeutic effects for city dwellers, offering diverse opportunities for psychological relaxation, stress reduction, and emotional rejuvenation (Virtudes & Manso, 2012). Furthermore, green walls function as a medium for horticultural therapy, which is increasingly utilised to assist individuals suffering from depression, anoxia, and other mental illnesses by fostering a sense of harmony and tranquillity (Bhargava et al., 2024). At a community level, these systems significantly enhance the quality of the city image and encourage the use of outdoor public spaces, thereby fostering social interaction, unity, and a sense of belonging among urban residents (Virtudes & Manso, 2012). Even in instances where the greenery is not physically accessible, the mere visual experience of viewing a green space is proven to effectively promote mental and physical well-being.

Green wall systems also provide economic benefits by increasing property values by approximately 2% to 16% (Virtudes & Manso, 2012). Finally, these systems reduce long-term maintenance costs by protecting the building's envelope from UV radiation and extreme weather (Safikhani et al., 2014).

2.4.3 Limitations

The implementation of green wall systems is primarily hindered by high initial investment and ongoing maintenance costs when compared to traditional building claddings (Yan et al., 2022). Installation expenses are driven by the requirement for complex components, including specialised support structures, automated irrigation systems, and the intensive labour necessary for professional assembly. Among the different technologies, living wall systems are significantly more expensive to install and maintain than green facades due to their material diversity and technological complexity (Madushika et al., 2022). Research indicates that the maintenance stage consumes the largest portion of a system's life-cycle cost, typically accounting for 51% to 78% of total long-term expenditures. These recurring costs involve periodic pruning, the manual replacement of roughly 5% to 10% of plants annually, and the energy required to run irrigation pumps. Furthermore, system components have limited service lives, as mentioned previously. Beyond direct financial burdens, maintenance barriers include building risks such as aggressive root growth damaging structural walls, increased humidity leading to mould problems, and the attraction of unwanted pests like mosquitoes (Ascione et al., 2020).

The significant weight load of living wall systems, which can exceed 100 kg/m² when accounting for plants, saturated substrate, and supporting hardware, requires a rigorous evaluation of the building's load-bearing capacity and the study of specialised anchorage systems (Gholami et al., n.d.). This is especially critical in regions prone to seismic events or extreme weather. Other identified risks include the vulnerability of the system to environmental forces, such as extreme winds that can strip foliage or heavy snow that adds to the structural load. Consequently, sophisticated considerations regarding plant species and system maintenance are necessary to prevent long-term damage to the building envelope (Ramadhan & Mahmoud, 2023).

The sustainability of green wall systems is often challenged by the high environmental burden of their constituent materials and the resource-intensive nature of their maintenance. Life-cycle assessments indicate that supporting structures, particularly those utilising stainless steel, can account for up to 96% of a system's total environmental burden in categories like Global Warming Potential. Certain technologies, such as continuous living walls based on felt layers, are deemed less sustainable due to their short life expectancy (roughly 10 years) compared to the time required to balance their manufacturing emissions, which can be as long as 23 years (Ascione et al., 2020). These multi-layered systems also pose significant recycling challenges because it is often impossible to separate the different components for processing at the end of their service life (Ottelé et al., 2011).

Green wall systems are uniquely vulnerable to rapid drying and drought stress due to their vertical orientation, which exposes a large surface area to the dehydrating effects of direct sunlight and wind (Prodanovic et al., 2019). Prolonged dry periods can lead to plant mortality if irrigation fails. To avoid drying out, continuous living walls often require high consumption of water and fertilisers, which can be seen as an unsustainable use of resources if not managed via rainwater harvesting or greywater recycling.

The broad adoption of these systems is also slowed by a lack of international construction standards, a shortage of specialised and trained designers, and the unavailability of certified commercial simulation models to reliably estimate long-term economic performance.

2.4.4 Green Walls and Possibilities of Wastewater Treatment

Constructed wetlands are engineered, human-made systems designed to treat wastewater, stormwater, or runoff by mimicking the natural processes of wetlands. They consist of shallow, engineered basins filled with

Green wall systems can be adapted into decentralised, on-site wastewater treatment solutions capable of treating greywater generated from household activities like showering, laundering, and handwashing through a combination of processes (Gholami et al., 2023). By treating greywater, these systems can substitute freshwater for non-potable demands such as toilet flushing and outdoor irrigation, potentially meeting 30% to 37% of a site's total water consumption (Gholami et al., n.d.). These systems function as vertical biofilters where greywater flows downward by gravity through various layers of lightweight substrate and vegetation root zones (Prodanovic et al., 2019). Green walls wastewater treatment rates are comparable to more space-intensive natural on-site systems like constructed wetlands, yet green walls offer a minimal horizontal footprint, making them suitable for dense urban environments where land is scarce. International studies have demonstrated high treatment efficiencies for these systems, with removal rates often exceeding 90% for COD, 98% for total suspended solids, and up to 93% for total nitrogen, although phosphorus removal is typically more limited (Gholami et al., n.d.). The resulting treated effluent significantly reduces the demand for freshwater and the energy costs associated with cen-

permeable media (soil, gravel, sand) and planted with aquatic vegetation. They remove pollutants through natural physical, chemical, and biological processes, including sedimentation, filtration, and nutrient uptake by microbes and plants.

tralised wastewater conveyance and treatment.

Green walls designed for greywater treatment most frequently take the form of modular living wall systems, because their flexible design allows for a significant volume of growing media to be arranged in series, facilitating extended pollutant contact time and supporting a high root density (Prodanovic et al., 2019). The physical infrastructure of these walls includes an integrated irrigation and drainage network that is often more complex than that of purely aesthetic walls. Drip lines are typically mounted at the top of the wall or at each row of modules, allowing the greywater to flow through the units by gravity. A drainage gutter or pipe is situated at the base of the wall to collect the treated effluent for reuse.

Treatment occurs through a complex synergy of physical, chemical, and biological processes as wastewater trickles vertically through the wall's substrate and plant root zones (Gholami et al., 2023). Physical mechanisms, such as filtration, straining, and sedimentation within the porous media, effectively capture particulate pollutants. Microbial communities and plant roots facilitate biological treatment. Plants contribute by providing oxygen to the root zone to promote aerobic bacterial activity and by directly assimilating nutrients like nitrogen and phosphorus into their own biomass. An example of a green wall designed for greywater treatment is shown in Figure 10.

Figure 10: Green wall design for greywater treatment from Prodanovic et al. (2019).

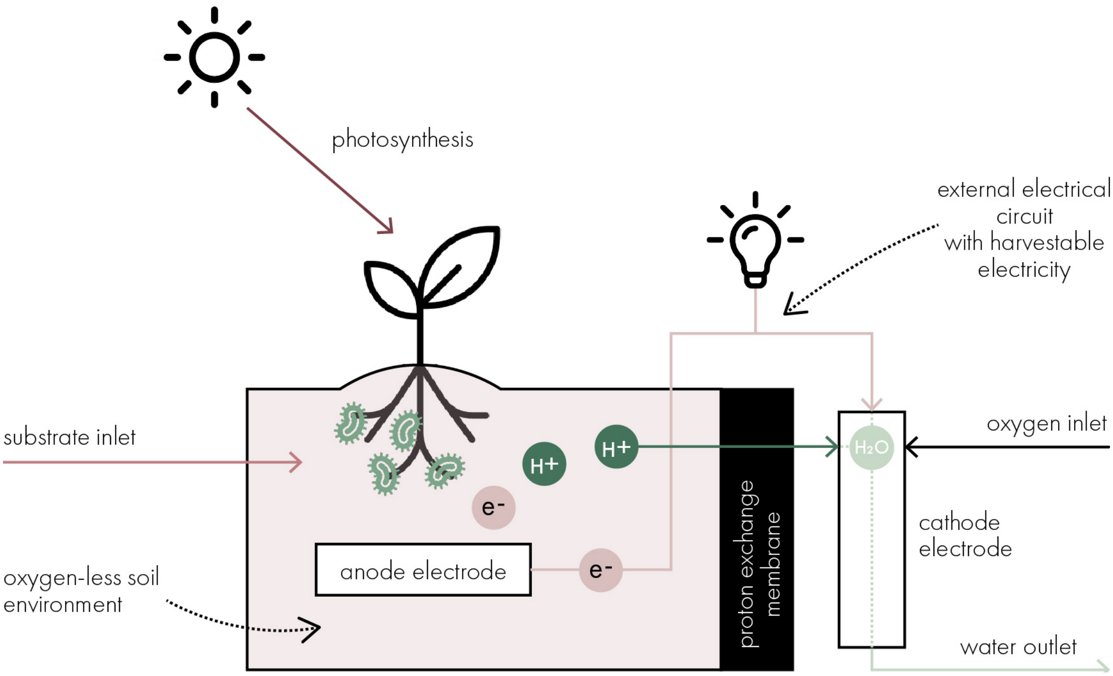
2.5 Microobial Fuel Cells that can be Implemented in a Green Wall for Electricity Generation and Wastewater Treatment

A few types of MFCs can be implemented in green walls to enable simultaneous electricity generation and wastewater treatment, including Plant Microbial Fuel Cells (PMFCs). PMFCs are a modification of Microbial Fuel Cells that utilise a unique relationship between plants and microbes located on plants' roots (Greenman et al., 2024). PMFCs exhibit the same benefits as MFCs, but they gain additional advantages by incorporating plants. Similarly, PMFCs face plant-dependent limitations on top of those of MFCs, like seasonal growth and additional maintenance of plants. As they have to accommodate plants in their design, they have a slightly modified working principle and have to integrate more components.

2.5.1 Working Principle

During the day, plants fix atmospheric carbon dioxide into energy-rich carbohydrates, and a significant portion of these organic compounds (roughly 40% to 70%) is subsequently released into the soil by plants' roots as rhizodeposits (Shaikh et al., 2020). Electrochemically active bacteria residing in the rhizosphere (a narrow region of soil or substrate immediately surrounding plant roots) digest these organic compounds and release protons and electrons. The anode, strategically placed near the plant roots, captures these electrons, allowing them to flow through an external circuit to the cathode, while protons migrate through a separator or the soil itself to maintain electro-neutrality. Finally, at the cathode, electrons and protons combine with oxygen to produce water as a byproduct. By these processes, the microbes surrounding plants' roots can generate clean and sustainable bioelectricity (Kuleshova et al., 2022). A schematic diagram illustrating the working principle of the PMFC is shown in Figure 11.

Figure 11: Working principle of PMFCs. Adapted from Liao and He (2023).



2.6.2 Microorganisms

The rhizosphere in PMFCs is composed of electrogenic and non-electrogenic microbes, as in addition to electroactive anode biofilm, both soil and plants have their own distinctive microbiomes (Shaikh et al., 2021). Non-electrogenic microbes do not contribute to bioelectricity generation because they lack the ability to transfer electrons to the anode.

These diverse microbial communities are both fuelled by rhizodeposits but have specialised metabolic processes to degrade them (Kuleshova et al., 2022). If conditions within the PMFC are favourable, these communities support one another rather than compete for resources. The composition and dominance of these microbial communities are shaped by specific plant species and soil properties, including pH, moisture content, and the carbon-to-nitrogen ratio (Chong et al., 2024).

2.5.2 Components

In addition to the anode and cathode that a typical MFC consists of, PMFCs have plants that support the biofilm by providing it with nutrients (Kuleshova et al., 2022). Basic PMFC constructions follow standard MFC design principles and are categorised into three main types (Kuleshova et al., 2022):

- Single-chamber PMFCs, which use one chamber for both anode and cathode in a membraneless setup.
- Double-chamber PMFCs, which include a proton-exchange membrane that separates the anode and cathode.
- Three-chamber PMFCs, which have an anode chamber separated by a membrane from two cathode chambers on both sides of the anode chamber.

As shown in Figure 12, these types can be designed differently to better fit the desired application.

Figure 12: Different PMFC designs from Greenman et al. (2024): a) artificial floating island, b) single drip hydroponic PMFC system, c) double chamber PMFC, d) membrane-less PMFC.

a)

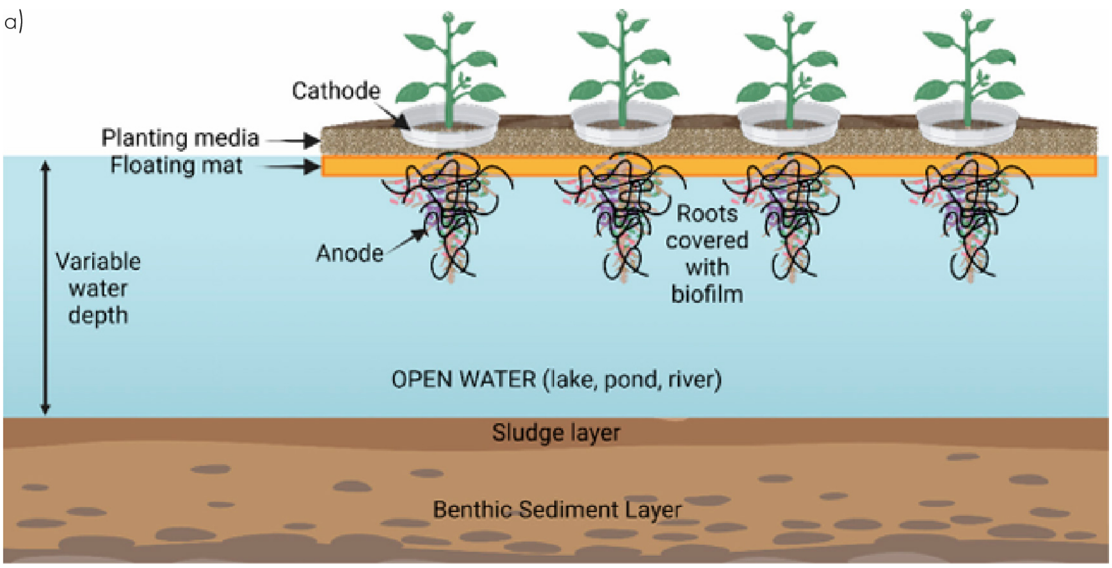
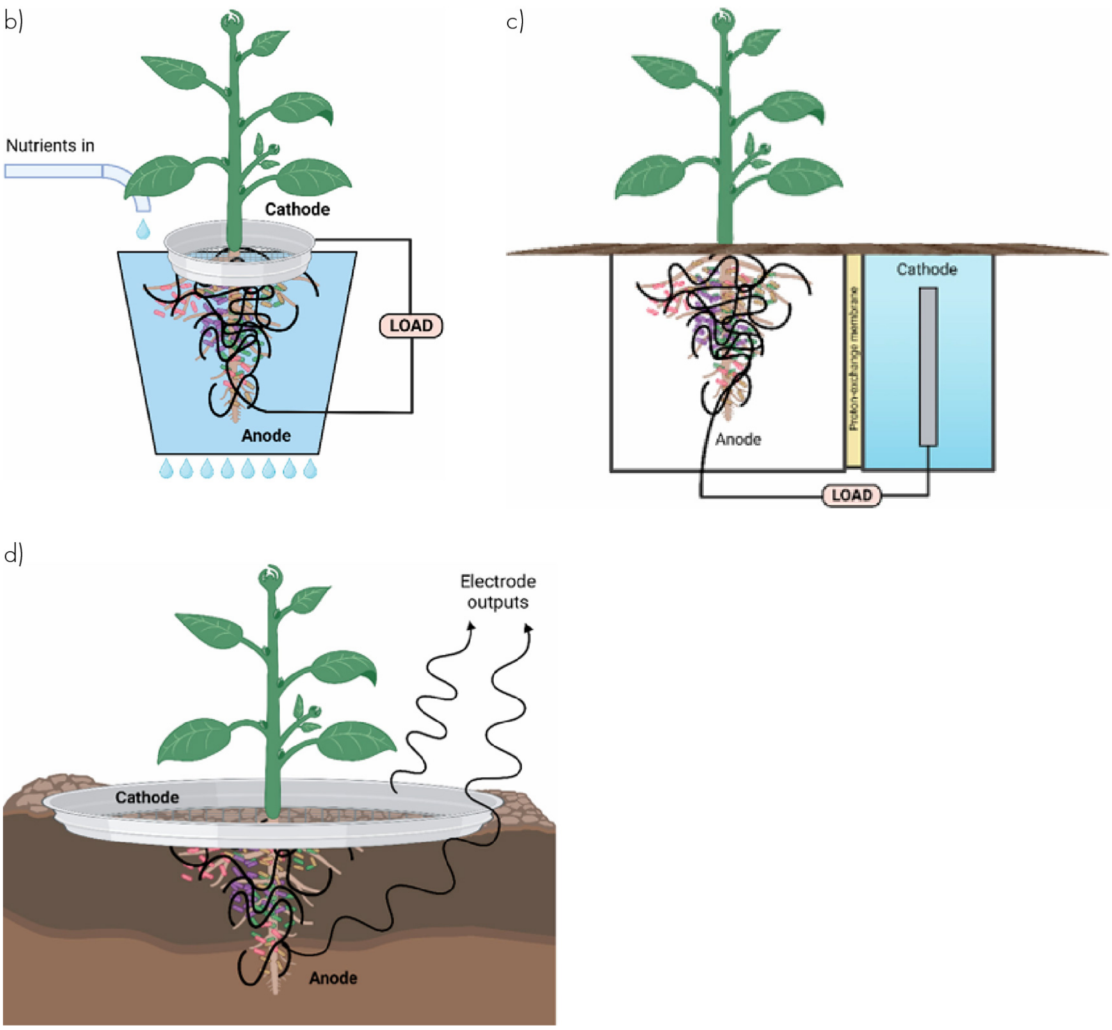


Figure 12: Different PMFC designs from Greenman et al. (2024): a) artificial floating island, b) single drip hydroponic PMFC system, c) double chamber PMFC, d) membrane-less PMFC.



2.5.3 Materials

The anode is strategically placed in the plant's rhizosphere and must be made of materials that are conductive, biocompatible, and non-corrosive, such as graphite felt, carbon fibre brushes, carbon cloth, or granular activated carbon (Shaikh et al., 2020). The cathode is typically positioned near the growing medium surface to utilise atmospheric oxygen as a terminal electron acceptor. In PMFC designs that include proton exchange membranes, similarly to MFCs, various types of ceramics can be used (Sarma & Mohanty, 2023). A few designs explored by researchers are shown in Figure 13.

Plants used in PMFCs are typically waterlogged, aquatic, or semi-aquatic species because their growth environments naturally facilitate the anaerobic conditions required at the anode for electricity generation (Shaikh et al., 2020). These plants are broadly categorised by their photosynthetic pathways into C3, C4, and CAM species (Tongphanpharn et al., 2021). C4 plants are, for example, the grass family, maize, and sugarcane.

Growing mediums in PMFCs range from natural soils to complex synthetic and recycled materials that provide structural support and a habitat for electrochemically active bacteria (Sarma & Mohanty, 2023). Natural soil is the most widely used medium. In hydroponic or soilless setups, researchers employ materials such as cocopeat, perlite, vermiculite, pumice, rice husks, and expanded clay aggregate, which are often chosen for their high-water retention and antifungal properties. The performance of these mediums can be further boosted by adding organic conditioners like compost, biochar, cow dung, and bioslurry, which stimulate both plant growth and microbial activity.

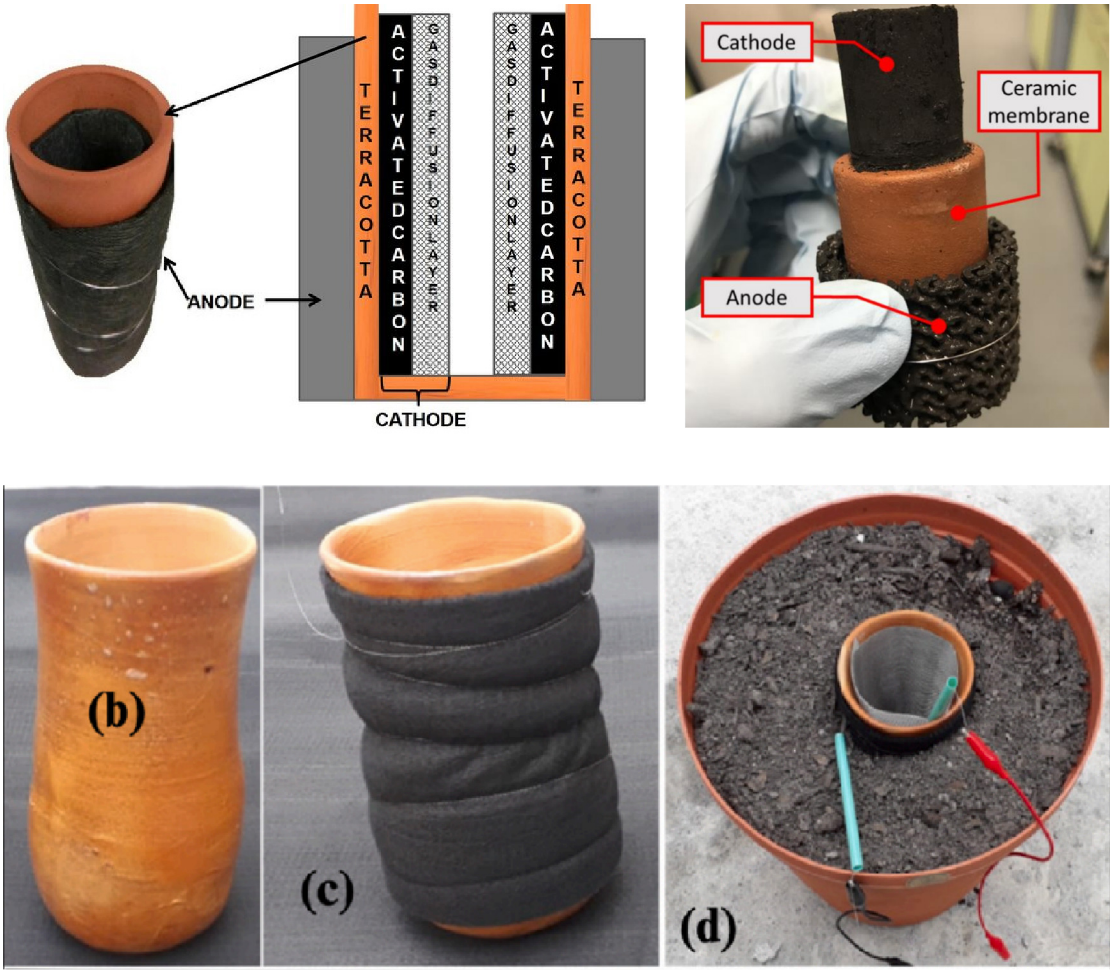


Figure 13: Examples of ceramic PMFC designs from Gajda et al. (2016) (top left), You et al. (2020) (top right), and Rusyn et al. (2025) (bottom).

2.5.4 Performance

The performance of plant microbial fuel cells depends on internal factors and external influences (Kuleshova et al., 2022). Internal factors include reactor design type, its architecture and materials. External factors include the physiological state of the plants, associated microbial communities, and environmental variables such as temperature, pH, and organic matter content in the growing medium. Kuleshova et al. (2022) discuss different plant species, used anode and cathode electrode materials, and respective power generation in various PMFCs shown in Appendix 3. The organic matter content in the growing medium is linked to the organic content in the substrate that plants are supplied with, and feeding plants with wastewater can increase the nutrient content in the growing medium.

In PMFCs, there is a direct connection between the composition of the provided substrate and the efficiency of wastewater treatment and energy generation (Xuan et al., 2025). Wastewater contains organic carbon (equivalent of COD) and chemical nutrients (nitrogen and phosphorus) simultaneously. When it is supplied to a PMFC, it triggers a multi-stage treatment process. Because carbon is the direct electron source in the electrical circuit, it is the primary driver of electricity generation (Shaikh et al., 2020). At low COD levels in the substrate, the electricity generation is limited and increases proportionally with the amount of carbon available to the biofilm. However, introducing an excessive amount suppresses the electricity generation because the microbes are unable to process it (Nitisoravut & Regimi, 2017). This causes the COD removal rate to drop, thereby reducing the efficiency of wastewater treatment. On the other hand, microbes need chemical nutrients to build proteins, DNA, and their cellular membranes. Chemical nutrients do not provide electrons directly, but they dictate the health and size of the microbial community. High concentrations of these nutrients cause the biofilm to undergo osmotic shock, and their metabolism and electrochemical reactions stall, leading to a drop in the electricity generation and nutrient removal rates. This process is immediate and can happen within seconds to minutes after the substrate is supplied to the PMFC.

As the microbes attempt to adapt to the stress caused by osmotic shock, the high COD content in the wastewater fuels a secondary process. Non-electrogenic communities coexist with electrogenic species, either helping them to break down organic carbon and chemical nutrients or competing with them for resources. When a high COD load enters the system, these non-electrogenic bacterial communities grow rapidly and effectively outnumber the electrogenic bacteria. Over subsequent days, non-electrogenic bacteria rapidly break down nutrients, which severely lowers the local pH. Low pH slows proton release from the biofilm, reducing the metabolic processes of electrogenic bacteria. At the same time, the non-electrogenic bacterial growth physically chokes the reactor and slows the processes occurring inside.

The performance of the PMFCs can also be limited if voltage reversal occurs. Voltage reversal (negative voltage) happens when nutrient supply is insufficient or when oxygen enters the anode chamber (Khudzari et al., 2017; Constantino et al., 2023). Low humidity and dry soil conditions limit the metabolic activity of the electrogenic bacteria, so even if fuel is present, they cannot process it effectively. Oxygen intrusion can occur when electrodes are in oxygen-saturated soil zones. Water shifts the soil zones from oxygen-saturated to oxygen-less by filling soil pores that would otherwise contain air. High soil moisture levels reduce the growing medium's porosity and oxygen permeability, and by that optimise conditions for electrogenic bacteria.

2.5.5 Applications

A primary use case of PMFCs is similar to that of MFCs – providing a sustainable power source for low-power electronic devices and remote sensors (Moqsud & Akamatsu, 2025). In the environmental domain, PMFCs are employed for the bioremediation of polluted sites, facilitating the removal or stabilisation of heavy metals (such as chromium, cadmium, nickel, and arsenic), petroleum hydrocarbons, pesticides, and synthetic surfactants from soil and water ecosystems (Jadhav et al., 2021). They are also integrated into wastewater treatment processes, effectively treating domestic, industrial (e.g., dairy or brewery), and agricultural effluents while simultaneously recovering nutrients like nitrogen and phosphorus and producing usable water (Chong et al., 2024). In urban environments, P-MFCs integrated into green infrastructure and rooftops help mitigate the Urban Heat Island effect, provide thermal insulation for buildings, and enhance stormwater retention (Guan & Yu, 2020; Rusyn & Hamkalo, 2020; Liao & He, 2023).

2.6 Integrating Plant Microbial Fuel Cells into Facade Living Walls

Both Plant Microbial Fuel Cells and green wall systems fundamentally rely on plants as their core functional element, creating a natural synergy for integration. Living wall systems, defined as employing pre-vegetated modular panels with integrated growing media that support plant growth independent of ground-level soil, match the optimal scale of a PMFC reactor and offer a practical basis for integrating PMFC technology, as their established components align well with the operational requirements of PMFCs. Living walls already incorporate growing media, irrigation systems, and plants. The rhizosphere of plants in a Living Wall serves as a natural electron donor, while the moist layer of growing medium provides the required anodic conditions. Living walls provide an easy pathway to supply necessary oxygen to the PMFC cathode, as the system's open exposure to atmospheric air naturally facilitates passive diffusion and aeration without requiring additional pumps or mechanical systems. Living walls already incorporate irrigation systems that are perfectly suited for PMFC integration by maintaining the consistent moisture and nutrient-rich flows essential for microbial activity in the rhizosphere. This pre-existing infrastructure can supply organics from greywater to feed anode bacteria without many custom modifications.

Living walls that are designed for greywater treatment already depend on microbial communities in the rhizosphere to break down organic pollutants. This established microbial activity provides a direct opportunity for energy harvesting using PMFCs, as the same exoelectrogenic bacteria can be directed to transfer electrons from substrate conversion to anodes rather than solely dissipating energy as heat or biomass. The modular nature of living walls enables ease of scalability for PMFC integration to boost overall power output and treatment capacity.

Successful PMFC implementation in Living Wall Systems requires several key design considerations to balance bioelectrochemical function and vegetation health. Structural frameworks need stable, lightweight support with integrated drainage to manage greywater flows and prevent waterlogging around reactors. Growing media must retain moisture for microbial activity. Irrigation systems require precise low-flow control for substrate delivery, effluent recirculation, and clogging prevention. Electrical integration calls for embedded wiring and monitoring ports to track voltage without frequent maintenance, alongside plant species tolerant of organic loads and pH variations that support rhizosphere microbes.

3. Plant Microbial Fuel Cell Integrated Facade Living Wall System

This part of the report translates the theoretical underpinning from the previous section into a practical design for the Plant Microbial Fuel Cell Integrated Façade Living Wall System. It provides a systematic breakdown of the system's key components. Based on the PMFCs and living wall systems requirements, six core elements of the designed system were identified:

— PMFC Reactor
— Vegetation
— Backing structure
— Module with containers
— Irrigation and water collection system
— Electrical wiring system

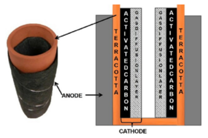
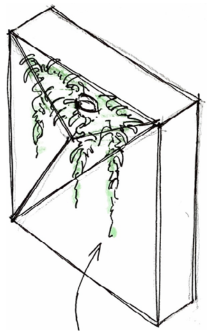
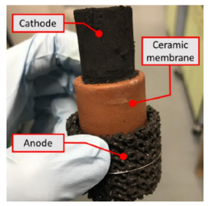
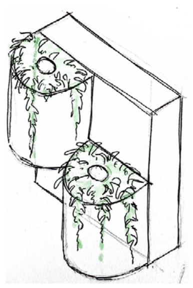
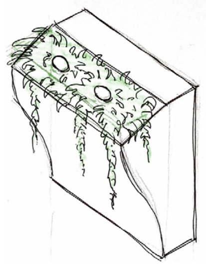
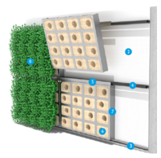
To explore the core elements of the design and how each influences the other, a design matrix (shown in Figure 14) is created. To arrive at a suitable final design, a set of design objectives is established for each element. The next sections discuss how these objectives inform and guide the design decisions for each core element. Additionally, necessary adaptations to the building, where the proposed system is applied, are explored.

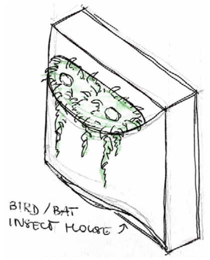
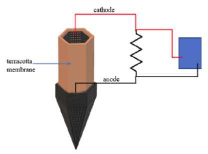
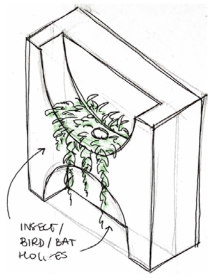
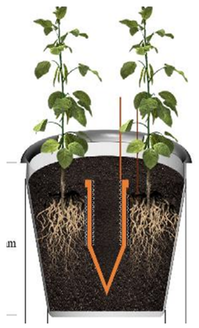
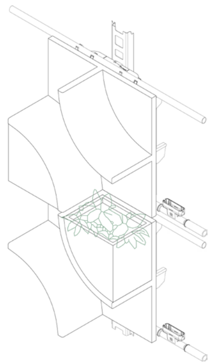
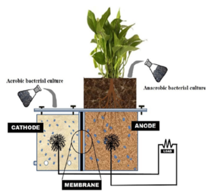
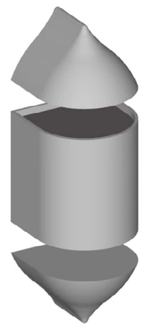
3.1 Case Study Selection

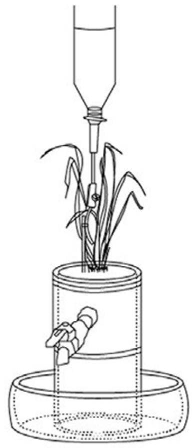
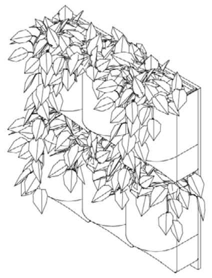
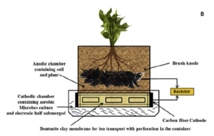
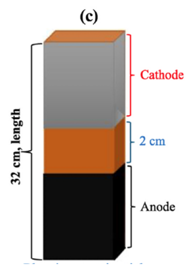
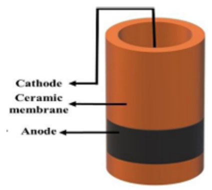
To situate the project and guide design decisions, a case study for implementation is selected. PMFCs require stable warm temperatures (20-35°C), high humidity (>70%), and consistent moisture for optimal performance. Singapore's tropical climate provides an optimal environment for PMFCs' performance, characterised by consistently warm temperatures ranging from 23 to 36°C and an average of 12 h of sunshine per day (Chew & Conejos, 2016). High, constant humidity levels (75-80%) make it easier to maintain soil moisture essential for anode processes without additional watering, as ambient moisture naturally minimises evaporation losses. Frequent rainfall (around 2,300 mm annually) further supplements the wall when building wastewater production falls short (Mughal et al., 2020). A Comparison of PMFC environmental requirements and Singapore climate is shown in Table 7.

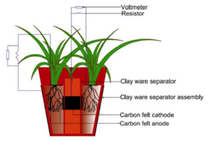
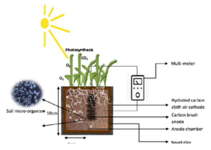
Singapore experiences a pronounced Urban Heat Island effect, which can reach up to 5°C in compact areas (Mughal et al., 2020). This intensity is primarily caused by radiation trapped within urban canyons and the gradual release of heat absorbed by building materials during the day. A major contributor to this warming is anthropogenic heat gen-

Figure 14: Plant Microbial Fuel Cell Integrated Façade Living Wall System design matrix.

PMFC Reactor	Vegetation		Modular Containers					Irrigation System			Supporting Structure		
PMFC designs from literature	**Plant species suitable for PMFCs**	**Plant species suitable for green walls in Singapore (NParks, n.d.)**	**Material**		**Manufacturing method**	**Growing medium**	**Shape**	**Wastewater Supply**		**Treated Water Collection**	**Type**	**Connection with the Building**	**Material**
Gajda et al. (2016) 	Glyceria maxima	Aeschynanthus parvifolius		Clay	3D printing	Soil-like substrate (peat-based or coco-coir based, often with compost and perlite)	Design proposal 1 	Direction of flow	Horisontal routing (irrigation lines are distributed in rows)	Bottom collection gutter (at the bottom of the whole wall or below each row of containers)	MobiPanel (omega profiles)  Mobilane. (n.d.). » MobiPanel living wall. Mobilane. https://mobilane.com/en/products/mobipanel-living-wall/	Fasteners	Corrosion-resistant Magnelis steel
You et al. (2020) 	Oryza sativa	Aglaonema costatum		NPSP tiles	Injection molding	Waterlogged substrate (flooded paddy soil or constructed wetland substrates with mixtures of sand, gravel and organic fines)	Design proposal 2 		Vertical routing (irrigation lines are distributed in columns)	Integrated drainage channel (a collection pipe integrated in the container itself, usually in the drainage layer at the bottom of the container)	Wooden studs		Wood
Rusyn et al. (2025) 	Spartina anglica	Asparagus densiflorus	Biocomposites	Lignitec panels	Hot pressing	Felt mat (only suitable for moss)	Design proposal 3 	Emmiter placement	Surface emission (irrigation lines are placed on top of the substrate)		Biopanel System  *Specifications and drawings | BioPanel system | Biotecture UK. (2026, February 3). Biotecture UK. https://www.biotecture.uk.com/living-walls/specifications-drawings/*	Cladding rail	Aluminium

PMFC Reactor	Vegetation		Modular Containers					Irrigation System			Supporting Structure		
PMFC designs from literature	Plant species suitable for PMFCs	Plant species suitable for green walls in Singapore (NParks, n.d.)	Material		Manufacturing method	Growing medium	Shape	Wastewater Supply		Treated Water Collection	Type	Connection with the Building	Material
Sarma and Mohanty (2021) 	Arundo donax	Bolbitis heteroclita	Plastics	Recycled plastic	Cold pressing		Design proposal 4 	Emmiter placement	Subsurface emission (irrigation lines are placed in the substrate)		Direct mounting		
Constantino et al. (2023) 	Pennisetum setaceum	Caladium lindenii		Recyclable plastic like EPP			Design proposal 5 	Type of flow	Drip emission (individual drops at continous low flow)				
Palmero and Pamintuan (2023) 	Cyperus involucratus	Dianella ensifolia					Design proposal 6 		Stream emission (short, low-energy stream)				
Sarma and Mohanty (2023) 	Lolium perenne	Dischidias					Design proposal 7 	Emmiter type	Point emission online (one emitter per plant or per container)				

PMFC Reactor	Vegetation		Modular Containers					Irrigation System			Supporting Structure		
PMFC designs from literature	Plant species suitable for PMFCs	Plant species suitable for green walls in Singapore (NParks, n.d.)	Material		Manufacturing method	Growing medium	Shape	Wastewater Supply		Treated Water Collection	Type	Connection with the Building	Material
Regmi et al. (2018) 	Eichhornia crassipes	Drynaria quercifolia					Design proposal 8 	Emmiter type	Line emission inline (continuous or closely spaced emitters along an irrigation line)				
Sarma and Mohanty (2018) 	Acorus calamus	Epiphyllums						Alternative methods	Cappilary				
Apollon et al. (2020) 	Ipomoea aquatica	Episcia fimbriata											
Kumar et al. (2020) 	Canna indica	Hoyas											

PMFC Reactor	Vegetation		Modular Containers				Irrigation System		Supporting Structure		
PMFC designs from literature	**Plant species suitable for PMFCs**	**Plant species suitable for green walls in Singapore (NParks, n.d.)**	**Material**	**Manufacturing method**	**Growing medium**	**Shape**	**Wastewater Supply**	**Treated Water Collection**	**Type**	**Connection with the Building**	**Material**
Kumar et al. (2018) 	Echinochloa glabrescens	Kaempferia pulchra									
Sophia and Sreeja (2017) 	Arundinella anomala	Nephrolepis exaltata									
	Physcomitrella patens	Pellionia repens									
	Dwarf rotala	Pileas									
	Sedum Hybridum	Platycerium ridleyi									
	Hypnum cupressiforme Hedw	Polypodium punctatum									
	Polytrichum commune Hedw	Pteris ensiformis									
	Leuco bryum glaucum Hedw	Scindapsus pictus									
	Epipremnum aureum	Selaginellas									
	Dracaena braunii	Tristellateia australasiae									
	Torenia fournieri	Clitoria ternatea									
	Kalanchoe blossfeldiana	Tetracera indica									
	Pentas lanceolata	Telosma cordata									
	Begonia semperflorens	Ipomoea mauritiana									

PMFC Reactor	Vegetation		Modular Containers				Irrigation System		Supporting Structure		
PMFC designs from literature	**Plant species suitable for PMFCs**	**Plant species suitable for green walls in Singapore (NParks, n.d.)**	**Material**	**Manufacturing method**	**Growing medium**	**Shape**	**Wastewater Supply**	**Treated Water Collection**	**Type**	**Connection with the Building**	**Material**
	Nephrolepis exaltata	Thunbergia grandiflora									
	Asplenium nidus	Cryptanthus bivittatus									
	Chlorophytum comosum	Syngonium podophyllum									
	Chasmanthe floribunda	Hoffmannia refulgens									
	Papyrus diffusus	Aeschynanthus speciosus hook									
	Chlorophytum comosum	Polyscias fruticosa dwarf									
		Davallia denticulata									
		Philodendron 'Gold'									
		Dissotis rotundifolia									
		Capsicum frutescens									
		Mentha cultivar									
		Allium fistulosum									
		Pandanus amaryllifollius									
		Arachis pintoi									
		Dieffenbachia amoena									
		Xiphidium caeruleum									
		Schefflera arboricola									

PMFC Reactor	Vegetation		Modular Containers				Irrigation System		Supporting Structure		
PMFC designs from literature	Plant species suitable for PMFCs	Plant species suitable for green walls in Singapore (NParks, n.d.)	Material	Manufacturing method	Growing medium	Shape	Wastewater Supply	Treated Water Collection	Type	Connection with the Building	Material
		Nephrolepis falcata									
		Strobilanthes dyerianus									
		Peperomia scanden									
		Aristolochia acuminata									
		Antigonon leptopus									
		Bauhinia kockiana									

Table 7: Comparison of PMFC environmental requirements and Singapore climate.

	PMFC Requirements	Singapore Climate
Temperature	20-35°C	23-36°C
Relative Humidity	>70%	75-80%

The heat index is a measure of how hot it really feels when relative humidity is combined with the actual air temperature. It accounts for the fact that high humidity prevents sweat from evaporating, making the body feel significantly hotter than the thermometer reads. "Extreme caution" is the second of four levels, and prolonged exposure and physical activity can cause heat cramps, heat exhaustion, or even heat stroke.

erated by air-conditioning systems, which can increase mean nighttime air temperatures by 1°C to 3°C. These issues are worsened by urban densification, as increasing building volumes store more heat and block vital ventilation corridors. Projections suggest that future compactness alone could lead to a 1.4°C temperature rise. The resulting thermal stress frequently elevates the Heat Index to "extreme caution" levels, posing significant health risks to Singapore's population. While mitigation efforts like cool roofs can reduce daytime temperatures by up to 1.3°C, they have negligible effects at night. Consequently, strategies for maintaining thermal comfort may require significant behavioural changes, such as raising indoor thermostat settings from 21°C to 25°C, which could reduce air-conditioning waste-heat discharge by approximately 20%. The need for abundant air-conditioning affects the city's image, especially in residential areas, as seen in Figure 15.

UHI can also be significantly mitigated through the strategic implementation of greenery and nature. Tree planting is recognised as one of the most effective methods for UHI mitigation because urban green spaces reduce heat storage and provide natural cooling (Chew & Conejos, 2016). Beyond traditional parks, the integration of skyrise greenery, such as green roofs and vertical green walls, helps cool ambient temperatures by absorbing solar radiation and providing thermal insulation for buildings in Singapore. Research indicates that these green spaces can reduce homogenous surface temperatures by up to 3.1°C (Lin-Heng, 2020). These efforts are central to Singapore's "City in Nature" vision, which seeks to extend nature throughout the island to create a more liveable and sustainable environment (Building and Construction Authority & Singapore Green Building Council, 2021). If applied, green walls offer a multifaceted range of economic, environmental, and social benefits that are particularly vital to Singapore's environment.

Figure 15: Urban landscape of residential areas in Singapore adapted from Aadhithyan Pandian, 2023, Pexels (pexels.com).

Singapore has implemented several strategic policies and incentive schemes to promote the use of green walls. A primary driver is the Building & Construction Authority (BCA) Green Mark Scheme, which awards points for the inclusion of vertical greenery, encouraging developers to integrate these systems to achieve higher environmental sustainability ratings (Chew & Conejos, 2016). This is supported by financial assistance provided through the Skyrise Greenery Incentive Scheme, which directly covers the costs of installing green walls and roofs (Building and Construction Authority & Singapore Green Building Council, 2021).

Productive façades are integrated systems combining vertical farming with solar technology.

Additionally, social acceptance of green walls and skyrise greenery in Singapore is generally high, with a significant majority of residents viewing these systems as a positive addition to the urban landscape (Yuen & Hien, 2004). Research into productive façades reveals that approximately 80% of residents agree that such features have a positive impact, with nearly 69% indicating they would prefer to live in a building that incorporates both energy and food-harvesting greenery (Kosorić et al., 2019).

On the other hand, Singapore is classified as one of the most water-stressed nations in the world, with internal renewable water resources of 110-172 m^3 per capita – a situation comparable to desertic Libya and Jordan (Lefebvre, 2017). Despite receiving abundant annual rainfall, the island's small land area provides insufficient space to capture and store this precipitation, and the nation lacks natural surface water sources, underground aquifers or groundwater (Hsien et al., 2019). Historically, these physical constraints resulted in a heavy dependence on imported water from Malaysia, a reliance viewed as a strategic vulnerability because the main remaining water agreement is set to expire in 2061 (Lefebvre, 2017). To mitigate this ongoing crisis and ensure national security, Singapore has implemented strategies for wastewater treatment.

Singapore treats its wastewater through a comprehensive and highly centralised system that ensures 100% of the nation's wastewater is collected and managed (Luan, 2010). The process begins with the collection of all domestic and industrial wastewater through an extensive network of underground sewers, which convey the effluent to centralised water reclamation plants. At these facilities, the wastewater first undergoes primary treatment in sedimentation tanks or clarifiers, where suspended solids settle out and floating materials, such as oils, are removed (Hsien et al., 2019). This is followed by secondary treatment, a biological process that uses bacteria to consume organic contaminants (Foley, 2010). The social acceptance of wastewater reuse in Singapore is exceptionally high, with NEWater, Singapore's high-grade reclaimed water, achieving a remarkable 98% acceptance rate among the public (Kog, 2020).

While the nation primarily relies on centralised reclamation plants, it increasingly promotes decentralised, on-site recycling (Lefebvre, 2017). For residential and commercial buildings, Singapore encourages greywater recycling for non-potable applications such as toilet flushing and landscaping irrigation (PUB, 2024). The implementation of on-site treatment is incentivised through the BCA Green Mark Scheme, the same one which awards points for including vertical greenery systems in building developments.

Singapore's primary residential typology, which accommodates 80% of the population, consists of high-density public housing blocks managed by the Housing and Development Board (HDB) (Lin-Heng, 2020). HDB residential blocks are typically high-rise buildings ranging from 10 to 50 storeys in height, as shown in Figure 16 (Cheng, 1990). In terms of materiality, modern HDB houses are primarily made of precast concrete components. This approach is part of a broader system of modular coordination introduced by the HDB in the mid-1970s to enhance construction efficiency, ease of development, and productivity in response to Singapore's high housing demand (HDB, 2014). Pre-cast structural elements include facades that are standardised within each project to allow for aesthetic variety across housing estates. The repeatability of these modular elements is strictly governed by a guideline requiring at least 100 repetitions of each component within a project. To prevent water seepage in Singapore's tropical climate, these blocks utilise a multi-layered waterproofing system at both horizontal and vertical joints, incorporating sealants, backing rods, and cementitious membranes. Furthermore, HDB blocks generally follow two major typologies with a uniform spatial structure (Kosorić et al., 2019).

Figure 16: Example of HDB residential blocks by Yr Wong, 2024, Shutterstock (shutterstock.com).

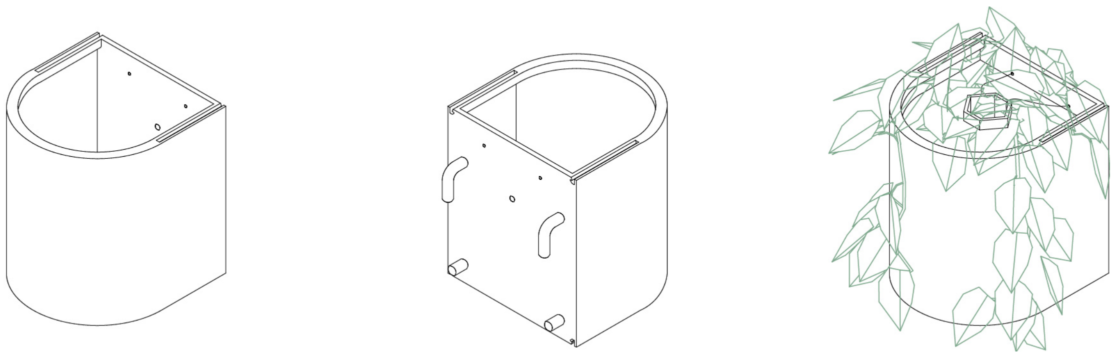
In conclusion, HDB retrofits and new builds provide an ideal case study for the Plant Microbial Fuel Cell Integrated Facade Living Wall System due to their modular, uniform façades, high waterproofing standards, centralised greywater collection, and government-mandated sustainability upgrades. In a broader context, Singapore's unique environmental, political, and social landscape makes implementing the designed system more feasible, positioning it as both a living wall that reduces urban heat and an on-site wastewater treatment plant using PMFC technology.

3.2 Plant Microbial Fuel Cell Reactor

Soil-based Plant Microbial Fuel Cells were chosen as the most suitable for green wall applications. A double-chamber PMFC reactor is selected over a single-chamber design because it offers higher efficiency and more stable power output, as the physical barrier isolates the distinct electrochemical environments (Chong et al., 2024). One of the barriers identified by researchers for the commercialisation of MFC technology was the cost of components. For this reason, ceramics were selected as a cheaper and more sustainable alternative to conventional MFC materials. An off-the-shelf terracotta watering cone was shown by researchers to be a well-suited proton exchange membrane for PMFCs, and thus it is selected for this design. Carbon felt is chosen as an electrode material for its porosity, compatibility, and durability in wet environments.

This PMFC reactor dictates the design and size of living wall containers. The optimal size of this reactor design is a 15 cm diameter tube, 18 cm high. The diameter cannot be too small to be able to fit the root system of the plant and allow for it to grow, but it also can't be too big, as large volumes of anode chambers are less efficient in terms of performance. The container must be tall enough to accommodate the terracotta cone and provide enough space for the roots to grow around the bottom of the membrane. The back of the PMFC container is made flat to better fit the wall and prevent sideways movement from the wind. The reactor design is shown in Figures 17 and 18.

Figure 17: Design of the PMFC reactor for PMFC Integrated Façade Living Wall System.



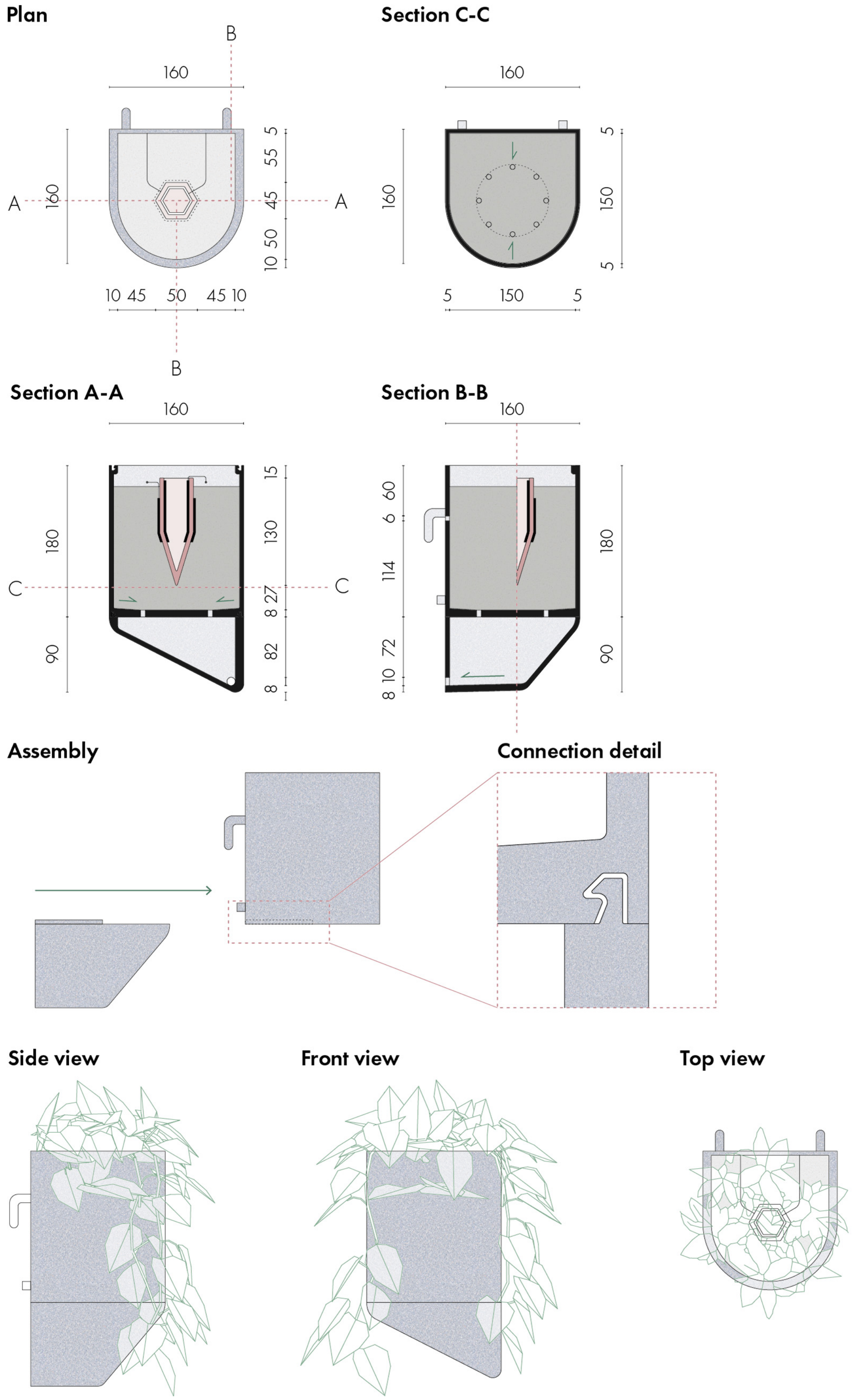


Figure 18:
Design of the PMFC reactor for PMFC Integrated Façade Living Wall System.

3.3 Vegetation

Plants used in the PMFC Integrated Façade Living Wall System have to be suitable for both PMFCs and living walls. They must be suitable for waterlogged conditions as biofilm in PMFCs requires constant moisture. From a living wall perspective, plants on vertical surfaces are more exposed to the elements than those on the ground, so they must account for wind and light exposure. As access to living wall modules is complicated, plants that require less maintenance are favoured.

From the reviewed literature, plant species used in PMFC systems are selected, and their reported performance is identified and shown in Appendix 3. The design matrix (Figure 14) additionally lists plants suitable for green wall applications in Singapore, based on the recommendations of Singapore's National Parks Board (NParks). This selection is then refined to species compatible with soil-based living wall systems and Singapore's climate, as shown in Figure 19. These species can be combined in the designed PMFC Integrated Façade Living Wall System to create different plant arrangements.

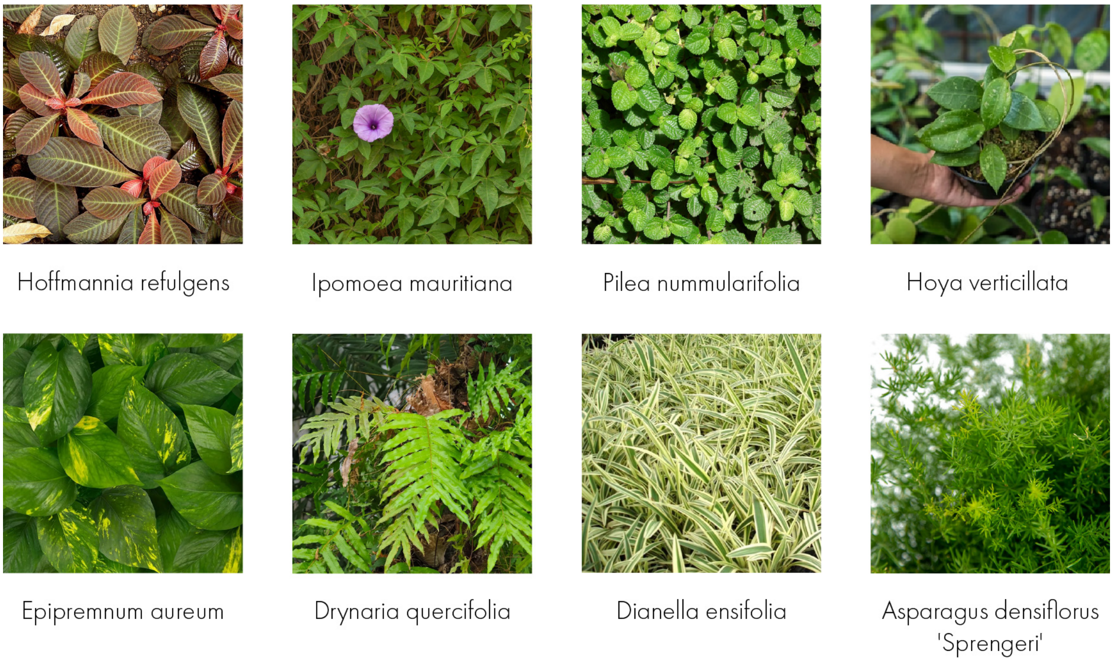


Figure 19: PMFC Integrated Façade Living Wall System plant catalogue. Adapted from NParks (n.d.).

3.4 Backing Structure

Various backing structures used in comparable living wall systems are examined. The selected structure must support the weight of waterlogged containers and the dynamic load of wastewater in the irrigation system, while providing flexibility in configuration and modularity to enable PMFC reactor scale-up. The backing structure must be suitable for both existing façades and new construction, as this was one of the design objectives. It has to provide enough space for routing electrical wires and sufficient ventilation between the façade and the living wall.

The Mobilane's MobiPanel system is selected as the base structure for the designed Living Wall, as it has proven successful in the market. The Mobilane panels employ Magnelis omega profiles, which are rigid C-shaped steel channels anchored to the wall. The omega profiles can be arranged both horizontally and vertically, offering adaptability for retrofit and new-build applications as well as placement on straight or curved walls. They have a standard length of 120 cm for ease of transport, but can also be cut to fit custom designs. To adequately support the system's weight, omega profiles must be attached to the building's structural elements. In the Mobilane's MobiPanel system, omega profiles are combined with a system of hangers that secure individual modules to the profiles. The modules slide into place on the profile using integrated hooks, enabling tool-free installation. The placement of the modules on the omega profile can be adjusted to fit the project, as omega profiles offer holes at 10 cm intervals. The Mobilane MobiPanel system is designed to have a 38 mm gap between the building wall and MobiPanel module to ensure proper ventilation. This gap also makes space to pass PMFC's electrical wiring through with ease. The original design of the Mobilane Mobipanel living wall system is shown in Figure 20.

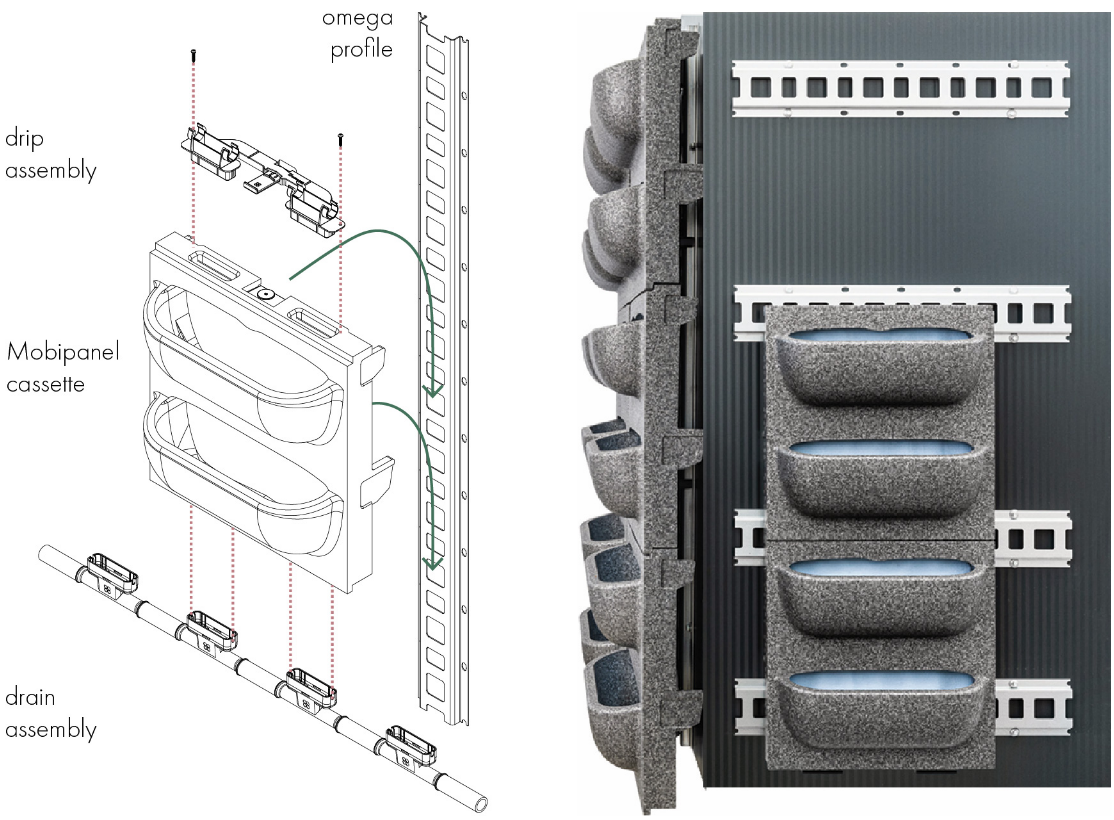


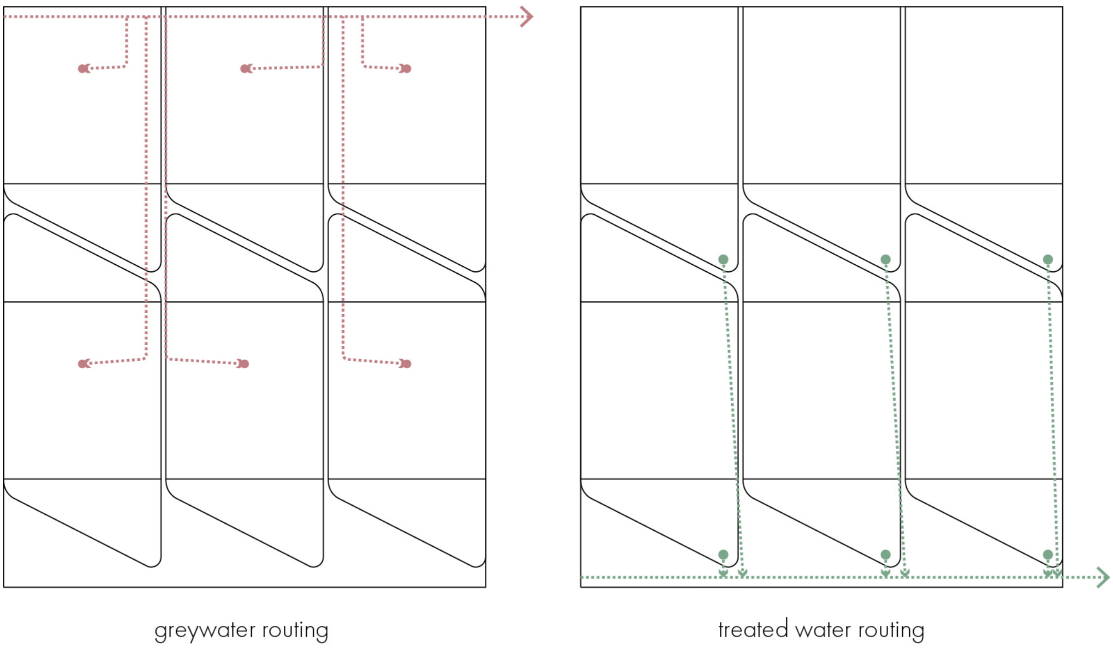
Figure 20: Original design of MobiPanel system. Adapted from Mobilane (2025).

3.5 Irrigation and Water Collection System

Mobilane MobiPanel system is also equipped with an automated irrigation and drainage system that can distribute and collect water for each row of modules. Each module has connections for attaching it to both irrigation and drainage pipes. This design is favourable for PMFCs, as each reactor should be supplied with sufficient nutrients from wastewater to ensure efficient bioelectrochemical reactions. MobiPanel's irrigation system is adapted here to accommodate wastewater, from which subsurface inline drip irrigation is routed directly to PMFC reactors, ensuring uniform delivery to the growing medium in the anode chamber. The irrigation system will deliver the required 1075 mL of wastewater per day to each reactor, using the original MobiPanel drippers mounted on the irrigation pipes of each row of modules on the façade.

Mobilane panels feature a collection gutter at the bottom of each module, which will collect water treated by PMFCs. Similar to the irrigation system, treated water will be collected in rows by gravity. According to the MobiPanel manufacturer, both irrigation pipes and collection gutters within the modules have sufficient slope to prevent water retention in the pipes and gutters. The exact routing of wastewater and treated water within one module of the designed Living Wall is shown in Figure 21.

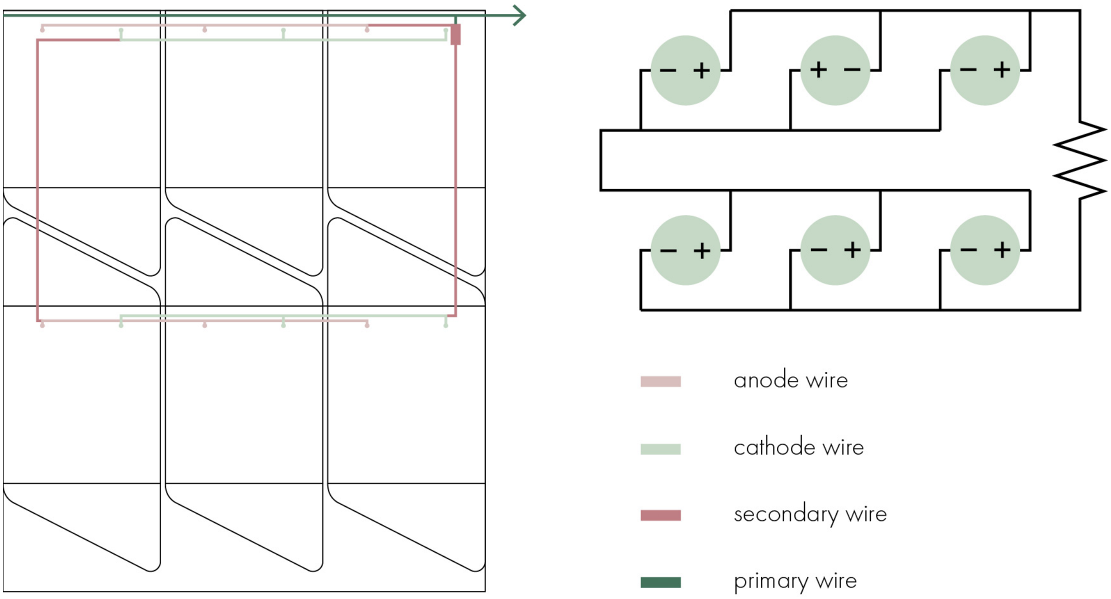
Figure 21: Routing of water in a module of the designed PMFC Integrated Façade Living Wall System.



3.6 Electrical Wiring System

Each PMFC reactor has two wires – an anode wire and a cathode wire, which have to be connected further to extract electrical current. To enhance the performance of the designed reactors and total power output, multiple units are connected in parallel and then in series. This configuration sums the currents across units while keeping the voltage. Parallel connections allow for the addition or removal of individual reactors without disturbing the operation of the others. The optimal number of reactors to connect is 2 rows of 3 reactors, which was chosen as the one module of the designed wall that can be further stacked and connected. The electrical connection between individual reactors is shown in Figure 22. Designing each module as a single scaled-up PMFC setup means each module has only one wire that must be connected to a collective line routed along each row's irrigation pipe. The current is then collected collectively from each row.

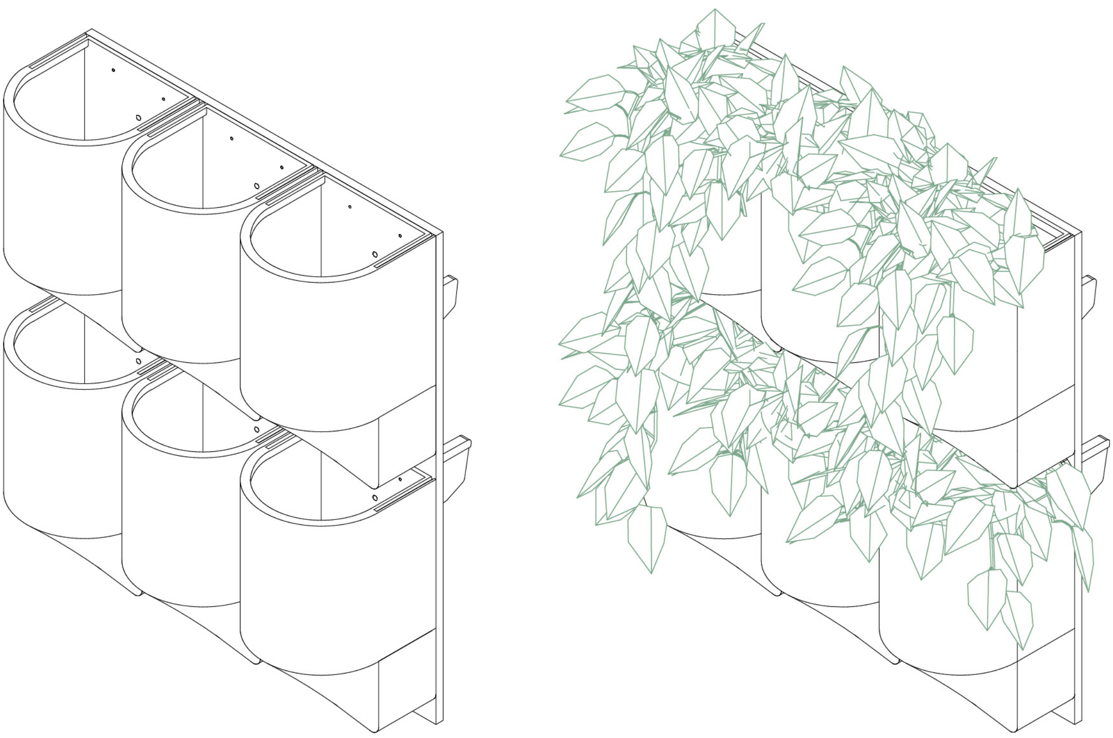
Figure 22: Electrical connections in a module of the designed PMFC Integrated Façade Living Wall System.



3.7 Module with Containers

MobiPanel is a fully functional living wall system, and each modular panel incorporates plant containers. During manufacturing, these containers are screwed to the back panel and secured with 6 screws, as each part is manufactured separately. The original containers (see Figure 20) are unfortunately too small for PMFC needs and thus, instead of using them, a new, customised design of the front of the module is proposed as shown in Figure 23. The customised part is designed to integrate PMFC technology while remaining compatible with Mobilane's existing structural solutions. The existing back structure remains in

Figure 23: PMFC Integrated Façade Living Wall System module design.



place, and the customised front of the module is secured using the pre-existing screw connections. These standardised connections facilitate maintenance and repair, and allow for easy replacement or reconfiguration.

The size of one module of the designed Living Wall was determined by the optimal number of reactors for maximised performance, the size of the MobiPanel back, and the HBD housing block façade module size. One panel has to accommodate six reactors, each 15 cm wide and 18 cm high, arranged in two rows of three. Additionally, the back of the Mo-

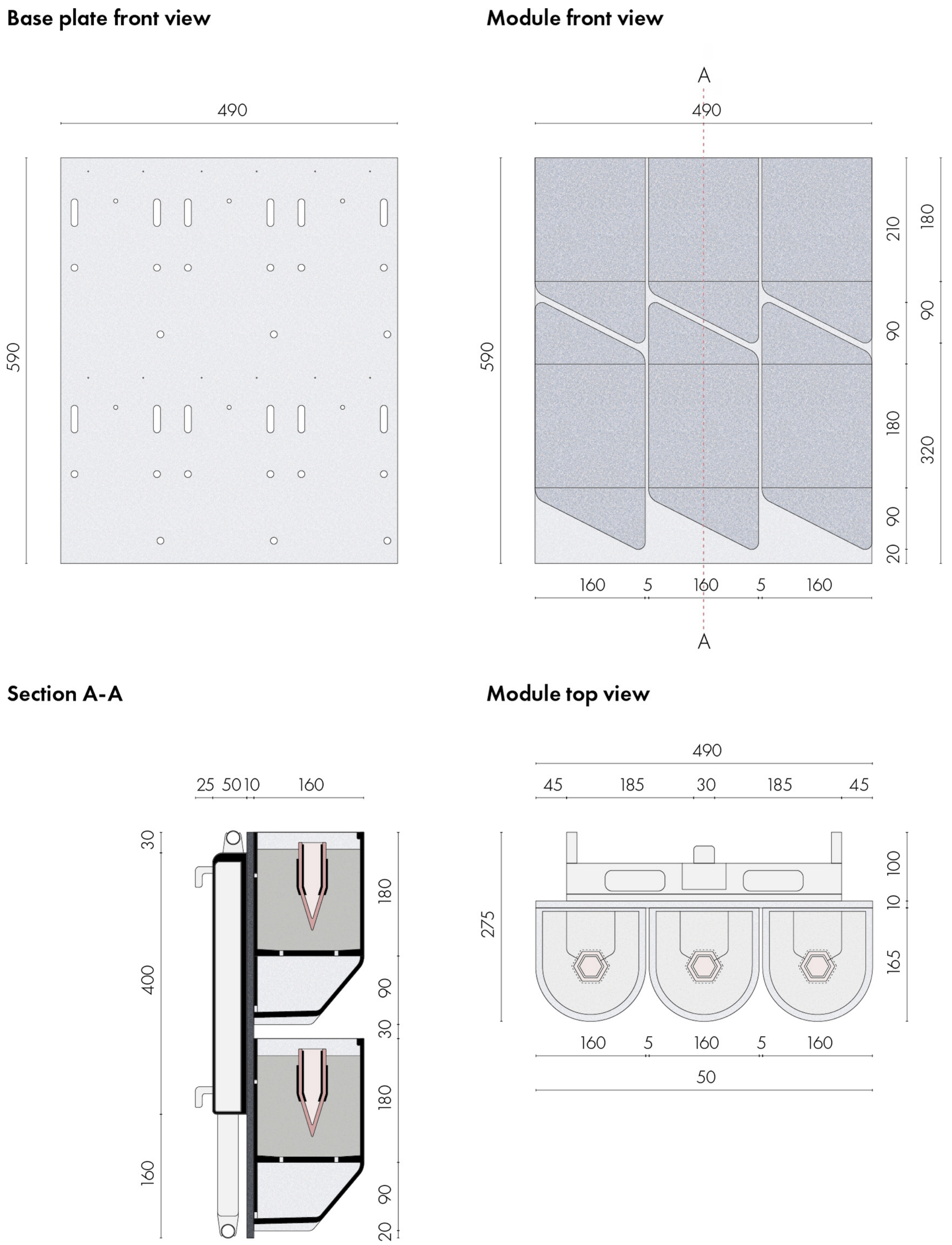
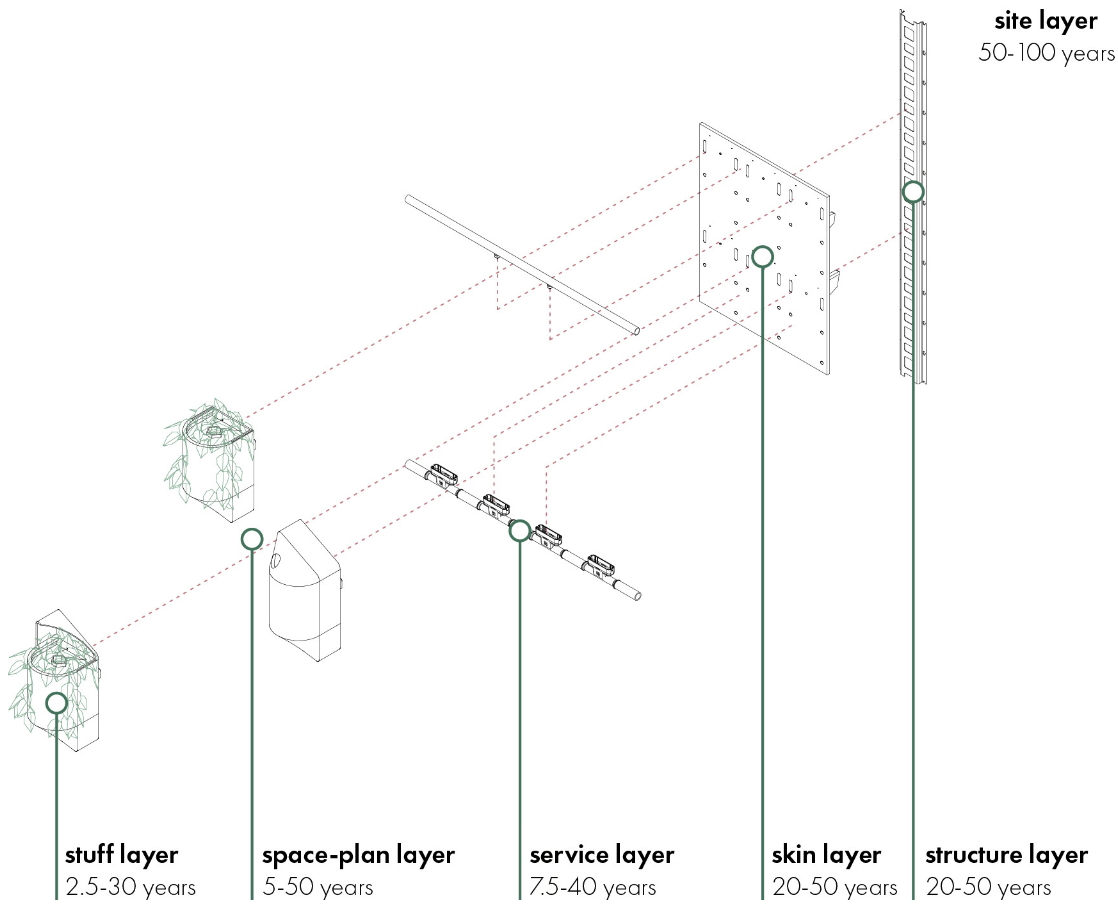


Figure 24: PMFC Integrated Façade Living Wall System module design.

biPanel measures 40 cm by 40 cm, with additional space required for the irrigation pipe on top and the collection gutter at the bottom. In HDB housing, a typical building has a space around 120 cm high and 300 cm wide between the windows of each floor. Taking these into consideration, the module size was set at 60 cm high and 50 cm wide, as shown in Figure 24.

The design of the entire module follows the concept of Brand's shearing layers, in which each functional layer has a different service life and can be detached independently for maintenance or replacement (Brand, 1994). Here, translated from a building scale to a façade. The building represents the site layer, which, for pre-cast concrete buildings in Singapore, has a lifespan of 50-100 years. The steel omega profiles represent the structure layer, with the second-longest lifespan of 20-50 years in humid environments. The back structure of the MobiPanel and customised front base panel, being the skin layer most exposed to weathering, has a lifespan of 20-50 years. The irrigation and water collection system, along with electrical wiring represent services layer with a lifespan of 7.5-40 years. To enhance the layering concept, containers with PMFCs are designed separately from the front base panel. To give more variety in the design and enhance biodiversity, in addition to the PMFC containers, containers functioning as birdhouses and insect hotels are introduced. The interchangeable assembly of these containers on the base panel represents a space-plan layer and has a lifespan of 5-50 years. The containers with PMFC reactors, as the most susceptible to fouling, represent the stuff layer and have the shortest lifespan of 2.5-30 years (Helder et al., 2013). The shearing layers of the designed PMFC Integrated Façade Living Wall are depicted in Figure 25.

Figure 25: Shearing layers of PMFC Integrated Façade Living Wall System.



As suggested by Brand (1994), all layers should be designed without permanent connections to allow replacement of each layer without dismounting the whole system. To replace the omega profile, two modules must be demounted, and after the profile is replaced, they can be put back and plugged in. This is done without damaging the modules, as they feature a system of hangers. The back of MobiPanel and the base panel are designed separately to enhance demountability and to protect the more vulnerable wiring. This also gives clear access to wiring and piping by simply unscrewing the front panel with containers. To replace the back of MobiPanel, the containers have to be removed, and the wiring and piping of each PMFC reactor detached. Dismounting piping is possible thanks to the MobiPanel drip assembly that slots the pipe into brackets without requiring permanent connections. As explained in the electrical wiring section, each module or container can be simply unplugged from the row's wiring and then plugged back in. Containers are attached only to the base plate, allowing individual reactor replacement if fouling occurs. They feature a pegboard-like system of hangers, allowing them to be reattached after replacing the other layers. They use the soil's self-weight to stay in place. The containers that enhance biodiversity also require periodic maintenance and cleaning, which are made feasible by the layered system design. The independent layers also enable functional and aesthetic redesign by realigning PMFC and biodiversity containers, providing flexibility to adapt visual arrangements over time without affecting structural or service layers. Furthermore, this approach facilitates future upgrades to PMFC components without structural modifications. The shape of the containers is made repetitive using similar components to allow for easy manufacturing. The container elements and their assembly for creating different container designs are shown in Figure 26.

The modules must be both weatherproof and waterproof to withstand tropical rain and high humidity. Their construction must remain lightweight, as the saturated soil already imposes a significant load on the supporting structure. Additionally, since the aim of this project is to enhance circularity, the design must be made from low-carbon, sustainable materials. The customised base panel and containers are designed to be manufactured from recycled plastics, reinforcing the project's circular design approach by giving a second life to waste material that would otherwise be disposed of. This choice is also practical because recycled plastics are lightweight, which helps limit the load on the backing structure. Recycled plastics are highly malleable and can be formed into custom shapes by injection moulding, the preferred method for this design. The back sections of MobiPanel are manufactured by injection moulding, and thus, customised base plates and containers can be produced in the same facility. In addition, using mixed recycled plastics creates natural variation in colour and texture, a design advantage that gives the façade a more dynamic, less uniform appearance. Different design assemblies and materiality explorations are shown in Figure 27.

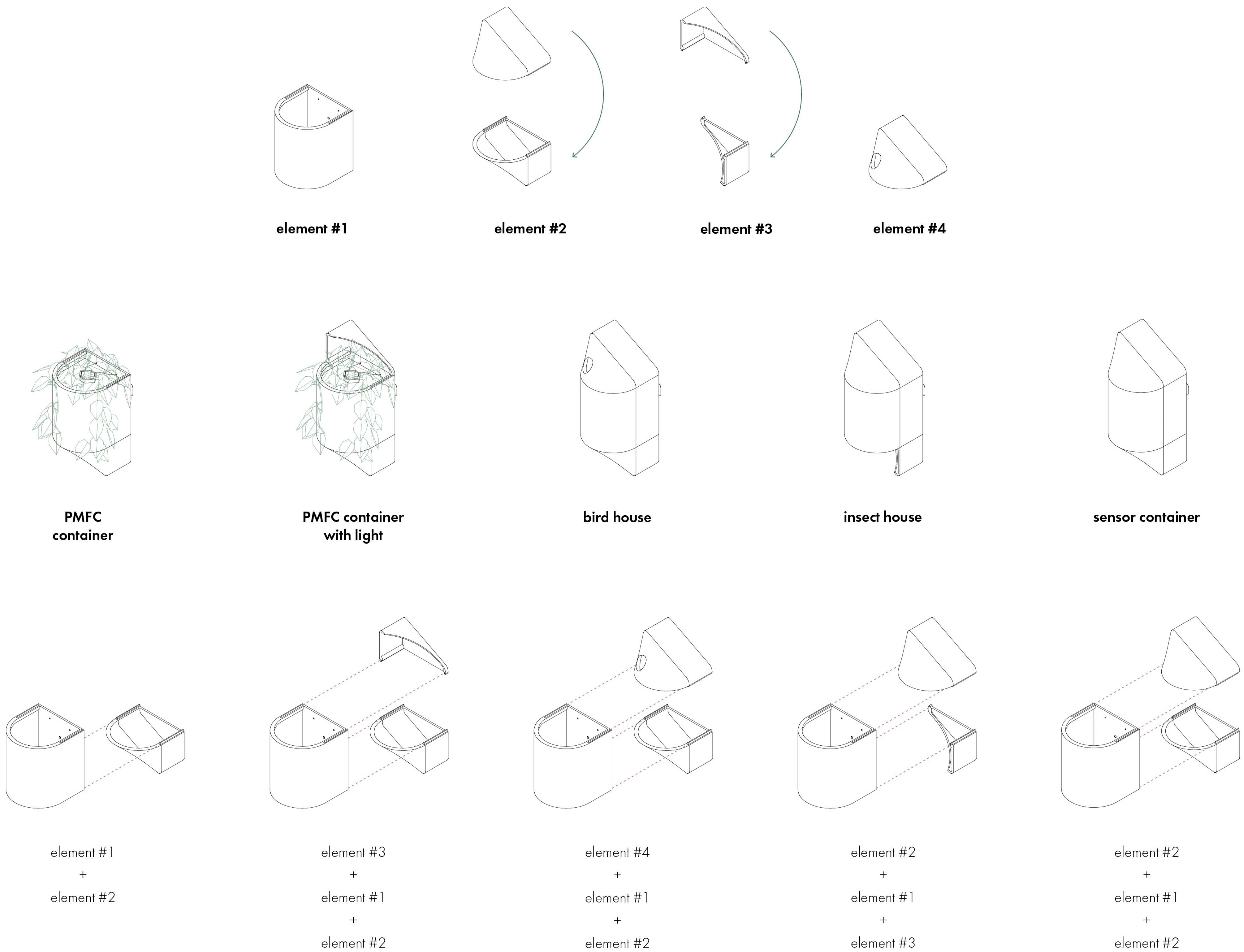
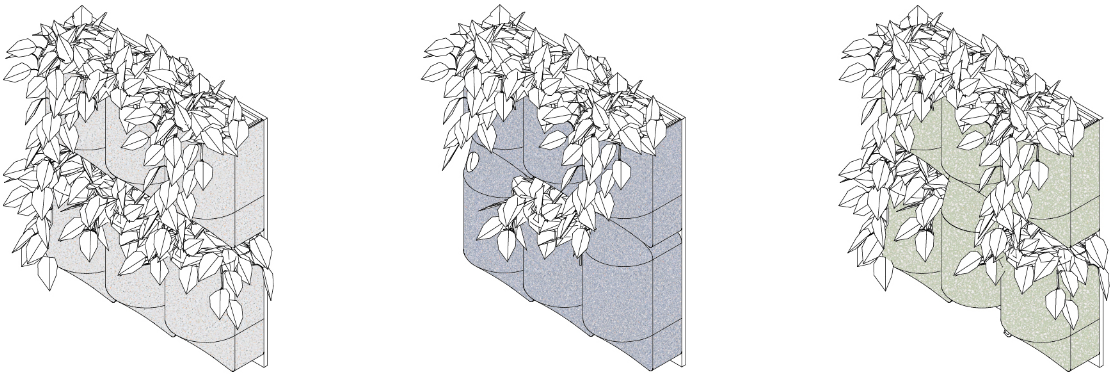


Figure 26:
PMFC Integrated Façade Living Wall System container design.

Figure 27: Design variants of PMFC Integrated Façade Living Wall System.



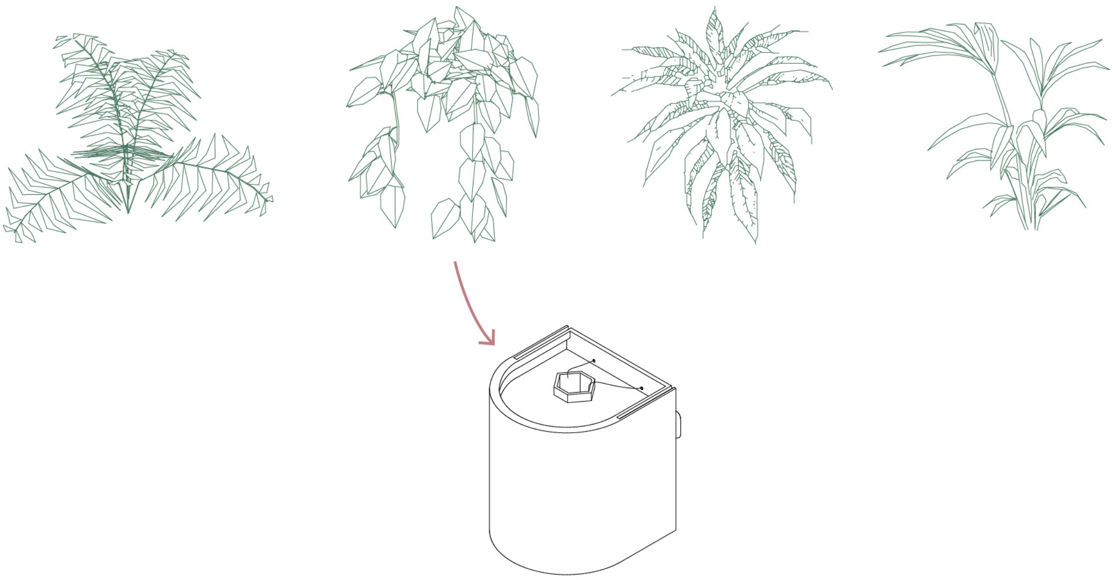
variant #1
with PMFC containers

variant #2
with bird house and sensor container

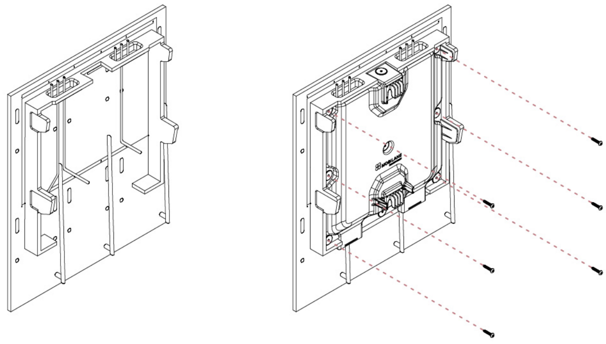
variant #3
with insect house

A step-by-step assembly and installation of the abovementioned components of the PMFC Integrated Façade Living Wall system is explained below in Figure 28.

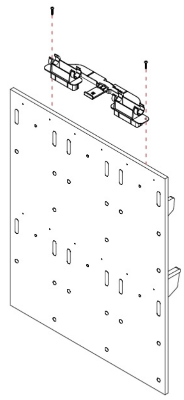
Figure 28: PMFC Integrated Façade Living Wall System installation.



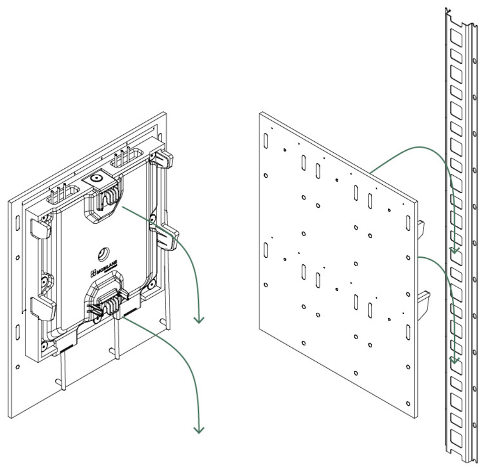
1. First step is to design a plant assembly and plan out which species are desired and where they will go on a wall. Additionally, other types of containers are also accounted for in this stage. This step dictates the type and number of containers, and thus how many PMFC reactors need to be set up. Based on the number and types of plants required, PMFC reactors are assembled in their target containers. This step must be performed in advance to allow enough time for the microbiome to start up and reach its final, stable performance before being placed on the wall. During this step, regular monitoring of microbiome health and development is required. When PMFC reactors are stable, the wall assembly can start.



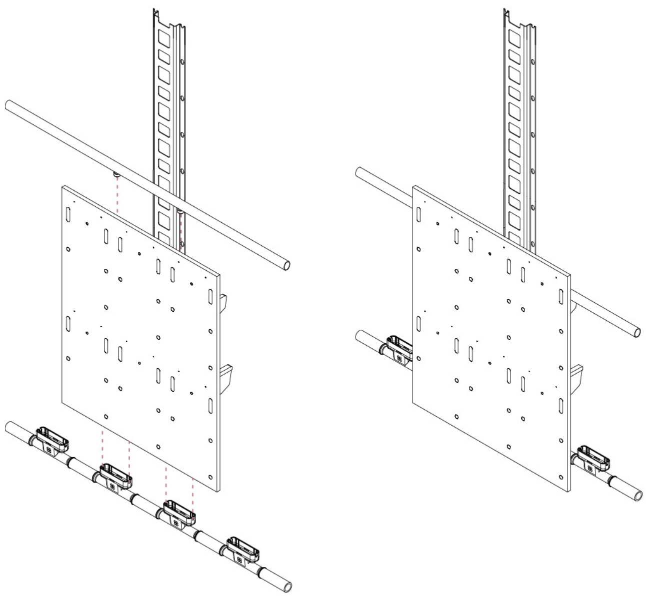
2. Electrical wiring, irrigation and collection piping are routed inside the back of MobiPanel and intertwined through pre-made holes in the module's back panels. The module's back panels are screwed to the backs of MobiPanels, creating a base for later attaching the containers.



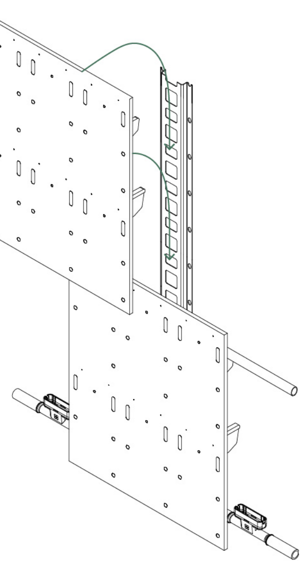
3. The drip assembly is connected to the module base.



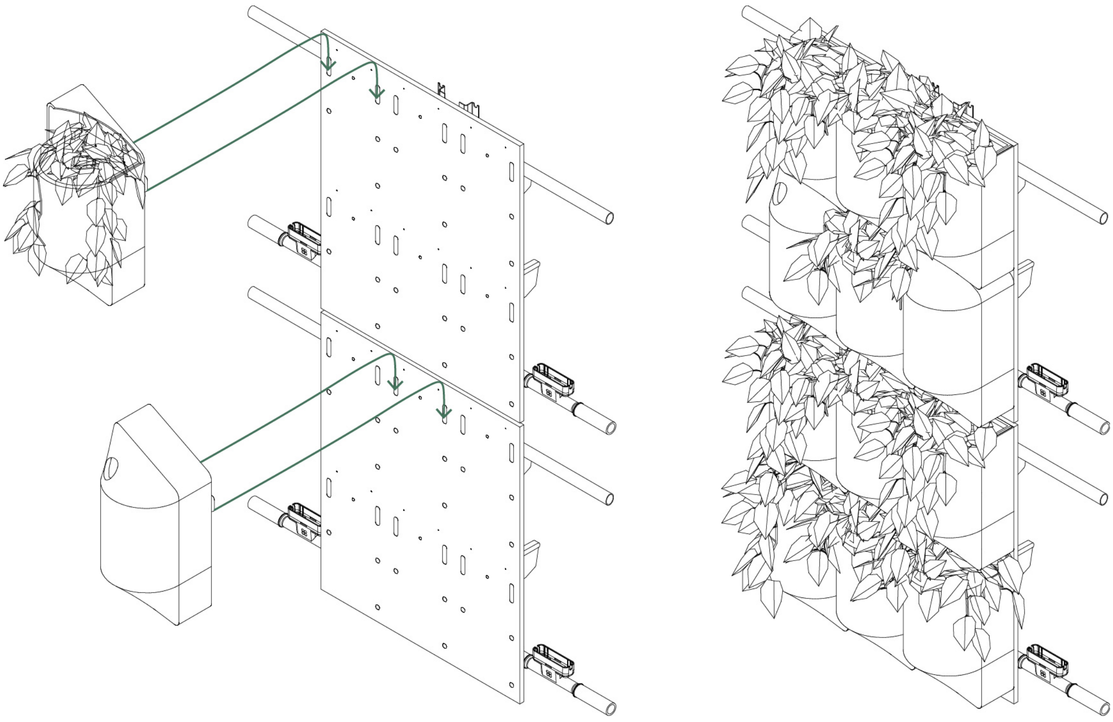
4. Omega profiles are mounted to the building wall. The first row of assembled module bases is hung on the omega profiles and secured with the lock on the drip assembly.



5. Irrigation pipes and collection gutters are connected within the rows of base modules. Wiring connections between modules are made.



6. Next rows of modules are hung on omega profiles, and the two previous steps are repeated for each assembled row.



7. The last step is to hang the containers according to the design and connect wiring and piping to the PMFC reactors.

3.8 Building Adaptation Measures

To successfully integrate a Plant Microbial Fuel Cell Integrated Façade Living Wall on HDB housing blocks, several considerations must be taken into account, and adaptations to the building infrastructure must be made. The design must start with the strategic placement of the Living Wall on the building with regard to sun orientation and the building's internal infrastructure. The building's internal plumbing needs to be reconfigured to route wastewater through the pre-treatment infrastructure and then the designed system. Once treated by PMFCs, the effluent must be collected for reuse in non-potable applications. After the collection, the effluent may require additional post-treatment. To use the PMFC-generated power, the collected current must be transformed, stored, and distributed to the building. Permanent maintenance access must be designed into the facade to allow for plant upkeep and reactor repair.

There are two distinct strategies for adapting the building, depending on whether it is a retrofit project or a new build. While new builds allow for the seamless integration of internal plumbing and reinforced primary structures from the start, retrofit projects necessitate structural evaluations and potential reinforcement of existing structural elements to support the designed wall's load and infrastructure. Checks whether new water and energy infrastructure can fit within existing shafts have to be performed. If this is not possible, new shafts have to be designed where space permits.

3.8.1 Location on Building

When choosing a building's façade for a Plant Microbial Fuel Cell Façade Living Wall, two aspects must be considered: ensuring sufficient sunlight to meet plant light requirements and avoiding excessive sunlight to limit soil evaporation. Higher light intensity can yield higher voltage and current by intensifying photosynthesis, but it also risks drying out the anode. In equatorial regions such as Singapore, the sun follows an east–west path and remains nearly overhead for most of the year. For this reason, aligning the Living Wall along this axis is generally preferred, as it enables consistent exposure to sunlight throughout the day as the sun moves across the sky. Positioning it on the east side of a building, towards the less heat-stressing morning sun, will protect the electrogenic bacteria in the soil from drying caused by the late-afternoon equatorial sun, while still providing enough radiation for effective photosynthesis. Shading of the plants significantly reduces electricity generation due to a decline in rhizodeposition, so when placing the system, locations under large overhangs, balconies, or canopies should be avoided.

The location of the Living Wall, regarding building water and sewage infrastructure, needs to take the risk of clogging into account. It is best to localise the main inlet of the irrigation system close to the wastewater storage tank and outlet of the wall's treated water near a main collection pipe within the building.

In terms of the building's structural safety, static (wall weight) and dynamic (moving water) loading should be considered. The soil saturation and loading rate of the irrigation and water collection systems can vary, and thus, margins should be taken into account when calculating structural loads.

3.8.2 Wastewater Routing and Pre-Treatment

In Singapore's residential buildings, wastewater is routed through a strictly managed internal plumbing system designed to separate different types of effluent and prevent environmental pollution (PUB, 2014). This separation is integral to the building design and enables potential on-site recycling. Regulatory frameworks require that blackwater is discharged directly into the public sewerage system, whereas greywater is collected through dedicated sanitary pipework. Inside high-rise HDB blocks, these plumbing systems typically utilise gravity flow to convey effluent from individual apartments down to the building's basement. The pipes are usually housed within standardised precast service ducts that are integrated into the building's modular design. Internal routing must include grease traps or similar interceptors before the effluent is permitted to enter the building's main used water system (Luan, 2010). Finally, the internal building pipes connect to the public sewerage system at ground level.

Greywater, originating from building sources such as showers, sinks, and laundry, is selected as the substrate for the PMFC reactors because it accounts for 60-75% of the volume of building wastewater and has a moderate organic loading. It provides suitable organic content for microbes without the high pathogen or nutrient loads of blackwater, which can risk fouling the reactors. In the basement, before the collected greywater enters the public sewage system, it will be rerouted to a storage tank equipped with an overflow line that, if the tank is full, will direct the greywater to the sewer. Before the greywater is distributed to PMFC reactors, its properties will be checked, and optional preconditioning of pH and organic content loading will be performed along with basic pre-treatment. Pretreatment infrastructure is essential to prevent clogging when greywater enters the PMFC Integrated Façade Living Wall's irrigation system. It typically involves grease traps and coarse screens (1-5 mm mesh) to remove solids. As grease traps are already incorporated at the appliance level, only basic screening and settling to remove solids is necessary. From the basement tank, through a filtration screen, greywater is pumped to the wall's irrigation system. The designed irrigation system prioritises minimal energy use through gravity-fed flow, eliminating the need for pumps where possible. As mentioned earlier, the irrigation system consists of a series of horizontal pipes that distribute greywater to each row of living wall modules. Horizontal pipes are connected to a main vertical pipe with a system of valves. The filtered wastewater is conveyed up the façade to enter the irrigation system at the top of the main pipe, and flows downward by gravity, filling each horizontal pipe in sequence. At every row level, the main pipe is equipped with a valve that closes once the corresponding horizontal pipe is full. This prevents the wastewater from continuously flowing to the bottom of the wall and instead ensures an even distribution across all rows. Consequently, the pump needs to be activated only when the sensors indicate that the horizontal pipes require refilling.

While wastewater is directed into the sewer, rainwater is captured by a separate system of rooftop drains that route it into the island's reservoirs (Luan, 2010). This means that during periods of lower greywater production or higher pollution, the irrigation system can be supplemented or diluted with rainwater from pre-existing collection infrastructure.

3.8.3 Effluent Routing and Post Treatment

Singapore's Public Utilities Board (PUB) provides strict technical guidelines to ensure that on-site wastewater treatment systems are safe and reliable (PUB, 2014). To safeguard public health, on-site systems are prohibited for individual household use and are instead managed at the building level by qualified people. Strict regulations also prevent any cross-connection between the non-potable greywater system and the potable water network, requiring physical separation of all pipes and tanks. A mandatory post-treatment requirement is the installation of a chlorine-dosing facility at the treated greywater storage and supply tank (PUB, 2014). This disinfection stage is necessary to ensure that the treated water remains sterile and bacterial regrowth is prevented. Finally, the treated water must be monitored to ensure its pH remains between 6 and 9 and is free of offensive odours to maintain user acceptance.

The treated effluent produced by the Plant Microbial Fuel Cell Façade Living Wall System can be reused within the building for various non-potable applications, such as toilet flushing, irrigation and general washing. While the PMFCs provide effective primary biological treatment, secondary polishing remains necessary for the treated water to meet the local water quality standards and safe reuse. Firstly, treated water is collected from each row of modules of the living wall by a main vertical collection gutter using gravitational flow. The main collection gutter, with a solid filter, transports treated effluent to a buffer tank in the basement, where it receives the necessary chlorine treatment. The polished water is then routed by dual-pipe distribution networks integrated into existing risers, delivering it directly to non-potable appliances.

3.8.4 Energy Collection

A multivibrator inverter circuit is a power conversion circuit that uses an oscillator to switch direct current on and off rapidly, which is then passed through a transformer to create alternating current. Essentially, it is a way to turn a steady voltage into the "wavy" electricity used by wall outlets.

To transform the current generated by PMFCs into usable electricity for a building, the designed system must manage energy harvesting, energy storage, and convert the collected power into a form compatible with standard appliances (Ballestas et al., 2023). Since PMFCs produce direct current (DC), the energy must pass through power inverters to be converted to alternating current (AC). A multivibrator inverter circuit can convert DC power into AC power, enabling PMFCs to serve as a power source for standard appliances, such as LED bulbs. Even with scaling up, the raw output from a PMFC is often too low and unstable to power standard electronics directly, as the power generated by PMFCs fluctuates based on microbial activity. To resolve this, energy must be stored in batteries or supercapacitors before using it in the building (Kuleshova et al., 2022).

Energy routing in HDB housing blocks is a highly standardised process. Buildings are designed to accommodate essential electricity infrastructure alongside water and sanitation infrastructure (Lin-Heng, 2020). Recently, photovoltaic systems have been installed on the roofs of residential blocks as part of a government programme to integrate renewable energy sources. Produced solar energy powers common services within the estate, including elevators, lighting for corridors and staircases, which have largely transitioned to energy-efficient LED technology, and water pumps that maintain the building's water supply. The current produced by these photovoltaics is also DC and requires the same processing and storage as that produced by PMFCs, enabling both technologies to share power management and distribution systems. The PMFC-generated energy can be routed alongside PV-generated energy to supplement power for common services, a model already established by the governmental solar energy programme.

3.8.5 Sensors

Plant Microbial Fuel Cells require specific conditions to deliver maximised output. Because the designed PMFC Integrated Façade Living Wall System is exposed to the outdoor environment, monitoring of meteorological data, electrical performance, and substrate quality is necessary to determine whether the system is working properly and to adjust operating conditions as needed.

In similar systems where PMFCs are integrated into green infrastructure, small weather stations (such as Vantage Pro2) are typically installed nearby to record ambient humidity, air temperature, rainfall, and solar radiation (Guan & Yu, 2020). Based on the meteorological sensor readings, the irrigation system can adjust substrate dosing to PMFCs and maintain appropriate soil moisture levels. Additionally, the soil moisture should also be monitored independently (Xuan et al., 2025). Next to soil moisture, PMFC performance and microbiome health are monitored by measurements of voltage using continuous data acquisition microcontrollers such as Arduino Uno (Guan & Yu, 2020). Sensors are often part of a larger Internet of Things (IoT) setup, in which data is recorded by loggers (such as the Keithley

2700 or PicoLog) and transmitted wirelessly for real-time monitoring (Guan & Yu, 2020).

For this system, joined monitoring of PMFC performance and wastewater flow through the living wall modules is needed. A weather station, flow meter, soil moisture sensors, voltage meters and effluent quality monitoring are designed. One weather station per system assembly is placed at the canopy level on one of the edge wall modules. To control substrate dosing, a flow meter is installed at the beginning of the main irrigation line. Moisture sensors are placed inside the soil in an anode chamber, in a pot at the end of each irrigation line, to ensure that the substrate is evenly delivered to each of the PMFCs along the line. Voltage sensors will be connected directly to the PMFC anode and cathode wires and placed in the middle modules, distributed every four rows (one sensor per building floor). For the effluent collection, a flow sensor is also designed to detect and control leaks, evaporation losses, or clogs. The exact placement of these sensors is shown in Figure 29. All the measured data will be recorded by a central logger to monitor the performance of the PMFC Integrated Façade Living Wall System in real time.

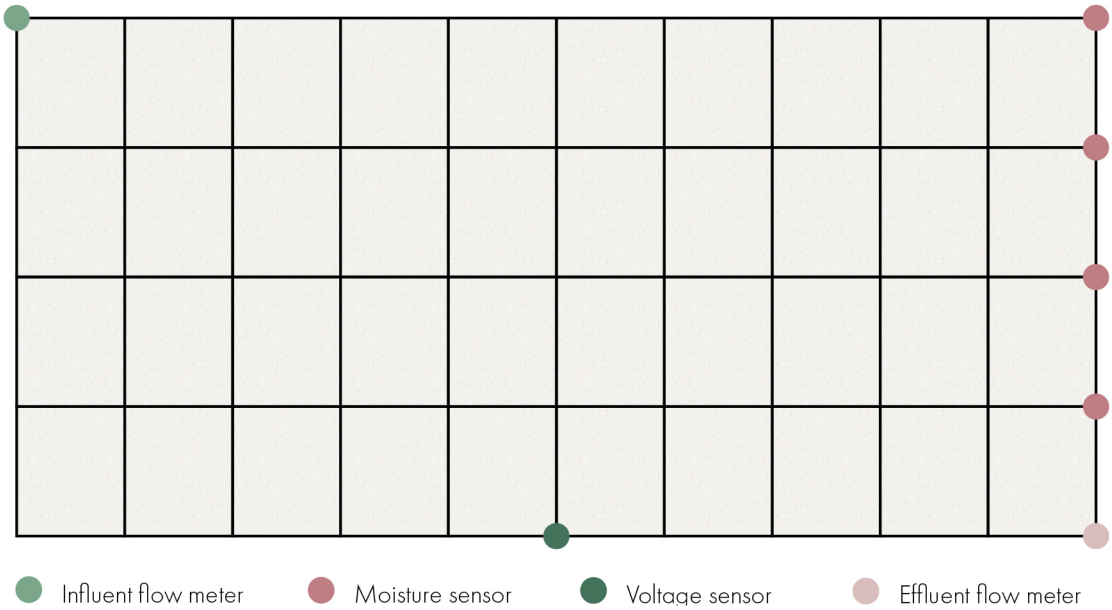


Figure 29: Placement of the sensors on a fragment of the designed PMFC Integrated Façade Living Wall System.

3.8.6 Maintenance

Living walls require more maintenance than simpler green façades (Theodoridou et al., 2025). If well maintained, they can live for 25 or even 40 years (Chew & Conejos, 2016; Manso et al., 2020). In terms of vegetation, maintenance includes removing plant litter, pruning, and controlling weed and insect infestations (Prodanovic et al., 2019). Maintaining a living wall involves replacing approximately 5–10% of its vegetation each year (Manso et al., 2020). Pruning is usually required once or twice a year to control growth, maintain foliage density, and keep vegetation away from windows, drains, and building fixtures (*Growing Green Guide*, 2014). For high-rise buildings, it often requires specialised equipment and trained staff. Small installations can be managed with ladders or mobile platforms, but larger systems may require cranes or roof-mounted swing stages.

Since HBD housing is usually high-rise blocks, a roof-mounted swing stage will be necessary to maintain the greenery of the designed PMFC Integrated Façade Living Wall System. This swing stage can, though, serve multiple purposes, such as maintenance of PMFC containers, piping, and wiring, or the cleaning of windows. The proposed system is designed to ease maintenance and repair by utilising demountable, modular components. To avoid clogging of irrigation and treated-water collection hardware, a set of filters is installed at the main inflow pipe, before the substrate enters the irrigation lines, and in every pot insert, before the treated water enters the gutter system. With the use of sensors, errors can be detected early. To avoid salt crystallisation, monitoring of the substrate's hardness and alkalinity will be incorporated into the pre-treating infrastructure. As the proposed system uses greywater, which provides sufficient nutrients for the plants, additional fertilisation is unnecessary.

4. System Evaluation

To evaluate the real-life performance of the proposed system design, prototypes of the Plant Microbial Fuel Cell reactors were constructed. Their wastewater treatment and energy-generating performance were compared with two control groups. The final setup of the experiment was then as follows:

- Test Group 1: Plant Microbial Fuel Cell reactors fed on wastewater.
- Control Group 2: Plant Microbial Fuel Cell reactors fed with tap water.
- Control Group 3: Plants without Microbial Fuel Cell reactors fed with wastewater.

Groups 1 and 3 were evaluated for wastewater treatment, and groups 1 and 2 for energy generation. Each group contained four samples. Images of each of the samples are depicted in Figure 30.

Figure 30:
Photographs of the constructed samples of Group 1 and Group 2.

Figure 30: Photographs of the constructed samples of Group 3.

Sample 9 Sample 10 Sample 11 Sample 12

Osmotic shock is the sudden damage or stress a microbe experiences when its environment changes concentration rapidly.

The experiment was conducted over 5 weeks, from 24/04/2026 to 25/05/2026. Weeks 1-2 were dedicated to microbiome stabilisation and plant adaptation to wastewater. Only the open-circuit voltage was measured to assess whether the microbiome was developing well. The amount of wastewater in the fed substrate was slowly increased to avoid osmotic shock. The evaluation of wastewater treatment performance for individual reactors began in the third week, when the reactors received the full wastewater concentration. The circuits in the reactors of Groups 1 and 2 were closed to measure the closed-circuit voltage. Evaluation of wastewater treatment and energy-generating performance continued until the end of week 5.

The experiment took place in a room located at the TU Delft campus. Samples were set up on the sill of a north-west-facing window, where they received 4 hours of direct sun between 4.30 pm and 8.30 pm. The temperature of the room where the samples were set up was kept between 21 and 26 °C. The room's relative humidity was between 60% and 80%. The experiment setup is shown in Figure 31.

Figure 31: Experiment setup.

Group 1 Group 2 Group 3

4.1 Experiment Setup

The samples were set up as soon as possible to achieve the full PMFCs performance before the end of this thesis. Due to the limited timeframe, the samples were established in available off-the-shelf components of the same size as the designed PMFC containers. Clear 2.4 L plastic pots with a top diameter of 17 cm, a bottom diameter of 13 cm, and a height of 15.5 cm were used to better observe plant root health and development. One plant species was selected to enable accurate comparison across all samples. Both Groups 1 and 2 had the same reactor design and the same composition of the growing medium. Synthetic wastewater was used as a feeding substrate for Groups 1 and 3, while Group 2 was fed with tap water. The components of the prototype are described in more detail in the following sections, and the materials used to fabricate the samples are shown in Figure 32.

Figure 32: Materials of samples with PMFC reactors.

4.1.1 Plant

For the prototype, the Epipremnum aureum plant, commonly known as Golden Pothos, was chosen because it is characterised by low light requirements and is suited to growing in both waterlogged conditions and soil (Rajpurohit & Behera, 2025). It performs well in PMFCs according to research papers, as shown in Table 8. Epipremnum aureum is also locally available in stores in the Netherlands. Plants were brought from a local garden centre to the place of experiment a week before the sample assembly to adapt to the new environment. The soil the plants were originally in was gently discarded, but the roots were not cleaned to avoid disturbing the bacteria already residing in the rhizosphere. Plants of similar size were placed in each sample around the terracotta cone so that their roots touch the anode electrode and facilitate the bioelectrochemical reaction.

Table 8: Epipremnum aureum performance in PMFC reactors.

Source	PMFC Setup	Wastewater treatment performance (COD removal)	Energy generating performance (power density)
Sarma and Mohanty, 2018	Soil-based PMFC	Not applicable	15.38 mW/m²
Sarma and Mohanty, 2018	Soil-based PMFC	Not applicable	24.56 mW/m²
Rajpurohit and Behera, 2025	Constructed wetland PMFC	94%	63.45 mW/m²

4.1.2 Growing Medium

Pots of Groups 1 and 2 were filled with 50% standard garden soil, 25% biochar and 25% lakebed soil. Pots of Group 3 were filled with 75% garden soil and 25% biochar. The pots were filled to 1 cm from the top to allow watering without water overflowing. The composition of garden soil and biochar is listed in Table 9.

Pyrolisis is a process of heating organic waste materials, such as agricultural residues, wood chips, or manure, at high temperatures (300-900°C) in a low-oxygen environment.

Standard garden soil was used because it has been shown to sustain an electrogenic bacterial community (Rumora et al., 2023). Biochar, a charcoal produced by pyrolysis, is used in green walls for wastewater treatment as a lightweight enhancement to improve treatment efficiency (Lakho et al., 2021). It also helps retain moisture in the reactors, which is beneficial for the biofilm. Lakebed soil, collected from nearby Delftse Hout, was added to inoculate electrogenic bacteria and accelerate biofilm startup, as has been done in Rajpurohit and Behera (2025). Lake sediments have been documented to host the specific bacteria required for bioelectricity generation, and they are naturally oxygen-less (Garbini et al., 2023). The exact bacterial content of the lakebed soil was unknown due to a lack of infrastructure for testing. Inoculation was not performed in Group 3, as this control group was used to assess the wastewater treatment efficiency of the growing medium without electrogenic bacteria, thereby simulating a living wall setup for wastewater treatment based on the constructed wetland principle.

Table 9: Properties of the growing medium ingredients – garden soil and biochar.

Property	Garden Soil	Biochar
pH	5.8	10
Carbon	-	80.0%
Potassium	-	4.2%
Calcium	450 mg/L	2.7%
Nitrogen	250 mg/L	0.3%
Magnesium	170 mg/L	0.5%
Sodium	-	0.05%
Phosphorus	250 mg/L	0.3%
Hydrogen	-	2.9%
Sulphur	-	0.7%
Carbon From Carbonates	-	1.4%
Water Holding Capacity	-	48.0%

4.1.3 Plant Microbial Fuel Cell Reactor

The PMFC reactor design was based on Palmero and Pamintuan (2023) (as shown in Figure 33) and modified to simplify prototyping. Similarly, a standard terracotta watering cone (13 cm height, 5 cm diameter) was selected as the proton exchange membrane due to its commercial availability, low cost and porous ceramic structure that permits proton transfer. The outside of the terracotta cone that touches the soil served as an anode chamber (2.29 L). The inside of the cone was acting as a cathode chamber (0.11 L) exposed to atmospheric air.

Instead of 3D printed electrodes as in Palmero and Pamintuan (2023) or Constantino et al. (2023), graphite felt electrodes (SGL Carbon SigraCell GFD 2.5 EA battery felt) were chosen for both anode and cathode electrodes. The exact properties of the product are listed in Table 10. Graphite felt has a porous surface that supports the attachment of microorganisms and provides a large surface area for efficient electron transfer between the bacteria and the electrode (Brugellis et al., 2025). It is also highly flexible and can be easily wrapped around the terracotta cone. Anode electrodes (rectangular strips of 5.2 cm height and 12.5 cm width) were wrapped around the cone's exterior and secured with a string, while cathode electrodes (rectangular strips of 7.3 cm height and 9.5 cm width) were placed inside the terracotta cone along the edge. The electrode locations on the terracotta membrane were the same as in Palmero and Pamintuan (2023). Two copper wires with a 0.2 mm diameter were used to connect the anode and cathode electrodes. They were placed along the terracotta membrane so that at least 3 cm of the wire was embedded in the electrodes.

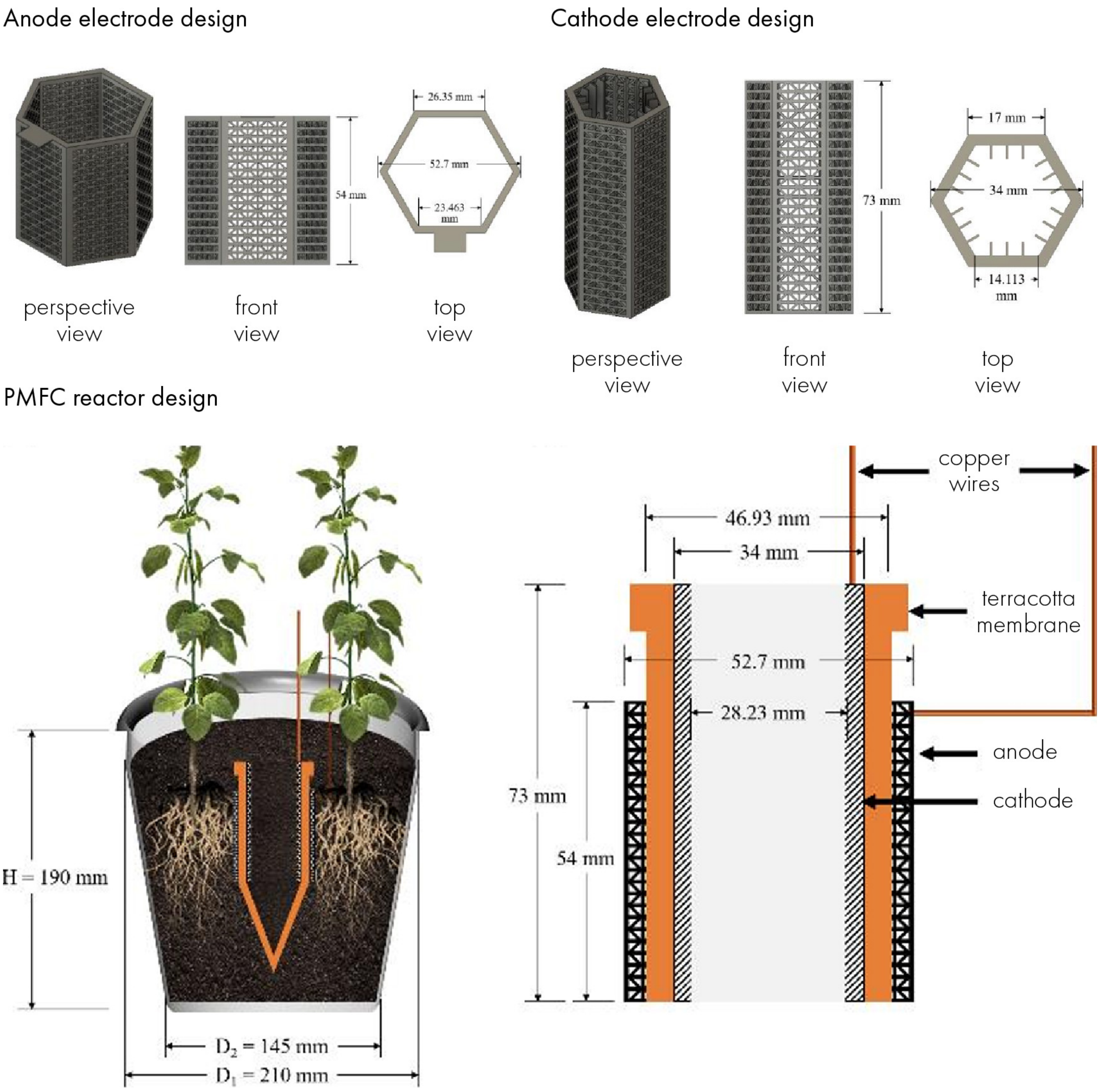


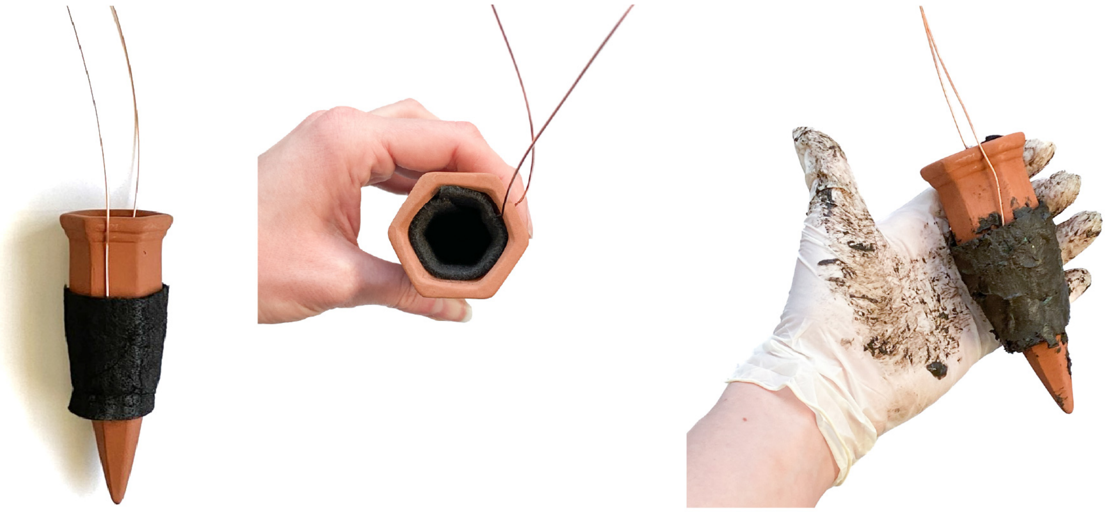
Figure 33: PMFC reactor design from Palmero and Pamintuan (2023).

Table 10: Properties of SGL Carbon Sigra-Cell GFD 2.5 EA battery felt. Adapted from SGL Carbon (2019).

Typical Properties	Units	GFD 2.5 EA
Carbon fibre precursor		PAN
Bulk density	g/cm^3	0.09
Nominal thickness	mm	2.5
Area weight	g/m^2	250
Open porosity	%	94
BET surface area	m^2/g	0.4
Electrical resistivity (vertical to longitudinal direction of felt)	Ωmm	<5
Electrical resistivity (parallel to longitudinal direction of felt)	Ωmm	<3
Area-specific resistance (vertical to longitudinal direction of felt)	Ωcm^2	<0.1
Total impurities	%	<0.05

Each step of the assembly of the PMFC reactors is visualised in Figure 34. In addition to growing medium inoculation, the lakebed soil was also put directly on the anode electrodes to establish the biofilm more quickly. The assembled reactors were then placed in the middle of the pots so that only 1 cm of each reactor protruded from the soil.

Figure 34: Assembly of a PMFC reactor.



Step 1 Step 2 Step 3

1. Anode wire is placed between the terracotta membrane and the anode electrode. The anode electrode is wrapped around the terracotta membrane and secured with a string.
2. Cathode wire is placed inside, between the terracotta membrane and the cathode electrode. The cathode electrode is placed inside the terracotta membrane.
3. Lakebed soil is put on the anode electrode to inoculate the microbes.

4.1.4 Substrate

Groups 1 and 3 were fed with synthetic wastewater, and Group 2 was fed with tap water. The watering schedule was the same for all groups to ensure similar conditions across all samples. Hydraulic Retention Time (HRT) is a fundamental engineering parameter defined as the average time a liquid substrate or wastewater remains in a PMFC for microbial oxidation. It is calculated as the ratio of the system's working anode volume (the anolyte) to its influent flow rate, representing the duration for which organic matter is available to the electrochemically active bacteria inhabiting the rhizosphere. This parameter is considered pivotal because it directly dictates the efficiency of the PMFC in both bioelectricity production and wastewater treatment (Regmi et al., 2018). Research indicates that an HRT of 2 days is recommended for soil-based PMFC setups to give bacteria sufficient time to fully decompose the substrate and achieve the highest outputs. Because of this, an HRT of 2 days was established for this experiment. The required amount of substrate was calculated to be 1075 mL per day using the formula below from Regmi et al. (2018):

$$\mathrm{Q}\ \left(\mathrm{mL/day}\right) = \frac{\mathrm{V}\ \ (\mathrm{mL})}{\mathrm{HRT}\ \ (\mathrm{days})}$$

Where:

- Q – required flow rate of wastewater per day.
- V – volume of the anolyte zone in the anode, assumed as 2150 mL (taken as volume from the bottom of the pot to the top level of the anode electrode, as the first 2 centimetres of the soil from the top were assumed to have aerobic conditions and thus are not taking part in the bioelectrochemical processes).
- HRT – hydraulic retention time of 2 days.

The samples were watered four times a day with small doses to simulate a continuous flow of substrate and to ensure that the substrate remains in the pot long enough to be treated. At each watering, the pH of the substrate was measured with a pH strip to ensure it remained within the desired neutral range of 6.5-7.5. During the first two weeks, the samples were watered with a smaller dose of water to allow the plants' roots to adjust to the new environmental conditions. The ratio of wastewater to tap water in the substrate was gradually increased to avoid osmotic shock of the microbial community. During the first week after establishment, no wastewater was introduced. In the second week, the dose was increased with each watering to reach a final wastewater concentration at the start of the third week of the experiment. A detailed watering schedule, including volume, pH, and wastewater concentration, is shown in Table 11.

Table 11: Watering schedule.

Date	Week	Influent Volume (L)	Wastewater Concentration in Influent (%)
24/04/26	1.1	0.5	0%
25/04/26	1.2	0	-
26/04/26	1.3	0.5	0%
27/04/26	1.4	0	-
28/04/26	1.5	0.5	0%
29/04/26	1.6	0	-
30/04/26	1.7	0.5	0%
1/05/26	2.1	0	-
2/05/26	2.2	0.5	33%
3/05/26	2.3	0	-
4/05/26	2.4	0	-
5/05/26	2.5	0.5	50%
6/05/26	2.6	0	-
7/05/26	2.7	0.5	50%

8/05/26	3.1	1	66%
9/05/26	3.2	1	66%
10/05/26	3.3	1	83%
11/05/26	3.4	1	83%
12/05/26	3.5	1	100%
13/05/26	3.6	1	100%
14/05/26	3.7	1	100%

For Groups 1 and 3, synthetic wastewater was prepared according to the recipe described by Kargol et al. (2023). Researchers turn to using synthetic wastewater when access to real wastewater is limited, as was the case in this thesis. The recipe for the experiment used a readily available, budget-friendly main ingredient – dry dog food. It was intended to mimic synthetic primary effluent, which is commonly used in oxygen-less reactors (Kargol et al., 2023). The base was prepared by soaking 60 g of Pedigree Small Dog Roasted Chicken, Rice, and Vegetable Flavour in 1.1 L of tap water at room temperature for 24 h. Then the solution was strained using a 2mm mesh bag to remove large food particles. To reach a desired carbon-to-nitrogen ratio, the base solution was supplemented with 3g of whey powder (Accelerate whey protein powder). The base solution was then diluted 1:10 to match the COD concentration of municipal wastewater in Singapore, 395-815 mg/L (Kog, 2020). The base solution was prepared the day before every watering to prevent a decrease in COD over time. Dry dog food was stored in an airtight container as suggested by Kargol et al. (2023) to avoid further decrease in COD.

Table 12: Properties of synthetic wastewaters.

	Experiment Base Solution	**Base Solution from Kargol et al. (2023)**	**Experiment Diluted Base Solution**	**Diluted Base Solution from Kargol et al. (2023)**
pH	6.8	6.4	7.0	7.5±0.5
COD (mg/ L)	Not measured	4870 ± 474	Not measured	1210 ± 35.2
Total nitrogen (mg/L)	Not measured	227 ± 37.4	Not measured	98.6 ±12.4
Ammonia (mg/L as N)	1.0	9.7 ± 0.6	1.0	2.25±0.01
Nitrate (mg/L as N)	4.0	12.2 ± 4.2	4.0	2.24±0.25
TSS (mg/L)	1333.33	1030 ± 250.0	666.67	23.3±0.3
Alkalinity	60	n.d.	60	450±50.1

The base solution was tested with aquarium test strips, which revealed that some of its properties did not match those of the wastewater prepared by Kargol et al. (2023), even though the same brand of dog food was used. The base solution prepared by Kargol et al. (2023) was tested using laboratory methods, whereas the aquarium test strips may be less accurate. Thus, the experiment continued with the synthetic wastewater prepared using the abovementioned method, assuming it has appropriate properties. The comparison of the measured properties is shown in Table 12.

4.2 Wastewater Treatment Efficiency Evaluation Methods

Properties of treated water samples collected from Groups 1 and 3 were compared with the provided substrate properties (see Table 13) to see how MFC technology influences wastewater treatment efficiency of green wall systems. The results of Group 1 were then further used to evaluate the performance of the proposed PMFC Integrated Façade Living Wall System design.

Table 13: Estimated COD, TSS and nutrients of used substrate.

Property of the provided substrate	Value
COD (mg/ L)	1210 ± 35.2
TSS (mg/L)	666.67
Ammonia (mg/L)	1.0
Nitrate (mg/L)	3.0
Nitrite (mg/L)	0.2
Phosphorus (mg/L)	0.5

Evaluation of wastewater treatment efficiency of green walls and Plant Microbial Fuel Cells usually involves analysing the provided substrate and the treated water quality for parameters such as Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), and nutrients (total nitrogen and phosphorus). COD represents the total quantity of oxygen required to chemically oxidise all organic material in a sample into carbon dioxide and water (Chong et al., 2024). In the context of PMFCs, it serves as a primary indicator of the organic matter content available for utilisation as fuel by electrogenic bacteria. TSS represents the concentration of solid particles suspended in the water, and its reduction is a primary indicator of a PMFC's effectiveness as a biofilter.

In this experiment, measurements of the substrate were performed once at the beginning of the experiment, as according to Kargol et al. (2023), the synthetic wastewater has consistent properties each time it is prepared. Twice every week (on Mondays and Thursdays), fresh samples of treated water from each pot were collected and tested.

COD testing requires specialised laboratory equipment that was not accessible at the time of this experiment. Based on the measured current, it is possible to calculate the oxidation rate within the PMFC, which reflects the speed of the wastewater treatment process. The oxidation rate directly determines the COD of the effluent. It dictates how much organic content is successfully destroyed before the wastewater exits the PMFC reactor and how quickly the COD value drops during treatment. A high COD value of the fed substrate requires a higher oxidation rate to achieve the same reduction percentage in a given time. The oxidation rate is calculated using the following formula from Fujii et al. (2021):

$$r\ \left(\text{mol e}^{-}/\text{s}\right) = \frac{I\ (\text{mA}) \div 1000}{F}$$

Where:

— I – measured electrical current.

— F – Faraday's constant (96,485 C/mol e^{-}).

A limitation of this method is that it is possible to measure only the oxidation rate, and thus the rate of wastewater treatment, of only Group 1, and comparison with other experiment groups is not possible.

For measuring TSS, a laboratory filter paper with a pore structure of 15-20 µm was used. 50 mL of water was poured over the filter, and then the filter was dried in an oven set to 105 °C for an hour to remove any excess moisture. The weight of dried samples was measured using a jewellery scale of accuracy of 0.01g. The TSS for each sample was calculated using the formula below from Adjovu et al. (2023):

$$\text{TSS}\ \left(\text{mg/L}\right) = \frac{(W_{\text{dried sample}}\ (\text{g}) - W_{\text{filter}}\ (\text{g})) \times 1000000}{\text{Sample Volume (mL)}}$$

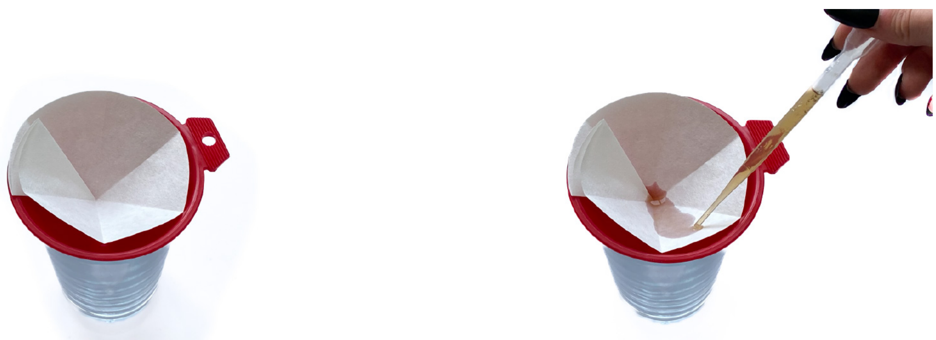
Where:

— $W_{\text{dried sample}}$ – measured weight of the dried sample.

— W_{filter} – weight of the filter used (1 g).

The TSS measuring process is visualised in Figure 35.

Figure 35: TSS measurment.



1. Place the filter on the funnel.

2. Pour 50 mL of treated water over the filter.

3. *Wait for the filtration to finish.*

4. *Once there is no liquid in the filter, it can be dried in an oven.*

5. *Weight the dried filter.*

To measure nutrient removal, an aquarium test strip was used, which changes colour when exposed to a specific concentration of compounds. These strips, unfortunately, do not measure total nitrogen, which comprises all nitrogen forms present in a sample, including nitrate, nitrite, ammonia, and organic nitrogen, but measurements of all except organic nitrogen can be performed with them. The strips were placed in the sampled effluent for 2 seconds, and after 30 seconds, the results were compared with a provided colour chart. For ammonia measurement, a drop of excitation solution was added directly to the ammonia measuring pad, and after 30 seconds, the result was also compared with the colour chart. To measure the removal of nitrate, nitrite, ammonia and phosphorus, the following equation from Zhang et al. (2023) was used:

$$R\left(\%\right) = \frac{C_{in} - C_{out}}{C_{in}} \times \ 100\%$$

Where:

- C_{in} – concentration of the nutrient in the substrate sample (mg/L).
- C_{out} – concentration of the nutrient in the treated water sample (mg/L).

The nutrient content measuring process is visualised in Figure 36.

Figure 36: Nutrient content measurment.

1. Prepare the sample.

2. Place the measuring strips in the sample for 2 seconds.

3. Wait 30 seconds.

4. Put the excitation solution on the ammonia measuring pad and wait 30 seconds.

5. Compare the measuring strip with the colour chart.

4.3 Energy Generating Performance Evaluation Methods

Groups 1 and 2 were used to measure and compare the influence of the provided substrate on the energy-generation performance of PMFC reactors. The measurements taken for Group 1 were used to evaluate the performance of the designed PMFC Integrated Façade Living Wall System for energy generation in a real-life scenario.

Open Circuit Voltage is the potential difference measured between the anode and cathode when no external resistance is connected and no current is flowing through the circuit.

Closed Circuit Voltage is the potential difference measured when the anode and cathode are connected through an external load (resistor).

Energy generation performance is usually measured in two stages. During the first stage of the experiment, the open circuit voltage (OCV) is measured daily. OCV indicates the maximum electrical potential of an individual PMFC and represents the energy accumulated within the biofilm, which is why it is used to assess microbial community health during the initial stages of the experiments (Liao & He, 2023). OCV is often independent of sunlight and time of the day, though it is influenced by soil moisture, pH and the specific composition of root exudates (Regmi et al., 2018). After the OCV readings stabilize the circuit can be closed, and the external load can be applied. When the circuit is closed, electrons begin to flow, and the measured voltage drops below the OCV due to internal resistance and various potential losses. Over the subsequent weeks, closed circuit voltage (CCV) is measured to evaluate the system's actual electricity generation potential during active operation. From CCV, current, current density, power and power density can be derived.

For this experiment, OCV was measured for the first two weeks, and during weeks 3, 4, and 5, CCV of individual reactors was evaluated against an external 1000 Ω resistor. The measurements were taken daily at 7 pm, when the samples received the most direct sunlight. All measurements were taken by connecting a digital multimeter (UNI-T UT33D+) directly to the reactors' copper wires with alligator clips. During OCV measurement, only voltage was reported, and during CCV measurement, current, current density, power, and power density for each sample were calculated from the recorded voltage. The voltage measuring process is visualised in Figure 37.

Figure 37: Voltage measurements.

Current (mA) is calculated using the formula below from Palmero and Pamintuan (2023):

$$I = \frac{V}{R}$$

Where:

- V – measured voltage (mV).
- R – resistance against 1000 Ω.

Current density (mA/m²) is calculated using the formula below from Palmero and Pamintuan (2023):

$$j = \frac{I}{A_c}$$

Where:

- I – calculated current (mA).
- A_c – area of the anode electrode (0.0065 m²).

Power (mW) is calculated using the formula below from Palmero and Pamintuan (2023):

$$P = \frac{V}{I}$$

Where:

— V – measured voltage (mV).

— I – calculated current (mA).

Power density (mW/m^2) is calculated using the formula below from Palmero and Pamintuan (2023):

$$P_d = \frac{P}{A_c}$$

Where:

— P – calculated power (mW).

— A_c – area of the anode electrode (0.0065 m^2).

4.4 Plant Health

In addition to wastewater treatment and energy-generation performance, plant health was monitored. Plant growth was assessed by the number of leaves as in Palmero and Pamintuan (2023). The leaves were counted at the beginning (24/04/2026) and at the end of the experiment (25/05/2026). Groups 1 and 2 were compared to assess the influence of wastewater on plant growth, and Groups 1 and 3 were compared to assess the influence of MFC technology.

5. Results

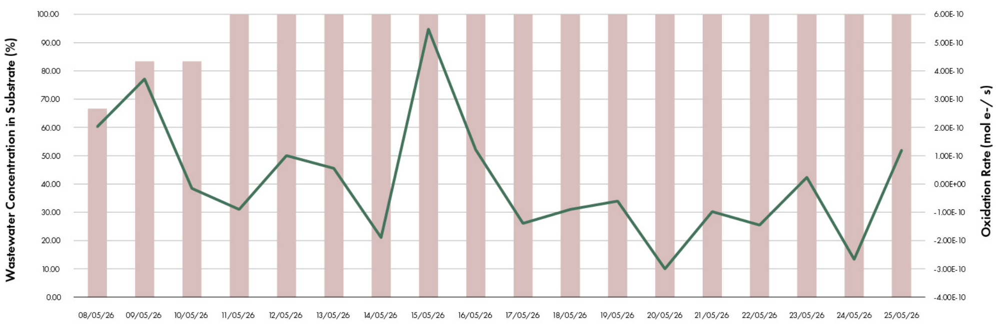
5.1 Wastewater Treatment Performance

5.1.1 Oxidation Rate

The oxidation rate, which indicates the system's wastewater treatment performance, was measured for Group 1. Group 1 is the only group equipped with PMFC technology and used for wastewater treatment. No direct comparison with the other groups was possible for this parameter. Appendix 4 shows the oxidation rate for each Group 1 sample over the measurement period. The results indicate generally low but measurable oxidation activity, with one clear peak observed on 15 May reaching 9.90086E-10 mol e^-/s. The peak on 15 May was associated with higher current production on that day, and its exact causes are explained in the following section about energy generation performance.

As shown in Figure 38, the oxidation rate decreased with increasing substrate COD.

Figure 38: Average oxidation rate of Group 1 and associated wastewater concentration in the provided substrate.



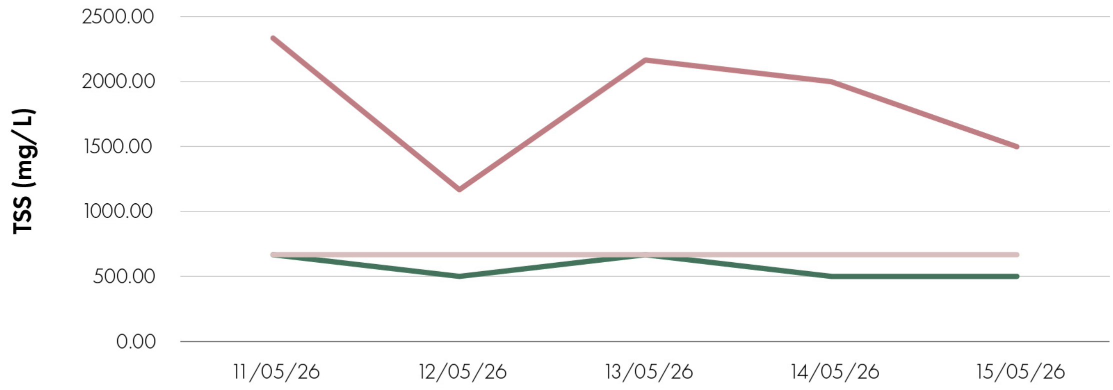
	08/05/26	09/05/26	10/05/26	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26	16/05/26
Wastewater Concentration in Substrate	66.67	83.33	83.33	100	100	100	100	100	100
Average Oxidation Rate	2.03E-10	3.71E-10	-1.58E-11	-8.95E-11	1.00E-10	5.53E-11	-1.90E-10	5.48E-10	1.21E-10

	17/05/26	18/05/26	19/05/26	20/05/26	21/05/26	22/05/26	23/05/26	24/05/26	25/05/26
Wastewater Concentration in Substrate	100	100	100	100	100	100	100	100	100
Average Oxidation Rate	-1.40E-10	-8.95E-11	-6.06E-11	-3.00E-10	-9.74E-11	-1.45E-10	2.37E-11	-2.66E-10	1.18E-10

5.1.2 Total Suspended Solids Removal Rate

As shown in Figure 39, Group 1 had less suspended solids than Group 3. Additionally, there were fewer suspended solids in Group 1 than in the provided substrate. Appendix 5 shows detailed measurements of TSS for Groups 1 and 3.

Figure 39: Average Total Suspended Solids of Groups 1 and 3.



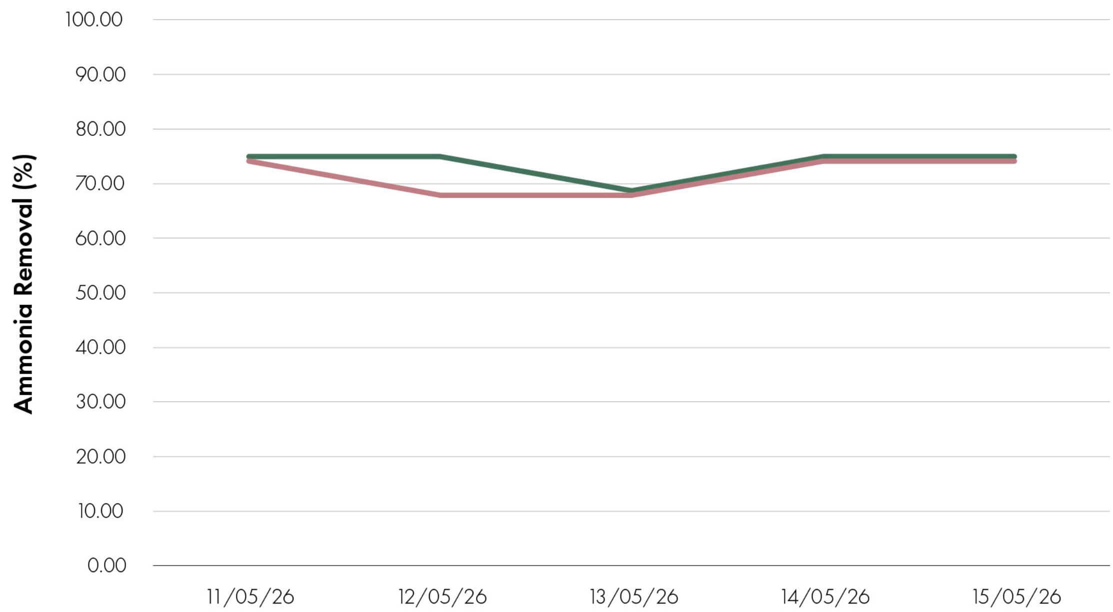
	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26
Group 1	666.67	500.00	666.67	500.00	500.00
Group 3	2333.33	1166.67	2166.67	2000.00	1500.00
Substrate	666.67	666.67	666.67	666.67	666.67

5.1.3 Nutrient Removal Rate

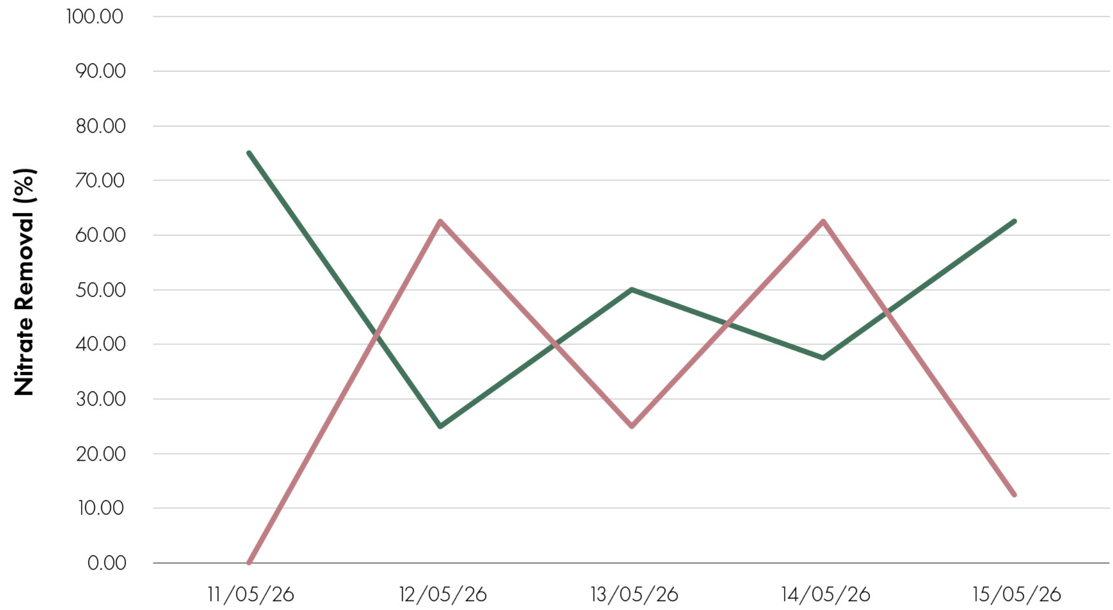
Group 1 exhibited good ammonia, nitrate and phosphorus removal rates, but nitrite removal was limited. Group 3 exhibited good ammonia and nitrate removal rates, but nitrite and phosphorus removal were limited. Of all the evaluated chemical nutrients, both groups performed best at removing ammonia. Group 1 showed increased phosphorus removal over time, but no trend was observed for the other nutrients.

The average removal rates of ammonia, nitrate, nitrite, and phosphorus for Groups 1 and 3 are shown in Figures 40, 41, 42, and 43, respectively. More detailed measurements for each sample are shown in Appendix 6 for ammonia, Appendix 7 for nitrate, Appendix 8 for nitrite, and Appendix 9 for phosphorus.

Figure 40: Average ammonia removal rate of Groups 1 and 3.

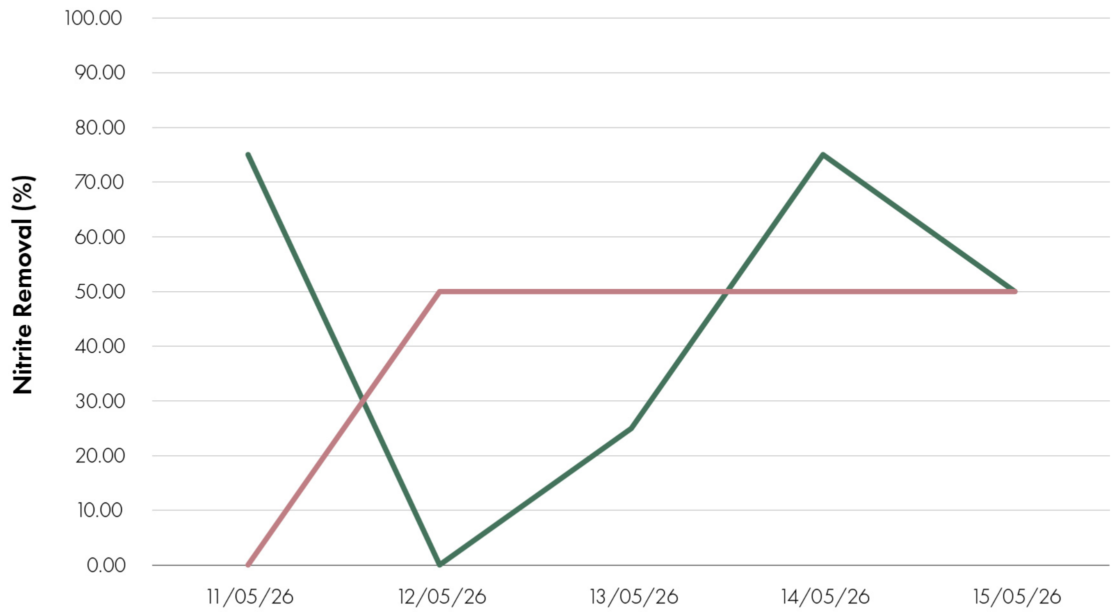


	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26
Group 1	75.00	75.00	68.75	75.00	75.00
Group 3	75.00	68.75	68.75	75.00	75.00



	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26
Group 1	75.00	25.00	50.00	37.50	62.50
Group 3	0.00	62.50	25.00	62.50	12.50

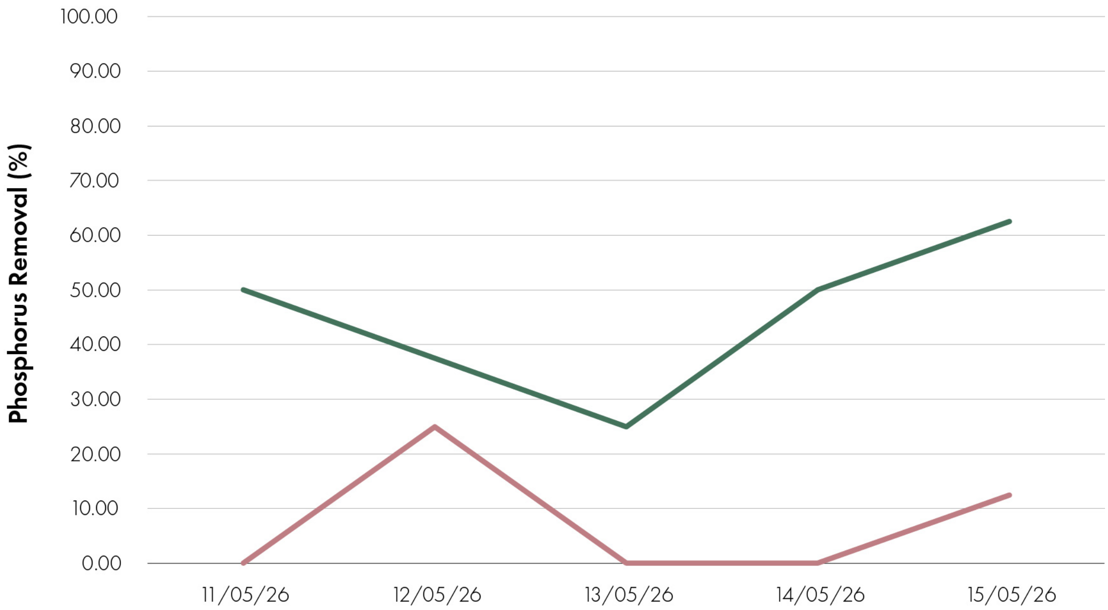
Figure 41:
Average nitrate removal rate of Groups 1 and 3.



	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26
Group 1	75.00	0.00	25.00	75.00	50.00
Group 3	0.00	50.00	50.00	50.00	50.00

Figure 42:
Average nitrite removal rate of Groups 1 and 3.

Figure 43: Average phosphorus removal rate of Groups 1 and 3.



	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26
Group 1	50.00	37.50	25.00	50.00	62.50
Group 3	0.00	25.00	0.00	0.00	12.50

5.2 Energy-generating Performance

5.2.1 Open Circuit Voltage Performance

During the first few days of the experiment, the open circuit voltage readings for both groups were steadily rising. Sudden drops in voltage were observed on 3/05/2026 and 6/05/2026. This was correlated to the watering schedule, which, for the initial two weeks, was watering the samples twice a week (Monday and Thursday at 5 pm) with 500 mL of substrate. After the first two weeks of the experiment, it was observed that on days without watering, the open-circuit voltage was lower than on days when samples were watered, and sometimes negative, as shown in Figure 44.

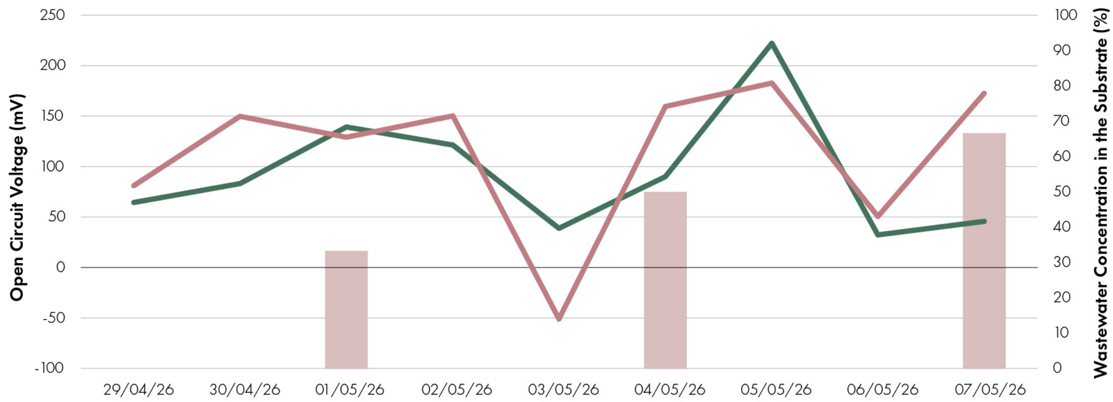
To avoid further negative voltage, the watering schedule was changed to daily watering at 1075 mL to maintain soil moisture and nutrient levels until the end of the experiment. Additionally, for Group 1, the open-circuit voltage reading began to drop as the concentration of wastewater in the provided substrate increased, as shown in Figure 45. The average voltage of Group 1 was lower than that of Group 2 as more wastewater was introduced into the substrate.

First, the multimeter readings weren't steady, but their stability gradually improved, and it was possible to read the final number more quickly without the multimeter's readings jumping from one number to another. Detailed results of Open Circuit measurements are included in Appendix 10. After 2 weeks, on the 8th of May, as the reading stabilised (and thus the microbiome), the circuit was closed using a 1000 Ω resistor.

Figure 44: Comparison of average open circuit voltage measurements and watering schedule at the initial stage of the experiment.

	29/04/26	30/04/26	01/05/26	02/05/26	03/05/26	04/05/26	05/05/26	06/05/26	07/05/26
Watering Volume	0.5	0	0.5	0	0	0.5	0	0	1
Group 1	64.5	83.25	139.5	121.25	39	90.25	222.25	32.5	45.75
Group 2	81.25	149.75	129	150.25	-50.75	159.75	182.75	50.75	172.5

Figure 45: Comparison of average open circuit voltage measurements and concentration of synthetic wastewater in the provided substrate at the initial stage of the experiment.



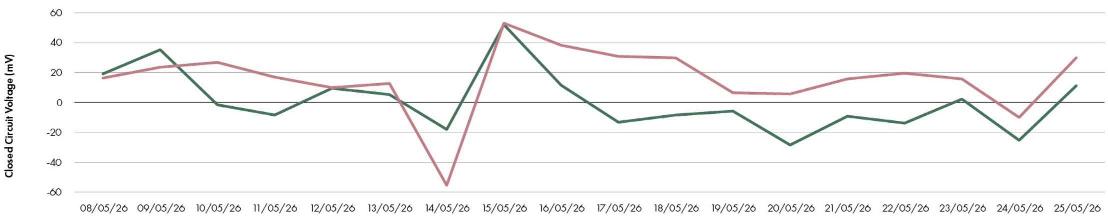
	29/04/26	30/04/26	01/05/26	02/05/26	03/05/26	04/05/26	05/05/26	06/05/26	07/05/26
Wastewater Concentration in Substrate	0	0	33.33	0	0	50	0	0	66.67
Group 1	64.5	83.25	139.5	121.25	39	90.25	222.25	32.5	45.75
Group 2	81.25	149.75	129	150.25	-50.75	159.75	182.75	50.75	172.5

5.2.2 Closed Circuit Voltage Performance

During CCV measurements, samples from both groups showed a steady rise in voltage output from the 8th to the 10th of May, and neither group performed visibly better. After the 10th of May, both groups' readings dropped, with visibly lower averages on the 14th and 15th of May. Sample 8 showed negative voltage readings from the start of the CCV measurement, possibly due to the soil's lower compactness and the presence of oxygen near the anode electrode at the start of the experiment. Samples from Group 1 experienced a larger drop in voltage values starting on the 11th of May, which was also the first day these samples received the full concentration of wastewater in the substrate. On May 15th, the wires in all samples were pushed deeper into the soil to better contact the parts of the anode electrodes that are in contact with the oxygen-less zone of the soil. Originally, the wire ends were not touching the bottom of the anode electrode. This caused both groups to match the average voltage measurements on that day. The readings started to drop again on the 17th of May, with Group 1 showing lower readings than Group 2. After the wire adjustments, the voltages of individual samples were no longer as steady, and each sample showed variable values, both positive and negative and no trend was possible to spot.

To limit surface evaporation, a new watering method was applied from the 20th of May onward. Instead of 4 waterings per day at 270 mL each, self-watering inserts with a total capacity of 500 mL were placed near the soil surface to maintain consistent soil moisture and substrate flow throughout the day. They were refilled once a day to reach 1075 mL of substrate per sample. After the introduction of self-watering inserts, the closed circuit voltage began to rise slowly for both groups at a similar rate.

The average closed circuit voltage for each group is shown in Figure 46, and the CCV measurements for each sample are presented in Appendix 11.



	08/05/26	09/05/26	10/05/26	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26	16/05/26	17/05/26	18/05/26	19/05/26	20/05/26	21/05/26	22/05/26	23/05/26	24/05/26	25/05/26
Group 1	19.25	35.25	-1.5	-8.5	9.5	5.25	-18	52	11.5	-13.25	-8.5	-5.75	-28.5	-9.25	-13.75	2.25	-25.25	11.25
Group 2	16.25	23.5	26.75	17	10	12.75	-55.5	53	38.25	30.75	29.75	6.5	5.75	15.75	19.5	15.75	-10	30

Figure 46: Average closed circuit voltage measurements for Groups 1 and 2 of the experiment.

As mentioned in the System Evaluation chapter, the current, current density, power, and power density were calculated based on the measured closed-circuit voltage. The actual resistance of the resistor was measured to be 984 Ω due to manufacturing inaccuracies, and this value was used in the calculations. Due to the same reactor design, the trends for each parameter are the same as those for the voltage readings. The maximum values of measured voltage, current, current density, power and power density are shown in Table 14.

The calculated current is shown in Appendix 11, the current density in Appendix 13, the power in Appendix 14, and the power density in Appendix 15.

Table 14: Maximum measured values of voltage, current, current density, power and power density for Groups 1 and 2 of the experiment.

	Group 1	**Group 2**
Voltage (mV)	94	93
Current (mA)	0.0955	0.0945
Current density (mA/m^2)	14.6967	14.5403
Power (mW)	8.9797	8.7896
Power density (mW/m^2)	1.2948	1.2674

5.3 Plant Growth

No yellowing or leaf drop was observed during the experiment. After the first week of the experiment, pest-related issues were detected. Thrips were seen on Sample 11, so all the samples were treated with a natural insecticide. The insecticide was used only on the foliage, avoiding spraying it on the soil to not affect the microbes. After the treatment, no more pests were seen. The infestation didn't affect the plants' growth. Table 15 lists the number of leaves of each sample at the two stages of the experiment.

Table 15: Comparison of leaf growth of Groups 1, 2 and 3.

		Number of leaves at the beginning of the experiment	Number of leaves at the end of the experiment	Growth
Group 1	Sample 1	13	20	7
	Sample 2	11	19	8
	Sample 3	13	22	9
	Sample 4	14	21	7
	Average	12.75	20.5	7.75
Group 1	Sample 5	11	17	6
	Sample 6	12	20	8
	Sample 7	12	21	9
	Sample 8	12	20	8
	Average	11.75	19.5	7.75
Group 1	Sample 9	10	17	7
	Sample 10	11	17	6
	Sample 11	12	21	10
	Sample 12	11	17	6
	Average	11	18.25	7.25

The average growth rates of Groups 1 and 2 were the same, at 7.75 leaves per sample over the course of the experiment. Group 3 had a smaller growth rate of 7.25 leaves per sample. Additionally, substantial root growth was observed. When the reactors were assembled, all the roots were placed around the PMFC reactor, and none were visible through the clear pots. After 3 weeks, roots began to grow near the pots' walls. The most visible root growth was observed in Group 2, as shown in Figure 47.

Figure 47: Growth of Sample 6.

24/05/2026 **25/05/2026**

6. Discussion

6.1 Interpretation of the Experiment's Results

6.1.1 Influence of Plant Microbial Fuel Cell Technology on Wastewater Treatment Efficiency

> ***Observation 1:***
>
> *As the COD content in the substrate increased, the oxidation rate of Group 1 decreased.*

Osmotic shock is the sudden damage or stress a microbe experiences when its environment changes concentration rapidly.

Based on the results for experimental Group 1, the bacteria likely experienced osmotic shock due to the high COD and chemical nutrient content in the provided substrate. This shifted their performance from oxidising nutrients to protecting themselves from stress, leading to an immediate decline in the overall wastewater treatment efficiency.

> ***Observation 2:***
>
> *Group 1 exhibited up to 100% TSS removal while Group 3 showed limited or no TSS removal.*

The literature indicates that configurations incorporating PMFC technology generally achieve improved TSS removal, as observed also in this study. This enhanced performance can be attributed to the presence of a more developed microbial community, which captures suspended solids in addition to the physical filtration provided by the growing medium. Group 1 demonstrated the highest performance, achieving up to 100% TSS removal, whereas Group 3 showed no measurable removal. The presence of additional solids in Group 3 is likely due to soil washout, possibly influenced by differences in growing medium composition, since Group 3 did not include lakebed soil.

> ***Observation 3:***
>
> *Group 1 demonstrated higher nutrient removal performance compared to Group 3.*

The improved nutrient removal observed in Group 1 compared to Group 3 can likely be attributed to higher nutrient uptake associated with increased plant growth rates in that group. Plants prefer ammonia as a direct nitrogen source because it requires less metabolic energy to assimilate, which may be why this nutrient was removed most in both groups. In addition, nutrient removal performance reflects the development and composition of the microbial community within Group 1. As with TSS removal, the PMFC environment supports a more active and diverse microbial community, which enhances nutrient removal rates.

6.1.2 Substrate Influence on Energy-generating Performance

> ***Observation 4:***
>
> *Group 1, fed with a high COD content substrate, experienced lower voltage readings than Group 2, fed with a low COD content substrate.*

The energy-generating potential of the PMFC is directly connected to the health of the microbes (Apollon et al., 2022). As mentioned in the preceding section, the osmotic shock experienced by the samples from Group 1 negatively affected their energy performance. This is supported by the performance results of Group 2, which was supplied with a substrate with lower COD and nutrient content and thus performed better in terms of energy generation. Unfortunately, both groups periodically experienced negative voltage readings, but the one fed with tap water had better results.

> ***Observation 5:***
>
> *As watering frequency and associated soil moisture increased, the open circuit voltage readings improved.*

The initial occurrence of the reversed voltage on the 3rd of May was attributed to low soil moisture due to insufficient watering frequency, as both groups were at that time watered with substrates of low COD and nutrient content. The second drop in readings on the 11th of May was attributed to oxygen intrusion into the anode chamber. As the samples were being watered, the soil compacted, exposing more of the PMFC reactors and causing more of the anode electrode surface to contact the oxygen-saturated zone of the soil. This way, even small surface moisture evaporation caused the oxygen levels in the soil to shift, exposing a larger area of the anode electrode to oxygen intrusion. After the wires in all samples were pushed down deeper in the soil, the readings improved for a few days. This proves that the oxygen-less zone shifted deeper into the soil.

6.1.3 Plant Microbial Fuel Cell Technology Influence on Plant Growth

The growth of plants within a PMFC is heavily dependent on the composition and richness of the feeding substrate, which must provide essential nutrients to support both the plant and the electrogenic microbes. The integration of PMFC technology with various feeding substrates has been shown not only to sustain but also to often enhance plant growth and development. The electricity collection process has no negative impact on plant development and is inherently non-destructive to the source (Apollon et al., 2022).

> ***Observation 6:***
>
> *Plants from samples containing PMFC technology grew more leaves than plants from samples without the PMFC technology.*

In many experimental configurations, plants in PMFC setups have outperformed control plants grown without an electrical circuit in terms of growth (Palmero & Pamintuan, 2023). This growth enhancement is largely attributed to the electrostimulation of plants by electrogenic bacteria in PMFC technology. The electric field generated within the plant boosts its nutrient uptake, allowing it to grow quicker. This process has been linked to significant increases in average daily leaf growth, plant height, and root dry mass compared with control plants receiving the same substrate. In this experiment, plants in Group 1 (with PMFC

> ***Observation 7:***
>
> *Group 2 with PMFC technology, watered with a low COD substrate, experienced the most substantial root growth.*

technology) grew faster than those in Group 3 (without PMFC technology), even though both groups were supplied with the same type and amount of substrate, consistent with the results of other experiments. On average, at the end of this experiment, Group 1 grew 0.5 more leaves than Group 3, which is about 6.9% faster than Group 2.

Regarding the influence of the substrate fed to PMFCs, wastewater generally outperforms tap water in promoting growth (Nair & Sreedharan, 2023). In such setups, wastewater serves as fertiliser, helping plants reach maturity and promote growth of leaves, stems and roots. However, the specific composition of the substrate is important, as excessive organic nutrient loads can suppress plant health (Regmi et al., 2018). While moderate levels of COD in wastewater fuel growth, very high concentrations can cause osmotic shock, lead ing to leaf yellowing, stunting, and a reduction in the number of living stems. While this wasn't evident in the leaf growth of the tested samples, the influence of the substrate COD content was visible in the root growth. Group 2, fed with a low COD substrate, exhibited more robust roots, which supports the conclusion that Group 1 was experiencing osmotic shock.

6.1.4 Comparison with Similar Experiments

The experiment in this thesis was compared with experiments reported in the literature that use PMFC set-ups to treat domestic or municipal wastewater to position its performance in terms of wastewater treatment efficiency and energy generation. These experiments and their associated performance were compared in Table 16. This study's experiment showed that the proposed reactor design for PMFC Integrated Façade Living Wall system performs competitively in terms of wastewater treatment, while its energy generation remains within the lower range of values reported for comparable experiments. In the wastewater treatment assessment, the reactors achieved clear reductions in total suspended solids and nutrients, which indicates that this design can effectively improve effluent quality. In terms of energy generation, the measured voltage and derived power output confirm that electricity production was successfully established, but the performance remained limited compared with other experiments. The results of this study, therefore, suggest that the main strength of the proposed system lies in wastewater treatment rather than in electricity production. Nevertheless, the fact that measurable electricity was generated while treatment was taking place is important because it confirms the multifunctional potential of the system. Compared with similar experiments, this study positions the PMFC Integrated Façade Living Wall System as a promising wastewater treatment strategy with supplementary energy-generating capacity.

Table 16: Comparison of performance parameters of this and comparable PMFC experiments.

Reference	Regmi et al. (2018)	Golzarian et al. (2022)	Nair and Sreedharan (2023)	Du et al. (2025)	Rajpurohit & Behera (2025)	This study
MFC Setup	Double-chamber, soil-based PMFC with vetiver grass	Dual-chamber CW-MFC with Cyperus papyrus	Single-chamber, soil-based PMFC with Amaranthus	Single-chamber CW-MFC with Acorus calamus	Dual-chamber CW-MFC with Epipremnum aureum	Dual-chamber soil-based PMFC with Epipremnum aureum
Components' Materials	Steel mesh anode electrode, graphite fiber cathode electrode, earthen pot PEM	Graphite plate electrode, PTFE PEM	Carbon cloth electrodes	Stainless-steel mesh anode and cathode electrodes	Stainless steel wire anode electrode, carbon felt cathode electrode, ceramic PEM	Graphite felt anode and cathode electrodes, terracotta PEM
Used Substrate	Synthetic wastewater (COD of 250 mg/L)	Municipal wastewater (COD of 1323 mg/L)	Synthetic domestic wastewater (COD: 3760 mg/L)	Synthetic domestic wastewater (COD of 321.71 ± 4.54 mg/L)	Synthetic domestic wastewater (COD of 200–800 mg/L)	Synthetic domestic greywater (COD of 1210 ± 35.2 mg/L)
Environment	Temperature: Humidity:	Temperature: Humidity:	Temperature: Humidity:	Temperature: Humidity:	Temperature: Humidity:	Temperature: 23.6 Humidity: 64.6 %
HRT	2 days	5 days	-	3 days	12–24 hours	2 days
Closed Circuit Voltage (mV)	800	-	260	503	-	94
Current (mA)	11.95	-	2.58	0.50	8.67	0.096
Power (mW)	-	240	670.8	251.5	-	8.98
Power Density (mW/m²)	68	-	-	-	63.45	1.3
Power Density (mW/m³)	-	-	-	1.05	-	0.57
Peak COD Removal (%)	99.0	61.75	40.0	97.2	94.0	-
Peak Oxidation Rate (mol e^-/s) calculated from current	1.23853E-07	Approx. 2.64023E-08	2.6771E-08	5.21325E-09	8.98585E-08	9.90086E-10
TSSRemoval (%)	-	-	54.7	-	-	100
Peak Ammonia Removal (%)	-	-	-	94.3	81.5	75
Peak Nitrate Removal (%)	-	-	59.3	-	56.9	100
Peak Total Nitrogen Removal (%)	95.3	-	-	90.0	72.9	-
Peak Phosphorus Removal (%)	95.3	-	32.2	74.7	66.0	50

6.1.5 Limitations

This study's experiment has several limitations that must be considered when interpreting the results. The experiment was conducted at a small prototype scale with only four samples per group, which limits the statistical robustness of the findings and makes the results sensitive to variation between individual plants and microbial communities. The total evaluation period was relatively short. Although the experiment ran for 32 days, the first two weeks were primarily dedicated to microbiome stabilisation, which limited the period of fully operational performance. Given that PMFCs are biological systems whose electrochemical behaviour can continue to change over longer periods, the measured treatment and energy-generation efficiencies may not represent the long-term steady-state performance of the proposed system.

Additionally, the experiment was conducted under non-laboratory conditions, which usually provide more controlled and favourable environmental conditions. These conditions differ substantially from the intended façade application in a tropical outdoor climate, where higher temperature, humidity, rainfall and solar exposure would likely influence both plant growth and microbial activity. As a result, the outcomes provide useful proof of concept, but they cannot be directly translated to real building-scale operation.

Another limitation is the use of synthetic wastewater rather than real household greywater. Although the selected recipe provided a practical substrate, it could not fully represent the variability, complexity and fluctuations in composition that occur in real wastewater streams. In addition, some wastewater characteristics could only be estimated or approximated, introducing uncertainty in the interpretation of treatment performance. This is particularly relevant for organic matter removal, because direct COD measurements were not possible, and oxidation rate had to be used as a proxy instead. Likewise, nutrient measurements were carried out using aquarium test strips, which are suitable for indicative comparisons but offer lower precision than laboratory analysis.

While using a fixed external resistance of 1000 Ω provides a consistent baseline for performance monitoring, it does not capture the maximum power density achievable by the PMFC system. Peak power output in bioelectrochemical systems occurs when external resistance matches the internal resistance of the PMFC. PMFC's internal resistance is highly dynamic, constantly changing with soil moisture, root activity, and bacterial growth. As a result, a fixed 1000 Ω resistor is likely to cause suboptimal operating conditions, constraining the PMFC below its full capacity. While the calculated power density accurately represents performance under this specific resistor, it must be viewed as a single operational data point rather than the maximum capability of the PMFC.

Finally, the reactor design itself was preselected from the literature, which means that the experiment did not evaluate alternative reactor geometries, materials, or configurations, including vegetation. While domestic wastewater can support plant growth in general, plant survival is species-dependent, with some plants showing high resistance to environmental stressors, whereas others require more precisely managed substrate conditions to thrive (Ballestas et al., 2023). For this reason, the fact that this study tested only one plant species limits the results to that species, and similar experiments should be conducted on other species recommended for this design.

6.1.6 Future Recommendations

The results of this experiment indicated the importance of appropriate reactor design and acclimatisation to prevent voltage reversal and osmotic shock. The reactor design should be revised to prevent oxygen from entering the anode chamber. This could be done by either placing the terracotta cones deeper in the soil or using a different proton exchange membrane design. The new design can have a similar shape but should allow for deeper electrode placement and more permanent wire attachment.

To provide a full performance evaluation, future experiments should be conducted over a longer period to capture the long-term behaviour of the microbial community, the stability of wastewater treatment performance, and the development of electricity generation under more mature conditions. Additionally, a longer acclimatisation period of the reactors is recommended to avoid osmotic shock of the microbes. Future studies should test the system under outdoor conditions and in the Singapore climate. Testing in real façade conditions would provide more representative insights into the influence of real wastewater and climate on both wastewater treatment and energy generation. The present study demonstrated proof of concept at the reactor level, but the next step is to evaluate the performance of a full module under conditions that more closely reflect the intended application in HDB housing in Singapore.

6.2 Practical Application of the Evaluated Plant Microbial Fuel Cell Integrated Façade Living Wall System in HDB Housing in Singapore

6.2.1 Wastewater Treatment Efficiency

As measured in this experiment, one proposed PMFC reactor can effectively treat 1075 mL of greywater per day. One module can then treat 6.45 L. This means that for one square meter of the designed living wall, 21.5 Liters of greywater can be treated daily. In Singapore, by 2030, each person's water consumption will be limited to 130 litres per day (PUB, 2022). Water from washing and laundry accounts for about 20% of the total usable greywater volume, and water from baths, showers, and washbasins accounts for approximately 40% (PUB, 2014). This means that, on average, one Singaporean produces 95 L of greywater daily. To treat one person's greywater production, 4.41 m^2 of the PMFC Integrated Façade Living Wall System is needed, which translates to 15 modules.

In HDB housing, the typical floor height is 2.8 m (Housing & Development Board, 2014). If there are no windows on the façade, four rows of modules can be placed per floor, and on facades with windows, two rows of modules can fit per floor. HDB housing typologies can be divided into slab-block and point-block. As mentioned before, the most beneficial placement of the PMFC Integrated Façade Living Wall is on the east façade. Given that the living wall will be installed on only that one façade, the number of modules per floor may vary depending on the typology and its orientation to the sun, as shown in Figure 48.

Figure 48: Typical floors of HDB point-block and slab-block from Kosorić et al. (2019) with the number of Living Wall modules that can be placed on each façade indicated.

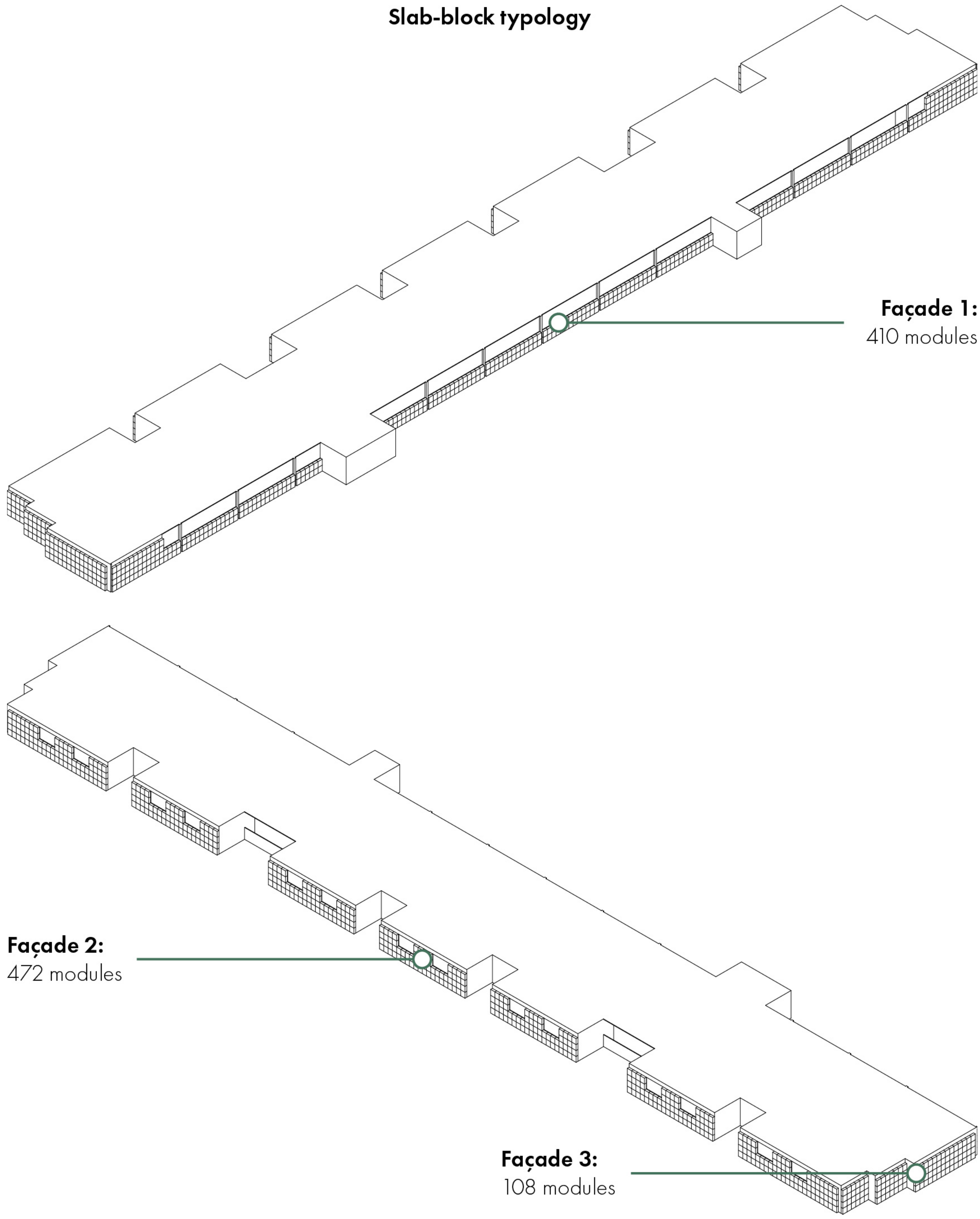
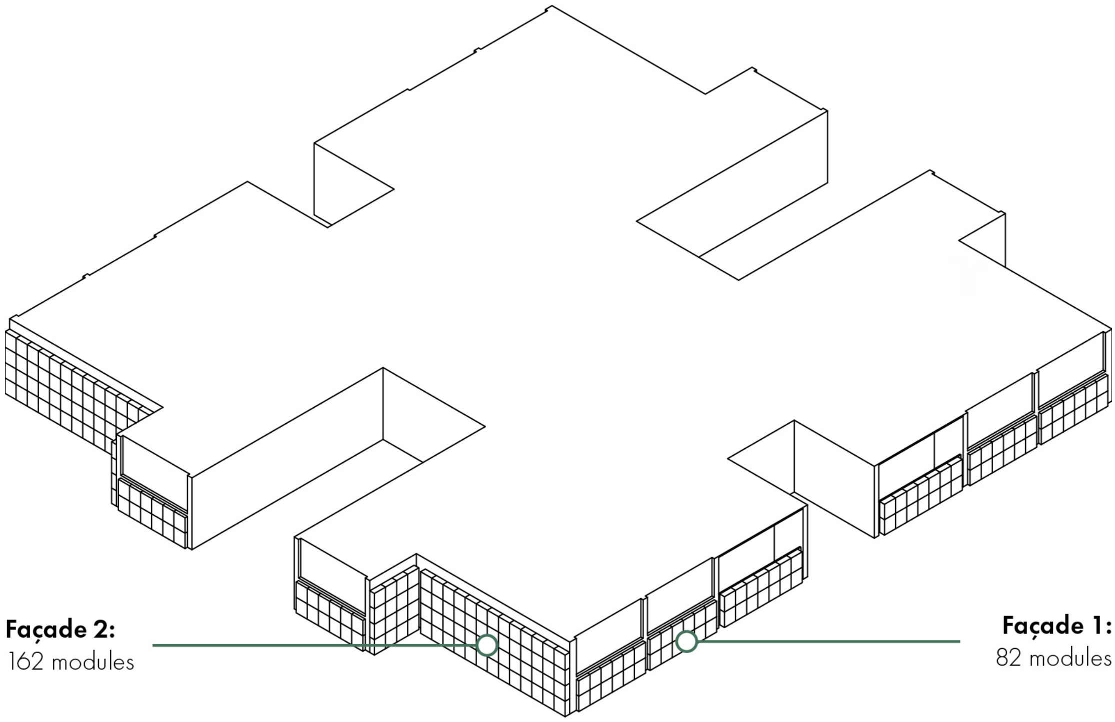


Figure 48: Typical floors of HDB point-block and slab-block from Kosorić et al. (2019) with the number of Living Wall modules that can be placed on each façade indicated.



For each façade, a different greywater treatment efficiency, in terms of the amount of greywater treated, can be achieved, as shown in Table 17. According to statistics, as of 2024, 3,190,590 people live in 1,153,080 housing units in Singaporean HDB estates, averaging 3 people per unit. For a slab-block typology, there are 14 units per floor, which gives an average of 42 people per floor, generating around 3990 L of greywater daily. For the point-block typology, there are 4 units per floor and around 12 people that generate 1140 L of greywater daily. This average daily greywater production per floor is compared with the amount of greywater that can be treated by the designed living wall installed on each HDB block façade per floor, as shown in Table 17. It is evident that, for both typologies, living wall modules on a single façade are insufficient to treat all the greywater produced. To facilitate full treatment, the designed system has to be installed on at least two parallel facades for the slab-block typology and on two neighbouring facades for the point-block typology.

The east orientation is the most beneficial, but the placement of the designed system is not limited to only that one façade. On other facades, the system may not be performing as efficiently as on the east façade. On the north and south facades, the system's sun exposure and moisture evaporation are limited, so these facades may require less substrate, meaning they can treat less greywater per day. On the west façade, there is a risk of soil drying out more quickly, and thus microbial performance may be lower due to worse environmental conditions.

Table 17: Efficiency of greywater treatment for different façades of HDB housing blocks.

Façade	Number of PMFC Integrated Living Wall modules on each façade	Amount of greywater treated daily by the modules	Average number of greywater produced per floor per day	Can the modules treat all daily greywater production?
Slab-block				
1	410	2622.5 L	3990 L	No
2	472	3044.4 L	3990 L	No
3	108	696.6 L	3990 L	No
1 + 3	518	3341.1 L	3990 L	No
2 + 3	580	3741 L	3990 L	No
1 + 2	882	5688.9 L	3990 L	Yes
Point-block				
1	82	528.9 L	1140 L	No
2	162	1044.9 L	1140 L	No
1 + 2	244	1573.8 L	1140 L	Yes

6.2.2 Energy Generation Performance

One module of the façade can generate 53.88 mW (6 reactors at 8.98 mW each), which translates to 179.6 mW per square meter of the façade. To function efficiently, the system requires various sensors and a pump; the power consumption of these devices is listed in Table 18.

Device	Power use
Voltage sensor	10 mW
Moisture sensor	15.6 mW
Data acquisition microcontroller	200 mW
Flow meter	5 mW
Weather station	Self-powered by a built-in solar panel
Pump	1000 W (1,000,000 mW)

Table 18: Power consumption of the designed PMFC Integrated Façade Living Wall System devices.

As explained in the "Building Adaptation Measures" section, these components do not operate continuously. As a result, their energy consumption occurs in short pulses rather than as a constant load, which significantly reduces their overall energy demand. In addition, the energy demand of the listed components is directly linked to the size and configuration of the designed living wall. Table 19 shows the number of sensors and their total power demand depending on the HDB housing block typology and the façade where the PMFC Integrated Façade Living Wall is applied. The majority of HDB housing estates are 10-13 stories high, and thus, 11 floors per building were used in this analysis. Regardless of the wall placement, one pump per building is required. Weather stations were excluded from Table 19 as they are self-powered.

As shown in Table 19, neither of the facades in the slab block and point block typologies can power the pump. On the other hand, all except one façade can power all sensors simultaneously and even have a surplus of generated power. This surplus can power the LED lights in the PMFC containers, which draw between 4000 and 6000 mW.

Although the calculated peak power of 179.6 mW per square meter of the façade provides a useful reference for the PMFC living wall's energy-generating potential, this value is not fully representative of the system's overall performance in practical operation. The reported value corresponds to a short-term peak condition measured under specific experimental circumstances. In addition, the experimental setup represents a single prototype configuration operating independently, whereas a full-scale PMFC living wall would function as a modular array of interconnected units. In such arrays, electrical losses due to wiring, internal resistance, power conditioning and energy storage are inevitable and would further reduce the net usable power at the system level. That said, PMFC reactors reported in the literature exhibit higher power, which suggests that if the recommended reactor alterations from the preceding section of this report are implemented, the overall performance of the system can be further improved.

Table 19: Efficiency of energy generation for different façades of HDB housing blocks.

Façade		Voltage sensors	Moisture sensors	Data acquisition micro-controller	Flow meter	Total demand	Total production	Surplus
Slab-block								
1	Number of sensors	33	110	3	6	2676	22090.8	19414.8
	Total power demand (mW)	330	1716	600	30			
2	Number of sensors	77	616	7	14	11849.6	25431.36	13581.76
	Total power demand (mW)	770	9609.6	1400	70			
3	Number of sensors	33	132	3	6	3019.2	5819.04	2799.84
	Total power demand (mW)	330	2059.2	600	30			
1 + 2	Number of sensors	66	232	6	12	5539.2	27909.84	22370.64
	Total power demand (mW)	660	3619.2	1200	60			
1 + 3	Number of sensors	110	726	10	20	14525.6	47522.16	32996.56
	Total power demand (mW)	1100	11325.6	2000	100			
Point-block								
1	Number of sensors	66	220	6	12	5352	4418.16	-933.84
	Total power demand (mW)	660	3432	1200	60			
2	Number of sensors	22	44	2	4	1326.4	8728.56	7402.16
	Total power demand (mW)	220	686.4	400	20			
1 + 2	Number of sensors	88	264	8	16	6678.4	12715.68	6037.28
	Total power demand (mW)	880	4118.4	1600	80			

7. Conclusion

The PMFC Integrated Façade Living Wall System developed in this study can be considered a regenerative system, as it transforms the building envelope from a static, passive barrier into an active ecosystem that restores and revitalises its surroundings. As explored in the preceding chapters, the system does not only aim to reduce wastewater generation or improve façade performance, but instead combines multiple processes, biological treatment, plant growth and electrochemical energy generation, within a single architectural element. This integration reflects a shift from mono-functional design towards multi-functional, process-based systems that more closely resemble natural ecosystems.

One of the core principles of regenerative design is a place-based design approach, which emphasises context and understanding of local environmental conditions, resource flows, and spatial constraints (Craft et al., 2017). Although the experimental work on the PMFC Integrated Façade Living Wall System was conducted under controlled indoor conditions, the system was conceptually developed for application in Singapore's tropical urban context. The system operates within existing building envelopes and engages with locally available greywater streams, suggesting an alignment between building operation and environmental processes. It responds to locally relevant challenges such as limited space for infrastructure and the need for decentralised water treatment.

A second strategy of regenerative design concerns the integration of the functional principles of natural systems (Hecht et al., 2024). This includes providing habitat, integrating living systems, increasing autotrophic biomass, maximising multifunctionality and developing reversible processes. The proposed system design reflects several of these principles by incorporating plants and microbial communities that actively participate in wastewater treatment and energy generation. The system introduces feedback loops that resemble those found in natural ecosystems. It provides physical space for biological processes, while plants and microbes act as active agents rather than passive elements. Through the combination of wastewater treatment, biomass production and energy recovery, the design demonstrates a degree of multifunctionality.

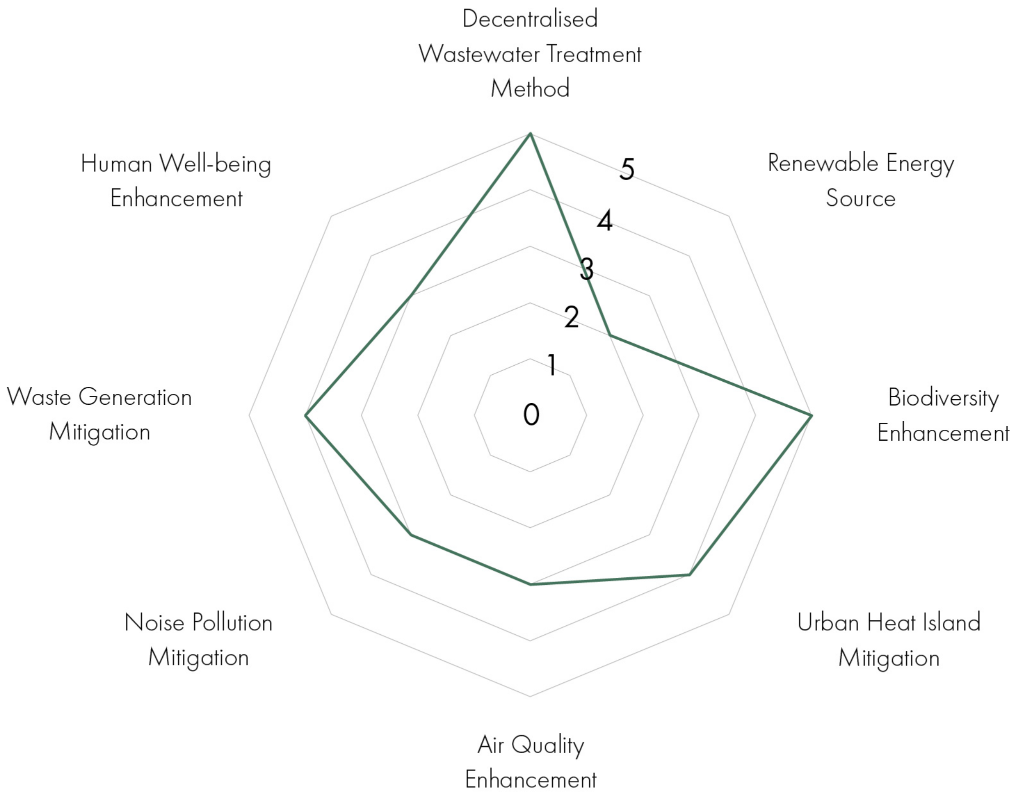
A third regenerative strategy concerns structural and material effectiveness, framing buildings as material systems designed for long-term adaptability and circular use (Craft et al., 2017). In this study, the design addresses reversibility and modularity by introducing shearing layers that organise the system into separable functional components. This enables individual layers to be accessed, maintained or replaced independently, supporting long-term adaptability and reducing the need for complete system replacement. The use of prefabricated, replicable reactor units suggests potential for scalable and adaptable configurations. Additionally, by using natural biological processes, the need for toxic chemicals in wastewater treatment can be limited.

A fourth strategy focuses on net-positive resource management, which aims to move beyond resource efficiency towards the generation and regeneration of resources (Attia, 2018). The PMFC Integrated Façade Living Wall system contributes to this strategy primarily through on-site wastewater treatment and energy generation. In addition, the integration of vegetation contributes to microclimatic regulation and potential improvements in air quality. However, the energy generated by the PMFC remains relatively low compared to system demand, indicating that while the system contributes to resource recovery, it does not achieve net-positive performance across all resource streams.

A final strategy addresses human well-being and biophilia, emphasising the integration of natural elements into the built environment to support both ecological and social systems (Attia, 2018). The system indirectly supports occupant well-being and biophilic design by incorporating visible, living elements into the façade. Although this aspect was not directly measured in the study, the presence of plants and biological activity can contribute to improved environmental quality. It also fosters a stronger connection between inhabitants and natural processes, contributing to local biodiversity.

The following sections explain how the PMFC Integrated Façade Living Wall System fits within this regenerative paradigm and offer suggestions for design alterations to better align with it. As noted, this design addresses multiple domains simultaneously but at different levels, as shown in Figure 49.

Figure 49: Multifunctionality of the designed system.



7.1 Plant Microbial Fuel Cell Integrated Façade Living Wall System as a Decentralised Wastewater Treatment Method

The PMFC Integrated Façade Living Wall can be interpreted as a decentralised wastewater treatment method because it relocates part of the treatment process from a centralised plant to the building envelope itself. In doing so, it influences the circulation of water within the built environment by transforming typically linear flows into partially circular ones. Instead of greywater being immediately discharged into the sewer network, it is retained, treated and temporarily reused within the façade system to support plant growth and microbial activity. This local recirculation extends the functional lifespan of water within the building system and introduces an intermediate treatment stage prior to discharge. As a result, water is no longer treated solely as a waste stream, but as a resource that sustains biological processes before re-entering the urban water cycle.

Through this localised treatment, the system modifies the relationship between the building and centralised wastewater infrastructure. Rather than aiming to replace conventional wastewater treatment infrastructure, the system aligns more closely with decentralised pre-treatment or load-reduction strategies. By treating greywater locally before reuse, systems of this type could reduce hydraulic and pollutant loads on central networks, particularly in high-density urban environments where decentralised solutions are increasingly considered as part of integrated water management strategies. By shortening the distance between wastewater generation, treatment, and reuse, the system reduces transport-related losses and can lower dependence on large-scale conveyance infrastructure. It also aligns with broader resilience goals, since local treatment capacity can help buildings cope better with future pressure on water supply, energy demand, and urban resource scarcity.

In comparison to traditional wastewater treatment methods, the PMFC Integrated Façade Living Wall operates under significantly different conditions. Conventional treatment plants rely on controlled environments, high energy inputs, chemical dosing and mechanical processes to achieve consistent performance. The façade-integrated system, by contrast, relies primarily on gravity-driven flows, passive filtration through substrate, and biological processes associated with plants and microbial communities. This results in lower operational energy demand and reduced chemical input, as well as lower sludge production compared to conventional systems. In Singapore, wastewater conveyance is largely gravity-driven, meaning that most energy use occurs during treatment, estimated at approximately 0.6 kWh per cubic metre. At the building scale, this translates to an energy demand of approximately 26.3 kW for slab block typology used in this study and 7.5 kW for point blocks when treated centrally. The PMFC living wall reduces the need for energy-intensive treatment by partially processing greywater on site, while its own operational demand remains relatively low, with a maximum of approximately 1.1 kW per building when all system components are active.

As an on-site system, the façade-integrated approach offers spatial advantages in dense urban contexts. Unlike conventional decentralised treatment systems such as constructed wetlands or sequencing batch reactors, which require dedicated horizontal space, the living wall utilises vertical surfaces that are already part of the building. The living wall for-mat offers a relatively compact treatment surface, since vertical façade area can be used more efficiently than ground-based systems in dense city environments. When compared to conventional green walls used for greywater treatment, the addition of PMFC technology introduces an additional functional layer. Traditional systems rely primarily on passive filtration and plant uptake, whereas the PMFC integration enables electrochemical activity that generates small amounts of electricity. Although the energy output is limited, the presence of electroactive bacteria may enhance treatment processes.

Despite these advantages, the system is subject to several limitations. The most significant constraint is the inherent variability of microbial processes, which depend on environmental conditions, substrate availability and system stability. This unpredictability can lead to fluctuations in treatment performance and energy generation, making it difficult to guarantee consistent outcomes. Furthermore, residential greywater production is highly variable, with pronounced peaks in the morning and evening. Still, these systems are not universally simple to deploy. They can face operational instability, maintenance demands, regulatory barriers, and public acceptance issues, especially when water reuse is involved.

Within the Singapore context, the system aligns with ongoing efforts to enhance water resilience and promote decentralised resource management. Although Singapore has a highly advanced centralised system, including water reuse and NEWater production, the integration of building-scale treatment systems could contribute to diversifying water management strategies. The vertical configuration of the façade system is particularly compatible with the high-density residential typologies found in Singapore, such as HDB blocks. However, the implementation of such systems also reveals gaps in the current regulatory framework, particularly regarding maintenance responsibilities in multi-tenant buildings. Under the Environmental Public Health Act, responsibilities for sanitation are distributed between Town Councils, building management and individual residents, but do not explicitly address decentralised treatment systems integrated into façades. In the event of system failure the allocation of liability remains unclear, highlighting the need for updated regulations that account for building-integrated infrastructure.

7.2 Plant Microbial Fuel Cell Integrated Façade Living Wall System as a Renewable Energy Source

Conventional green wall systems already rely on electrically powered components, most notably pumps for irrigation. These systems are therefore not energy-neutral and typically depend entirely on external electricity supply. In this context, the integration of PMFC technology offers an additional benefit. While the wall's generated power is insufficient to fully offset the total energy demand of the system, it represents locally generated renewable energy that would otherwise not be present in a standard green wall installation. The PMFC Integrated Façade Living Wall therefore does not introduce new energy-consuming elements, but rather augments an already energy-dependent system with an embedded energy-producing function. Moreover, because irrigation pumps and monitoring systems in green walls generally operate intermittently rather than continuously, even relatively small amounts of locally generated electricity can contribute meaningfully to system operation when combined with appropriate energy storage or control strategies. In this sense, the

PMFC does not need to fully power the system to be beneficial. Instead, it can partially offset energy consumption, support low-power sensing or control functions, or reduce reliance on external electricity during specific operating periods. Compared to a conventional green wall, the PMFC-integrated design therefore offers multifunctional performance: wastewater treatment, façade greening and supplementary energy generation within the same spatial footprint. This added functionality strengthens the overall system concept, even if energy generation remains a secondary output rather than the primary function.

By integrating Plant Microbial Fuel Cells into the façade living wall, the designed system alters the building's energy flow from a predominantly unidirectional model toward a more circular one, where electricity is recovered directly from an existing internal resource stream and returned to building operation. In this sense, energy recovery is not introduced as an additional "production layer" that requires new external inputs (e.g., irradiation or wind exposure), but as a conversion of chemical energy already embedded in wastewater and plant–microbe metabolism into usable electrical current. The system therefore reframes part of the building's waste-handling process as an energy-yielding process, contributing to circularity by harvesting value from a stream that would otherwise be treated solely as a waste stream.

Within the global clean-energy matrix, bio-electrochemical generation can be positioned less as a high-yield renewable equivalent to solar or wind, and more as a carbon-neutral, low-intensity baseline source that complements intermittent renewables. The microbial energy is beneficial in terms of low dependence on local weather conditions and the ability to generate electricity continuously as long as an organic substrate is supplied, which supports relatively stable output throughout day–night cycles. In contrast, many building-integrated renewables are variable and dependent on time of day or meteorological conditions, often requiring storage and continued grid connection to meet demand. Bio-electrochemical electricity is also carbon-neutral because CO_2 released corresponds to carbon previously fixed through photosynthesis, and the process generally avoids toxic residues beyond CO_2.

On the other hand, PV and wind systems can achieve higher power densities than façade-integrated bioelectrochemical systems. They are also mature, scalable technologies with established performance models and well-developed maintenance regimes for installation. The designed system is also constrained by the start-up complexity in PMFC components. The most realistic application of the electricity produced by the designed system is therefore not to offset high-voltage household demand, but to support low-power functions, particularly monitoring and control devices that are already necessary for safe system operation, and potentially other small communal loads. This is consistent with the established model for Singapore's residential blocks, where rooftop photovoltaics are routed to supply common services. By the same logic, the PMFC Integrated Façade Living Wall's electrical output can be positioned as a dedicated offset to the communal estate's operational footprint rather than as a replacement for the primary household supply.

At the same time, both PV and wind depend on critical raw materials. Recycling pathways for PV and wind are advancing but remain a major systemic challenge because large-scale end-of-life flows are only now emerging globally, and material recovery depends on infrastructure, design-for-disassembly and economics. The PMFC Integrated Façade Living Wall does not avoid critical materials entirely. As with PV panels and wind turbines, electrochemical systems still rely on conductive materials, wiring, and power-conditioning electronics, but they deliver additional benefits that PV or wind do not inherently provide, namely, wastewater treatment and façade greening within the same spatial footprint.

7.3 Influence of Plant Microbial Fuel Cell Integrated Façade Living Wall System on Biodiversity

Contemporary high-rise urban envelopes, particularly in dense typologies such as Singapore's HDB housing, are largely defined by sealed, repetitive concrete surfaces that remain ecologically inert. While efficient from a construction and maintenance perspective, these façades contribute little to urban ecological networks and reinforce the fragmentation of habitats caused by urbanisation. The PMFC Integrated Façade Living Wall challenges this condition by transforming the envelope into a vertical micro-habitat. By combining vegetation, substrate, and continuous greywater flows, it creates stable ecological niches that can support biological activity. As previously identified for green walls, such systems can act as "stepping stones" that reconnect fragmented habitats across dense cities. Embedding biodiversity within the façade introduces ecosystem services at multiple scales. At the building level, insects and microorganisms contribute to pollination, decomposition, and nutrient cycling, supporting plant health and system stability. At the urban scale, distributed vertical habitats can facilitate species movement and enhance ecological connectivity. Insects or birds can influence urban ecosystems by regulating pests, and dispersing seeds, while microbial communities simultaneously underpin both ecological processes and wastewater treatment.

In Singapore, biodiversity is actively promoted through the "City in Nature" vision, which seeks to integrate ecological systems into the built environment without requiring additional land. The PMFC Integrated Façade Living Wall aligns with these conditions by embedding bird and insect enclosures in the design. Within this context, the system can host a range of species inhabiting tropical urban environments.

However, increasing biodiversity at the façade level introduces tensions with user acceptance. While greenery is widely appreciated, especially in Singapore, the proximity of wildlife to residential units can raise concerns about noise, droppings, and perceived pests. As a result, the integration of biodiversity must balance ecological performance with human comfort. Design strategies such as selective species choice, controlled placement of habitat elements, and regular maintenance become essential to mitigate conflict.

7.4 Influence of Plant Microbial Fuel Cell Integrated Façade Living Wall System on Urban Heat Island Effect

The Urban Heat Island effect in dense cities such as Singapore is largely driven by the thermal behaviour of conventional building materials. High-rise concrete façades absorb solar radiation during the day and release it slowly at night, contributing to elevated urban temperatures. The PMFC Integrated Façade Living Wall has the potential to mitigate UHI through three primary mechanisms. First, vegetation provides direct solar shading, reducing the amount of radiation absorbed by the façade. Second, evapotranspiration from plants and the water-saturated substrate actively cools the surrounding air. Third, the layered structure of the wall introduces additional thermal resistance, limiting heat transfer into the building. At the building scale, the influence of the system becomes measurable even with partial façade coverage. However, meaningful impact at the urban scale requires distributed implementation across multiple buildings, reflecting the collective nature of UHI mitigation.

In comparison to conventional green walls, the PMFC-integrated system offers enhanced cooling potential due to its continuously waterlogged condition. While standard systems rely on periodic irrigation, the PMFC Integrated Façade Living Wall ensures waterlogged conditions within the substrate. This sustained hydration supports more consistent evapotranspiration rates, reducing the risk of thermal performance decline during dry periods. As a result, the system can maintain its cooling effect more reliably over time and under varying climatic conditions. In addition to reducing external temperatures, the system acts as a thermal buffer that directly influences indoor conditions. Lowering heat gain through the façade reduces reliance on air-conditioning systems, which are a major contributor to anthropogenic heat release in Singapore's urban environment. Limiting the need for air-conditioning can also change the city's visual appearance, as shown in Figure 50. This creates a feedback loop in which reduced cooling demand lowers waste heat emissions, further limiting UHI intensity.

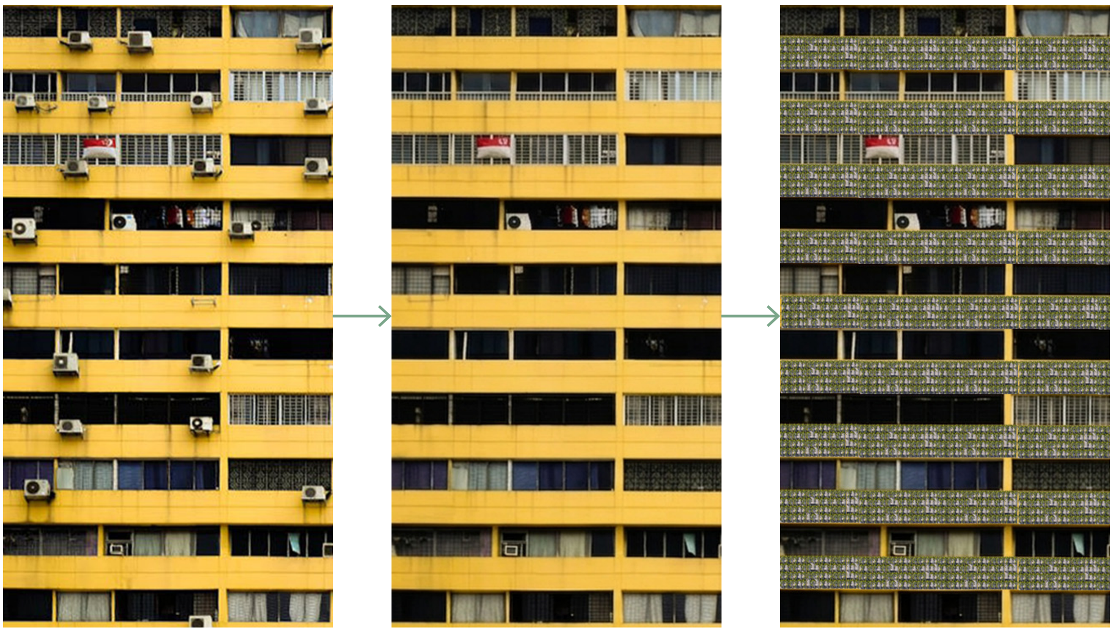


Figure 50: Visual changes to Singapore's city landscape if the PMFC Façade Living Wall System is applied. Adapted from Aadhithyan Pandian, 2023, Pexels (pexels.com).

7.5 Influence of Plant Microbial Fuel Cell Integrated Façade Living Wall System on Air Quality and Noise Pollution

The PMFC Integrated Façade Living Wall contributes to improved urban environmental quality by addressing two closely related issues in dense cities: air pollution and noise exposure. As with conventional green wall systems, vegetation and substrate layers act as active filters, while the integration of PMFC technology reinforces these effects through sustained moisture and biological activity. In terms of air quality, the system functions as a biological filtration interface. Plant foliage captures particulate matter on leaf surfaces, while photosynthesis contributes to carbon dioxide uptake and oxygen production. At the same time, the substrate and associated microbial communities facilitate the breakdown of certain airborne and deposited contaminants. The wall's consistently waterlogged conditions support more active microbial communities, enhancing decomposition processes and pollutant transformation. As a result, the façade operates as a distributed air-cleaning surface, with cumulative benefits when applied across multiple buildings.

The system also provides acoustic benefits by acting as a porous, multi-layered sound-absorbing barrier. Vegetation diffuses and scatters sound waves, while the substrate absorbs acoustic energy. As previously identified, the acoustic performance of green walls depends strongly on the properties of the growing medium and its moisture content. In the PMFC system, constant water saturation increases substrate density and reduces air gaps, enhancing sound attenuation. This makes the system more effective than conventional green walls. Additionally, quieter and cleaner micro-environments can support a broader range of urban species, reinforcing ecological resilience alongside human comfort.

7.6 Influence of Plant Microbial Fuel Cell Integrated Façade Living Wall System on Waste Generation

The PMFC Integrated Façade Living Wall reframes building systems by transforming several conventional waste streams into usable resources. At its core, the system reduces waste through the treatment and reuse of greywater, limiting the volume of wastewater discharged to centralised infrastructure and decreasing the generation of sludge associated with conventional treatment processes. At the material level, the design further contributes to waste reduction through the use of recycled plastics. Each container within the system incorporates approximately 1.4 kg of reused plastic, while all the customised elements of a single module incorporate around 10 kg of plastic. Given the scalability of the system across large façade areas, this represents a significant opportunity to redirect plastic waste into long-term building components. In this sense, the façade acts not only as an environmental system but also as a material storage that prolongs the lifecycle of otherwise discarded resources.

However, the integration of vegetation introduces new waste streams, most notably plant biomass resulting from pruning and replacement. Compared to standard green walls, the continuous nutrient supply from greywater can accelerate plant growth, potentially increasing the volume of organic waste generated. To minimise this impact, maintenance strategies can prioritise low-growth, low-maintenance species adapted to vertical conditions, as well as cyclical pruning regimes that align with plant health rather than aesthetic uniformity. Organic waste produced during maintenance can be further valorised through composting or conversion into soil amendments such as biochar used in the growing medium of the design, thereby reintegrating it into material cycles rather than treating it as waste.

7.7 Influence of Plant Microbial Fuel Cell Integrated Façade Living Wall System on Human Well-being

The integration of living systems into the built environment directly relates to the concept of biophilia, which describes the inherent human need to maintain a connection with nature. In contemporary high-density urban contexts, such as Singapore's high-rise residential blocks, this connection is often limited due to the dominance of artificial materials and the scarcity of accessible green spaces. The PMFC Integrated Façade Living Wall addresses this condition by reintroducing visible natural elements directly into the everyday living environment. Even when not directly accessible, such exposure to greenery has been shown to support psychological well-being by reducing stress and improving overall comfort, as previously discussed in relation to green wall systems. In addition to visual benefits, the system contributes indirectly to well-being through environmental improvements. By reducing ambient temperature, improving air quality, and attenuating noise, the façade creates more comfortable indoor and outdoor conditions. These environmental effects are particularly relevant in high-density housing, where thermal discomfort, noise, and pollutant exposure are common stressors. The integration of these functions within a single system amplifies their cumulative impact on daily living conditions.

The system also introduces a subtle shift in the relationship between residents and urban ecological processes. By making wastewater treatment, plant growth, and energy generation partially visible, it increases awareness of resource flows that are typically hidden within infrastructure. This can foster a stronger sense of connection to natural cycles and encourage more conscious interaction with environmental systems. At the same time, the integration of living systems at the façade scale requires careful consideration of user acceptance. As discussed in previous sections, factors such as maintenance visibility, proximity of vegetation, and potential interaction with fauna can influence how residents perceive the system. However, when appropriately designed and maintained, the presence of greenery and ecological activity is generally associated with positive perception and improved quality of life in urban settings.

7.8 Economic Values of Plant Microbial Fuel Cell Integrated Façade Living Wall System

The economic value of the PMFC Integrated Façade Living Wall lies in its ability to combine multiple building functions within a single system, shifting the evaluation from individual component costs to overall system efficiency. If these functions were implemented separately through conventional green walls, decentralised treatment units, and renewable energy technologies, the combined investment and spatial requirements would be significantly higher. By overlapping these functions within a single layer, the system reduces both material demand and spatial allocation, which is particularly valuable in high-density urban contexts where façade area is one of the few available resources.

The experimental results indicate that the cost of one PMFC reactor can be reduced to approximately 3.35 €, which corresponds to roughly 67 €/m² of façade. The exact breakdown of the price of one PMFC reactor of the components is shown in Table 20. At this level, the technology remains relatively low-cost compared to other building-integrated renewable systems. In comparison, building-integrated photovoltaic (PV) panels and façade-mounted wind systems generally require higher upfront investments per square metre, primarily due to material intensity and manufacturing complexity. While exact costs vary depending on technology and installation, PV systems typically range significantly higher than the PMFC layer alone. At the same time, PMFC integration introduces higher maintenance requirements as the PMFC components require monitoring and more frequent periodic replacement. Since both systems require similar infrastructure, such as energy storage, conversion, and distribution, the cost comparison at the façade level suggests that PMFC integration is economically competitive as a surface treatment, though it produces substantially lower energy output and may require more costly maintenance.

The integration of such a system can also influence property value. As discussed in earlier sections, green walls are associated with increased property attractiveness and value due to their aesthetic, environmental, and well-being benefits. The addition of functional performance further strengthens this effect by positioning the building as a high-performance, sustainable asset. In addition, the system provides indirect economic benefits by protecting the building envelope. Vegetation layers act as a buffer against solar radiation, temperature fluctuations, and mechanical weathering, reducing façade degradation over time. This can lower maintenance and replacement costs, extending the service life of building materials. In tropical climates, where exposure to UV radiation and humidity is high, such protective effects become particularly relevant.

Table 20: Costs of the proposed PMFC reactor.

Component	Price
Proton exchange membrane	1.44 euro per piece
Electrodes	120 euro per m²
Wires	0.3 euros per meter
Total	3.35 euros per reactor

7.9 Plant Microbial Fuel Cell Integrated Façade Living Wall System Material Choices

In terms of circularity of the PMFC Integrated Façade Living Wall, several components demonstrate strong potential. The use of recycled plastics for containers directly diverts waste streams into long-term building applications, while the modular design allows these elements to be replaced or reconfigured as needed. Similarly, ceramic-based proton exchange membranes offer durability and potential for reuse for their intended function, especially when compared to conventional synthetic membranes. Biological components, such as plants and substrate, are inherently circular, as they can be composted or reintegrated into ecological cycles at the end of their lifespan.

However, not all components achieve the same level of circularity. The most problematic elements are the electronic components, including sensors, wiring, and control systems. These rely on complex material compositions that are difficult to separate and recycle, often containing mixed metals, plastics, and electronic parts. Conductive materials such as metals used in wiring and sensors rely on mined resources, and while used in relatively small quantities, they still contribute to the system's material footprint. Their relatively short lifespan compared to structural elements further increases their environmental burden. The most sustainable approach would then be to limit the use of these throughout the system. Once the system is established and its performance is mature and more predictable the use of sensors could be limited. The amount of wiring can only be limited by optimising routing, thereby limiting the required length.

From a production perspective, several components involve energy-intensive processes. The manufacturing of cement-based structures, steel support systems, and certain electrode materials is associated with high embodied carbon. Injection moulding of plastic containers and the production of electronic components also require significant energy input. Nevertheless, these impacts can be partially offset by the system's long service life, modular repairability, and the incorporation of recycled materials.

7.10 Plant Microbial Fuel Cell Integrated Façade Living Wall System Design Recommendations

Based on the findings and reflections presented in the previous sections, the PMFC Integrated Façade Living Wall demonstrates clear potential but also reveals several areas for further optimisation. The experimental study highlighted key limitations related to system performance and stability. These include relatively low and fluctuating energy output compared to literature values, voltage instability caused by oxygen intrusion into the anode, and sensitivity of the microbial community to substrate composition, particularly to osmotic shock at high COD concentrations. The following recommendations outline general strategies to address these limitations and improve overall system performance, reliability, and integration in real-world contexts.

When improving the efficiency in terms of the amount of wastewater treated, the flow of greywater cannot simply be increased. As the amount of greywater fed to the PMFCs increases, the HRT decreases. To treat more water daily and still ensure optimal HRT of 2 days, a larger volume of the waterlogged anode zone (electroactive anolyte zone) is needed. The active anode zone is limited by surface evaporation of moisture and by oxygen intrusion into the anode chamber in places where the soil is exposed to atmospheric air. To maximise the anolyte zone, the area of surface soil should be minimised, and the volume of soil increased. This way, the soil is used most effectively, as the area where oxygen intrusion into the anode chamber can appear is limited. This can be achieved by elongating the container design.

8. Reflection

This thesis began with a relatively straightforward question:

> *How can building façades become more than passive barriers using Microbial Fuel Cell technology?*

Through the development and testing of the PMFC Integrated Façade Living Wall System, this question gradually evolved into a broader exploration of what it means for architecture to actively participate in human and non-human ecosystems.

Research demonstrated that it is possible to combine vegetation, wastewater treatment, and energy generation into a single system. However, the performance and efficiency of these processes can vary, and one element can outperform the other. It revealed that the value of the designed system lies not in maximising a single output, but in the cumulative effect of multiple overlapping functions operating within the same spatial framework. One of the insights gained through this research was that façade systems can operate as interfaces rather than boundaries. By incorporating living matter, water flows, and microbial processes, the building envelope becomes part of a larger network of exchanges between the building and its environment. This challenges the conventional perception of façades as inert and optimised solely for protection and efficiency. Instead, it suggests a shift toward façades that contribute to ecological continuity, resource cycling, and environmental regulation. For humanity, the main value lies in resilience and access. For ecosystems, the value lies in lower pollutant discharge, reduced freshwater extraction, and the possibility of turning wastewater into a usable resource rather than a waste stream.

A critical observation is that the system proposed in this thesis operates closer to a proof of concept than a readily deployable solution. While the idea of a regenerative façade remains valid, the technical maturity of PMFC technology limits its applicability in real-life. The reliance on biological processes introduces unpredictability that contrasts with the expectations of contemporary construction, where reliability, durability, and low maintenance are prioritised. Unlike conventional building technologies, PMFC performance cannot be fully standardised or predicted. It depends on dynamic interactions between biological, chemical, and physical conditions. This introduces a level of uncertainty that contrasts with the nature of most architectural systems. As a result, designing with such technologies requires a different mindset, one that accepts variability, prioritises adaptability, and recognises that performance may fluctuate over time.

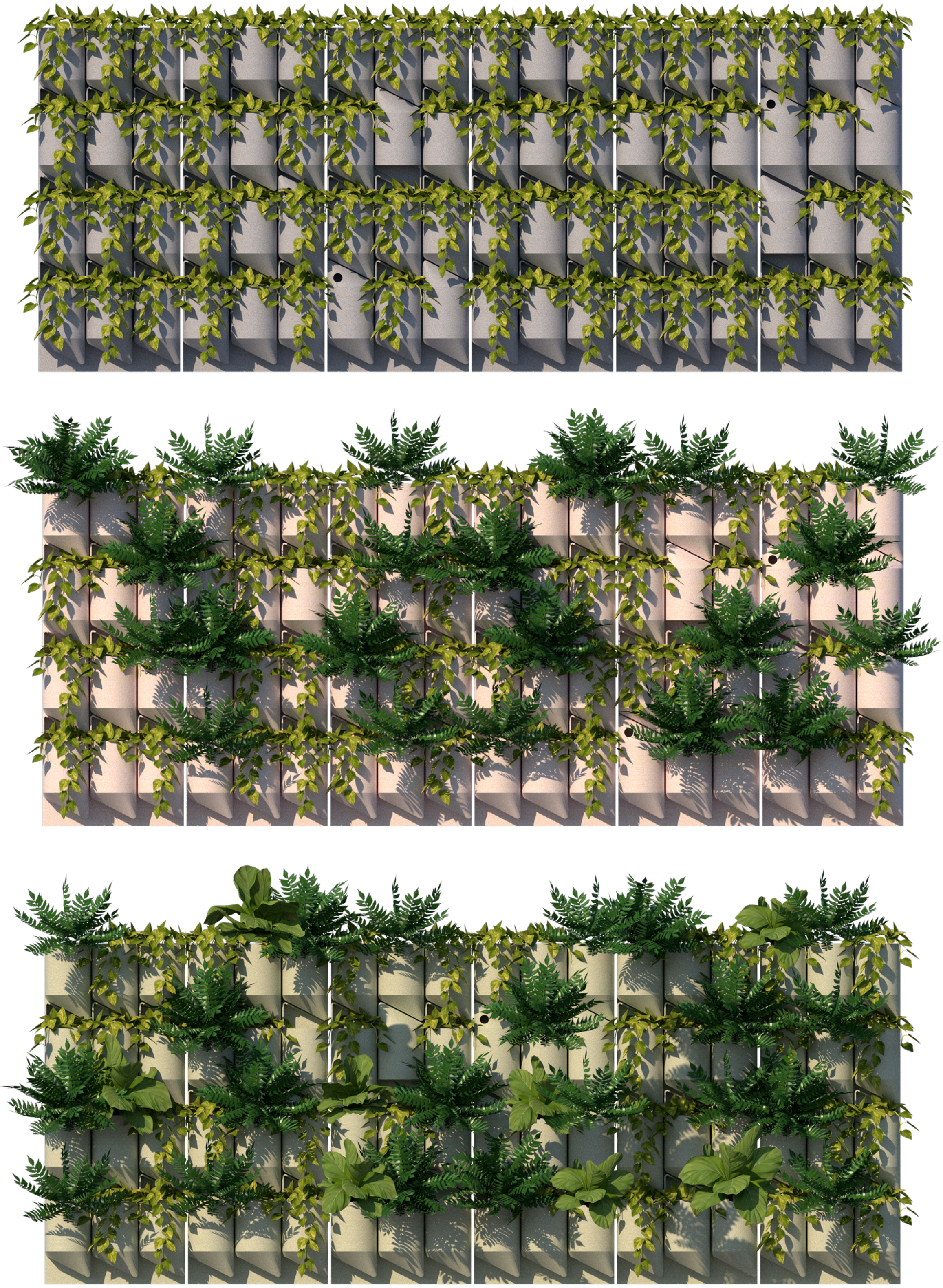


Figure 51:
Visualisations of the developed Plant Microbial Fuel Cell Façade Living Wall System.

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10. Appendices

10.1 Appendix 1: Electricity generation using different wastewaters according to Sonawane et al. (2024).

Types of Waste	Power Generation	References
Palm oil mill wastewater	504.1 ± 8.7 mW/m^3	Ng et al. (2023)
Septic tank wastewater	147 ± 10 mW/m^2	Thulasinathan et al. (2021a)
Septic tank wastewater (Pseudomonas otitidis)	280 mW/m^2	Thulasinathan et al. (2021b)
Food based industrial waste	428.71 mW/m^2	Ramu et al. (2020)
Rice mill wastewater	656.10 mW/m^3	Raychaudhuri and Behera (2020)
Agro-food wastewater	27.00 W/m^3	Cecconet et al. (2017)
Electroplating waste	150.50 mW/m^2	Kim et al. (2017)
Swine wastewater	37.50 W/m^3	Ding et al. (2017)
Seafood processing wastewater	105.00 mW/m^2	Jayashree et al. (2016)
Ethanolamine wastewater	1990.00 mW/m^2	An et al. (2016)
Distillery wastewater	72.90 mW/m^2	Lin et al. (2015)
Mustard tuber wastewater	246.00 mW/m^2	Guo et al. (2013)
Food waste leachate	1500.00 mW/m^2	Rikame et al. (2012)
Cassava mill wastewater	1771.00 mW/m^2	Kaewkannetra et al. (2011)
Grass silage	54.00 mW/m^2	Catal et al. (2010)
Canteen food waste	107.89 mW/m^2	Goud et al. (2011)
Biodiesel production waste	2110.00 mW/m^2	Feng et al. (2010)
Rice mill wastewater	172.20 mW/m^2	Behera et al. (2010)

Food industry waste	78.00 mW/m^2	Cercado et al. (2009)
Azo dye	552.20 mW/m^2	Li et al. (2010)
Composite veg waste	57.38 W/m^3	Mohan et al. (2009)
Distillery wastewater	124.34 mW/m^2	Mohankrishna et al. (2009)
Starch processing wastewater	239.40 mW/m^2	Lu et al. (2009)
Chemical wastewater	198.00 mW/m^2	Mohan et al. (2008)
Cereal wastewater	381.00 mW/m^2	Oh and Logan (2005)

10.2 Appendix 2: MFC Building Integration Matrix

	Integration strategy		
	Bricks	Green Roof	Interior Wall
Reference	You et al. (2019)	Guan and Yu (2020), Liao and He (2023)	Hogle et al. (2023)
Status	Lab and small pilot scale, with real bricks tested as MFC reactors and clear data on power, material behaviour and plumbing concepts (TRL ≈ 3–4). Low power per brick, dependence on brick porosity and separator thickness, electrode and cathode fouling, drying or flooding in wall cavities, and lack of long-term field data in real façades.	PMFC green roofs have been demonstrated at lab and small outdoor pilot scale (e.g., Helder's greenroof PMFC pilots in the Netherlands; sedum PMFC modules in recent prototypes), so the integration is around TRL 3–4. Known issues include low and variable power density, sensitivity to drought or waterlogging, seasonal performance loss (e.g., freezing of plants on roofs), and longterm durability of electrodes in soil.	Proof-of-concept modular wall demonstrated at pilot scale in controlled/experimental building settings (approx. TRL 4–5: lab validation and early integrated prototype).
Location	As part of exterior or interior masonry walls or ventilated brick façades, usually within the outer wythe or cavity wall. Uses roughly the same footprint as a conventional brick wall; extra space needed for manifolds, collection channels, and wiring at the back of the wall or in the cavity.	On the roof as an extensive or semi-intensive vegetated system, generally above the waterproofing layer with standard green-roof stratigraphy (drainage, substrate, vegetation). Requires roof area similar to a conventional green roof (often tens to hundreds of m^2); the MFC hardware (anodes, cathodes, wiring) is embedded in the substrate layer and does not fundamentally change the footprint, but needs space for edge terminations, cabling, and any manifolds if used for wastewater dosing.	Interior wall-like partition within dwellings or comparable interior spaces. Runs along a wall line (similar thickness to a service wall or thick partition); requires access to daylight or artificial light for photobioreactor bricks.

Power Output	Approximately 13.5–32.8 mW/m².	1–50 mW/m² of anode/ground surface. Electricity is an auxiliary benefit while the main functional gains are stormwater management, cooling, and modest wastewater polishing.	10–30 mW/m² of projected wall/electrode area. Individual urine-fed MFC bricks of similar designs have achieved power densities on the order of a few to a few tens of mW per m² of projected electrode or wall area, electricity is a secondary function.
COD Removal Rate	Single-stage brick MFCs treating urine or diluted urine in household contexts have shown COD removal around 35–55%, depending on dilution and configuration. In multi-brick series (wall section), overall COD removal can be increased (potentially approaching 60–80% under favourable HRT and loading), but full replacement of conventional treatment is not yet demonstrated.	70–90% COD removal.	50–80% COD removal. Moderate COD removal, with individual MFC stages contributing significant COD reduction but usually not sufficient alone to meet discharge standards.
Costs	Uses relatively cheap, widely available bricks, but adds cost for electrodes, catalysts, wiring, manifolds, and installation labour; currently at prototype pricing rather than mass production.	Incremental CAPEX over a standard green roof due to electrodes, wiring, sensors, and possible distribution/collection systems for influent and effluent.	As an H2020 research demonstrator, LIAR is currently high in CAPEX per m² wall.
Preferred Substrate	Source-separated urine, diluted urine (urine + bath/shower water), or low-strength greywater are the most common and suitable feeds.	Rainwater or stormwater retained in the substrate. Optionally, low-strength wastewater or nutrient-rich water (e.g., diluted greywater, hydroponic drainage).	Domestic liquid wastes produced by the building itself, primarily urine and greywater.

Products	Low-level electricity. Partial wastewater treatment (COD and nutrient reduction), and potential nutrient-rich effluent suitable for further polishing or reuse.	Direct products: Low, continuous bioelectricity from the plant–microbe system. Co-products: Stormwater retention and peak flow reduction, improved roof thermal performance, habitat and biodiversity, and partial removal of organic matter and nutrients from influent water.	Direct products: Bioelectricity. Treated water suitable for reuse. Co-products: Oxygen from algal/photobioreactor bricks. Recovered polyphosphate and other nutrients for fertilizer, biomass/proteins and fibre, and potentially biodegradable detergents.
Required Environment	Protected by the wall; operates near indoor/outdoor wall temperatures, typically in the mesophilic range; must avoid bricks drying out completely or remaining permanently flooded.	Exposed rooftop conditions, so systems must tolerate seasonal temperature swings, high solar radiation, wind, and occasional drought or saturation; plant and microbial communities must be selected for local climate (e.g., sedum in temperate climates, other species in tropical setups). Root-zone pH in the near-neutral range and avoidance of toxic pollutants or high salinity; sufficient moisture must be maintained in the substrate for microbial activity and electrical conduction.	Indoor temperature and protected environment, pH in the near-neutral range, avoidance of toxic shock loads photobioreactor bricks need light exposure and sufficient gas exchange to handle CO_2 and other gases.

Required Infrastructure	Piping or channels to distribute urine/greywater through or behind the brick layer and to collect effluent; venting/odour control in cavities. Low-voltage DC collection from each brick or string of bricks, with busbars or cabling inside the cavity and possible power conditioning for aggregation.	Standard green-roof build-up plus drainage, with additional distribution for any intentional wastewater dosing (e.g., piping or drip systems bringing greywater/hydroponic water to the roof and collection of percolate if reuse or controlled discharge is intended). Embedded anode and cathode networks with cabling to a DC bus, data-logging, or low-power applications; optional power conditioning electronics if power is aggregated.	Piping or manifold system to deliver urine and greywater to the wall, controlled distribution across bricks, and drainage/collection for treated water and concentrated by-products. Low-voltage DC collection from MFC bricks, power conditioning, sensing network, and decentralized/ programmable control hardware to manage microbial consortia and flows.
Required Inputs	Building-generated urine and/or greywater (possibly diluted), air access at cathode side.	Rainfall or irrigation water (often already present for green roofs). Sunlight for plant growth and occasional nutrient additions if the roof is designed as an intensive PMFC system.	Domestic urine and greywater from building occupants. Air and/or flue exhaust supplying CO_2 and certain gaseous pollutants. Light (sunlight or artificial) for photosynthetic bricks, and occasional nutrient adjustments or buffering agents if required for microbial stability.
MFC Materials and Components	Ceramic dual-chamber MFC; fired clay brick as structural separator between anode (urine-filled pores) and cathode chambers. Conventional fired clay or air bricks act as both structure and ceramic separator; carbon-based anodes and cathodes. Internal chambers or pores are used as anode and cathode chambers.	Single-chamber plant-microbial fuel cell (PMFC); sediment-style with buried anodes in rhizosphere substrate, surface/air cathodes. Anodes buried in the root zone (often carbon-based materials), cathodes nearer the surface or exposed to air (e.g., graphite or other conductive materials), and wiring to connect cells or modules.	Dual-chamber microbial fuel cell (MFC) with synthetic consortia; stacked modular bricks (anode chamber filled with wastewater, ceramic separator, air cathode). Stacked, hydraulically sequential bricks combining MFC units, photobioreactors and other synthetic-microbiology modules in a programmable wall array.

System Design Considerations	Must coordinate with cavity wall design, damp proofing, structural detailing, and service zones for plumbing and cabling; easiest in new builds or major façade refurbishments. Requires deliberate routing of urine/ greywater to the wall instead of directly to sewer, and routing of low-voltage DC to storage or building systems.	Needs coordination with roof structural capacity, waterproofing, drainage, and any greywater or reuse system; if using building-generated wastewater, routing to and from the roof must be designed carefully.	Must interface with building plumbing (for separated or partially separated wastewater), ventilation/flue systems, and low-voltage electrical systems. Conceptually applicable to both new build and retrofit, but current form is more suited to new or heavily renovated buildings where wall space and service routing can be designed around the bioreactor wall.
Maintenance and Operation	Periodic inspection for leaks, blockages, and salt or biofilm build-up in channels; possible retrofitting or replacement of degraded electrodes via accessible cavities.	Similar to conventional green roofs (vegetation care, inspection of drainage and waterproofing), plus periodic checking of electrical connections and replacement of any corroded or degraded electrode elements.	Periodic inspection of bricks, cleaning of channels, checking for leaks or clogging, replacement or refurbishment of underperforming modules, and calibration of sensors and control systems. Requires more active monitoring and occasional expert intervention than passive infrastructure, due to living consortia and programmable elements; long-term operational cost data are still uncertain.
Scalability	Each brick is a unit; façades can contain hundreds or thousands of bricks wired in series/parallel.	Highly modular by nature of green-roof construction; each roof zone can host PMFC modules, and larger surfaces can be equipped as budget and complexity allow.	Modular and scalable via tiling of bricks into larger wall arrays.
Benefits of the System	Turns a traditional material into an active energy-and-treatment element without dramatically changing the architectural language of brick façades; distributed treatment reduces central pipe loads and offers continuous small-scale power. Retrofit potential into existing brick typologies and the possibility of "electrifying" walls at unit level without large standalone reactors.	Combines standard green-roof ecosystem services (cooling, stormwater management, habitat, aesthetic value) with low-level renewable electricity generation. Uses space that is already being "paid for" by the green roof to additionally produce electricity and, where applicable, provide light-touch treatment for certain water streams.	Turns an interior wall into a multifunctional, programmable "organ" of the building that treats wastewater, scrubs air, and produces electricity and useful by-products.

Limitations	Very low power per unit area and moderate COD removal; performance highly dependent on ceramic properties and moisture; risk of clogging and management of odours/salts.	Very low power density and strong dependence on moisture and plant health; seasonal/diurnal variability and potential performance loss in cold or very dry periods. Additional detailing, installation complexity, and limited direct financial payback from electricity alone, so implementation is more easily justified where green roofs are already desired for other reasons.	Low power density relative to conventional power technologies, complexity of multi-organism consortia, potential reliability issues, and sensitivity to load variations. High prototype costs, need for specialized expertise, and unproven long-term performance in ordinary occupied buildings.
Circularity	Utilises building-generated urine/greywater and partially recovers energy and treats organics at the façade, potentially reducing centralised treatment burden. Uses durable ceramic bricks that already have long service lives; electrodes and wiring could be recovered or recycled at end-of-life, but this has not yet been optimised.	Can use locally generated water (rainwater, sometimes greywater) and convert a fraction of contained organics and nutrients into plant biomass while generating electricity.	Designed explicitly to recover water, nutrients (e.g., phosphates), and carbon (via biomass and oxygen), closing loops at the building scale. Can reduce the need for external water and fertilizer inputs.

10.3 Appendix 3: Different plant species, used anode and cathode electrode material and respective power generation in the various pMFCs from Kuleshova et al. (2022).

Plant	Electrode material	Maximum Power output (mW/m^2)	Reference
Epipremnum aureum	Anode- Carbon fiber brush Cathode- Carbon fiber cloth	14.05	Sarma et al. (2018)
Dracaena braunii	Anode- Carbon fiber brush Cathode- Carbon fiber cloth	12.78	Sarma et al. (2018)
Glyceria maxima	Anode- Graphite granules Cathode- Graphite felt	80	Timmers et al. (2012)
Spartina anglica	Anode- Graphite granules Cathode- Graphite felt	79	Timmers et al. (2010)
Oryza sativa	Anode – Carbon felt Cathode- Nickle mesh	41	Khudzari et al. (2019)
Oryza sativa	Anode- Carbon fiber Cathode- Carbon fiber	23	Moqsud et al. (2015)
Oryza sativa	Anode-Graphite felt Cathode- Graphite felt	16.8	M mohan et al. (2020)
Spartina anglica	Anode – Graphite rod Cathode- Graphite felt	1.04	Sudirjo et al. (2019)
Vetiveria zizaniodes	Anode- Steel mesh with graphite fiber Cathode- Graphite fiber	68	Regmi et al. (2018)
Puccinellia distans	Anode- Carbon felt Cathode- Nickle mesh	83.7	Khudzari et al. (2010)
Chlorophytum comosum	Anode- Graphite sheet Cathode- Graphite sheet	18	Azri et al. (2018)
Brassica juncea	Anode-Carbon brush Cathode- Carbon cloth	69.32	Sophia et al. (2017)

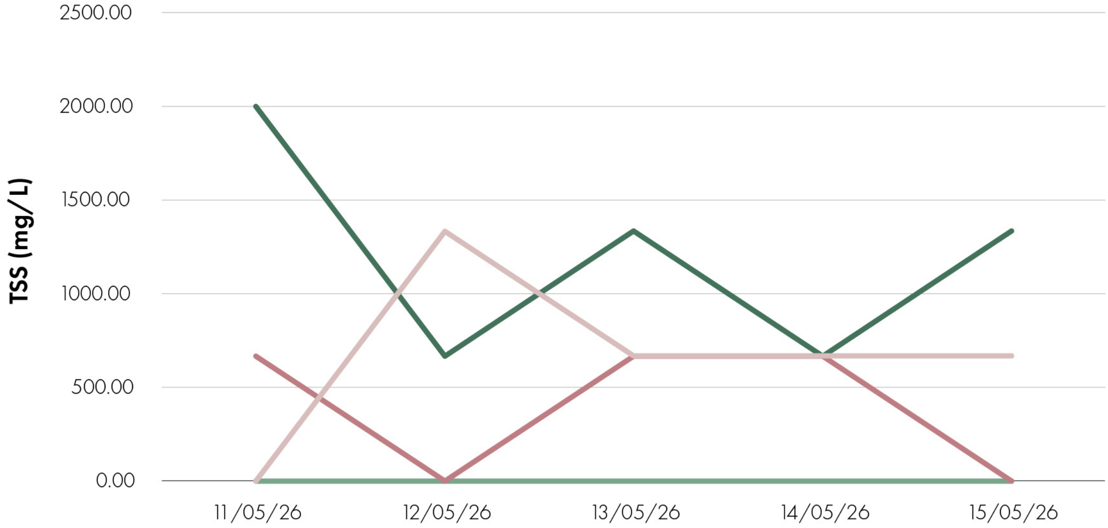
Trigonella foenum-graecum	Anode-Carbon brush Cathode- Carbon cloth	80.26	Sophia et al. (2017)
Canna stuttgart	Anode-Carbon brush Cathode- Carbon cloth	222.54	Sophia et al. (2017)
Phragmites australis	Anode- Graphite felt Cathode- Graphite felt	22	Wetser et al. (2017)
Canna indica	Anode- Graphite felt Cathode- Graphite felt	22.76	Sharma et al. (2021)
Ipomoea aquatic	Anode- Activated carbon with stainless steel mesh Cathode- Stainless steel mesh	10.60	Liu et al. (2021)

10.4 Appendix 4: Oxidation Rate Results

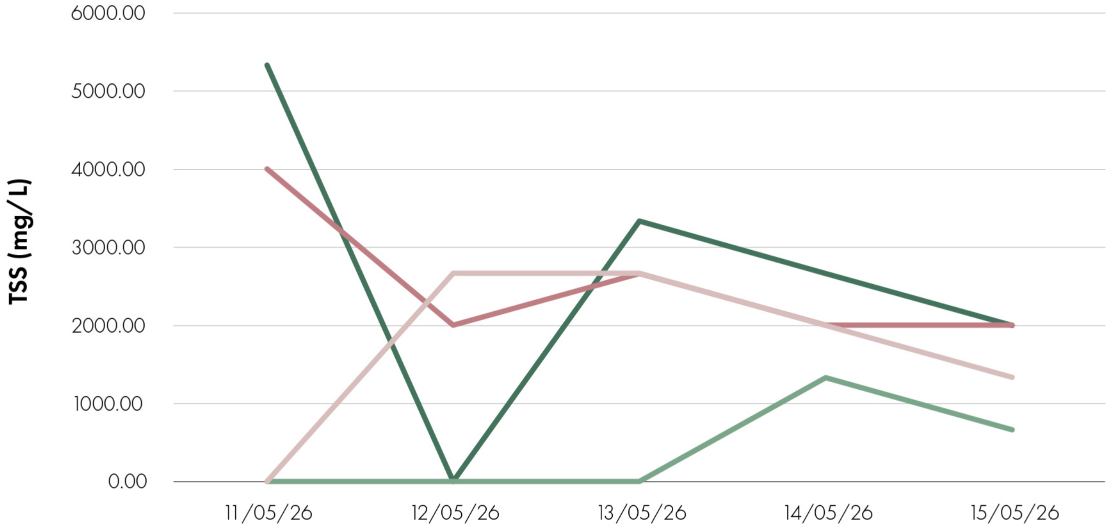
	08/05/26	09/05/26	10/05/26	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26	16/05/26
Sample 1	1.47E-10	3.69E-10	-1.47E-10	-5.58E-10	1.37E-10	-1.05E-11	-4.00E-10	4.63E-10	-2.74E-10
Sample 2	3.05E-10	7.27E-10	-1.37E-10	-1.05E-11	-2.11E-11	-1.05E-10	-1.47E-10	9.90E-10	2.32E-10
Sample 3	1.37E-10	1.69E-10	7.37E-11	3.16E-11	3.16E-11	2.42E-10	5.27E-11	4.53E-10	2.21E-10
Sample 4	2.21E-10	2.21E-10	1.47E-10	1.79E-10	2.53E-10	9.48E-11	-2.63E-10	2.84E-10	3.05E-10

	17/05/26	18/05/26	19/05/26	20/05/26	21/05/26	22/05/26	23/05/26	24/05/26	25/05/26
Sample 1	-4.00E-10	-1.47E-10	-3.69E-10	-3.79E-10	-3.37E-10	-2.63E-10	-2.11E-11	-7.37E-11	1.47E-10
Sample 2	-5.58E-10	-4.74E-10	2.11E-10	-5.16E-10	-6.74E-10	-4.21E-11	5.27E-10	-4.63E-10	6.95E-10
Sample 3	3.16E-11	1.16E-10	-2.95E-10	-4.21E-10	4.74E-10	-4.42E-10	-4.63E-10	-6.00E-10	-5.37E-10
Sample 4	3.69E-10	1.47E-10	2.11E-10	1.16E-10	1.47E-10	1.69E-10	5.27E-11	7.37E-11	1.69E-10

10.5 Appendix 5: Total Suspended Solids Removal Rate Results

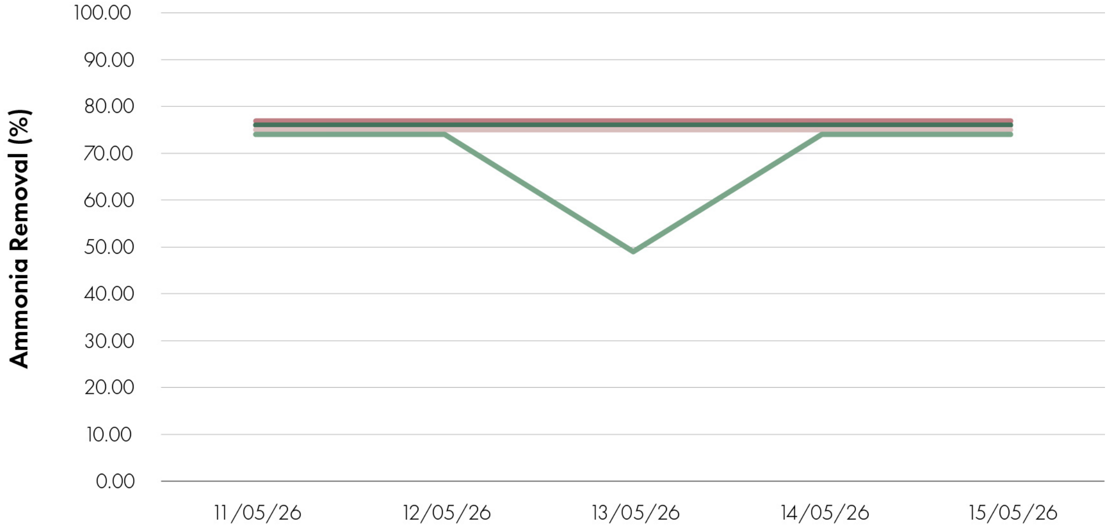


	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26
Sample 1	2000.00	666.67	1333.33	666.67	1333.33
Sample 2	0.00	0.00	0.00	0.00	0.00
Sample 3	666.67	0.00	666.67	666.67	0.00
Sample 4	0.00	1333.33	666.67	666.67	666.67

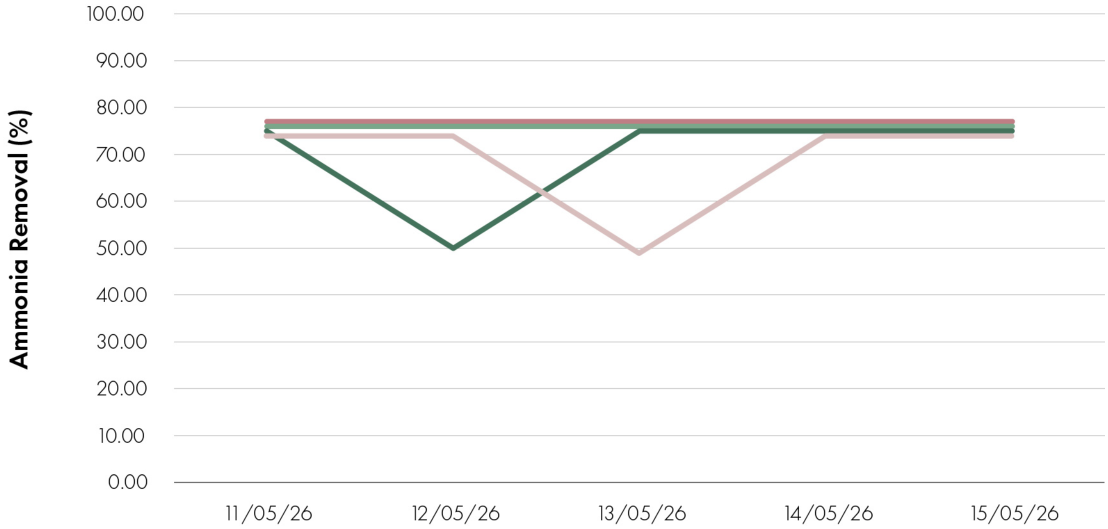


	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26
Sample 9	5333.33	0.00	3333.33	2666.67	2000.00
Sample 10	0.00	0.00	0.00	1333.33	666.67
Sample 11	4000.00	2000.00	2666.67	2000.00	2000.00
Sample 12	0.00	2666.67	2666.67	2000.00	1333.33

10.6 Appendix 6: Ammonia Removal Rate Results

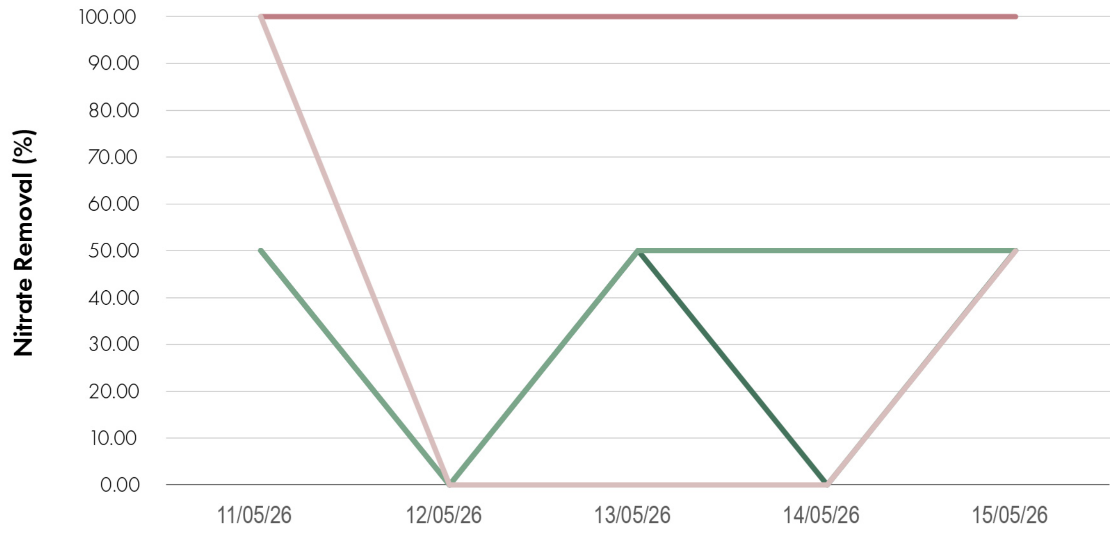


	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26
Sample 1	75.00	75.00	75.00	75.00	75.00
Sample 2	75.00	75.00	50.00	75.00	75.00
Sample 3	75.00	75.00	75.00	75.00	75.00
Sample 4	75.00	75.00	75.00	75.00	75.00



	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26
Sample 9	75.00	50.00	75.00	75.00	75.00
Sample 10	75.00	75.00	75.00	75.00	75.00
Sample 11	75.00	75.00	75.00	75.00	75.00
Sample 12	75.00	75.00	50.00	75.00	75.00

10.7 Appendix 7: Nitrate Removal Rate Results

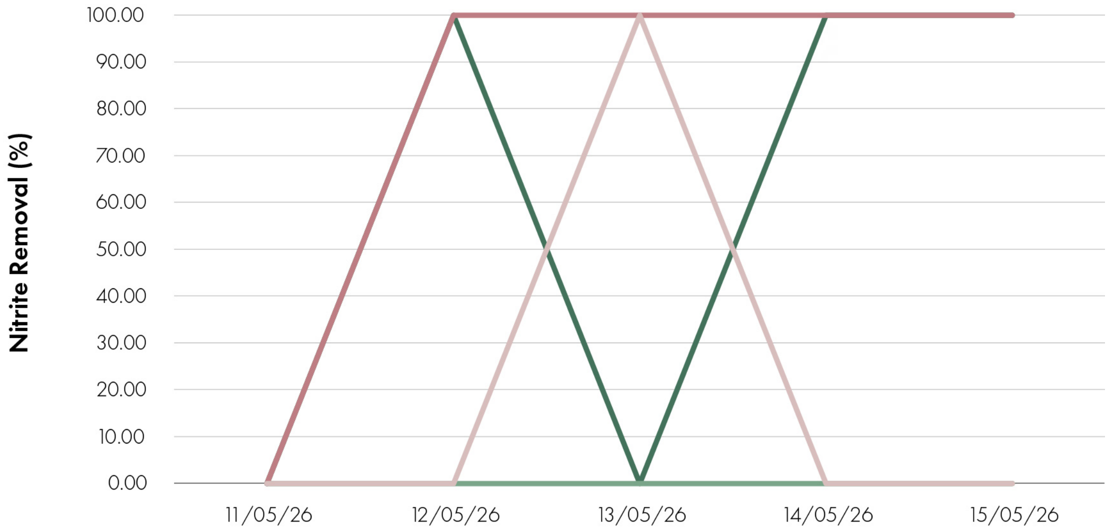


	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26
Sample 1	50.00	0.00	50.00	0.00	50.00
Sample 2	50.00	0.00	50.00	50.00	50.00
Sample 3	100.00	100.00	100.00	100.00	100.00
Sample 4	100.00	0.00	0.00	0.00	50.00

	12/05/26	13/05/26	14/05/26	15/05/26
Sample 9	100.00	50.00	50.00	0.00
Sample 10	0.00	0.00	50.00	0.00
Sample 11	100.00	0.00	50.00	0.00
Sample 12	50.00	50.00	100.00	50.00

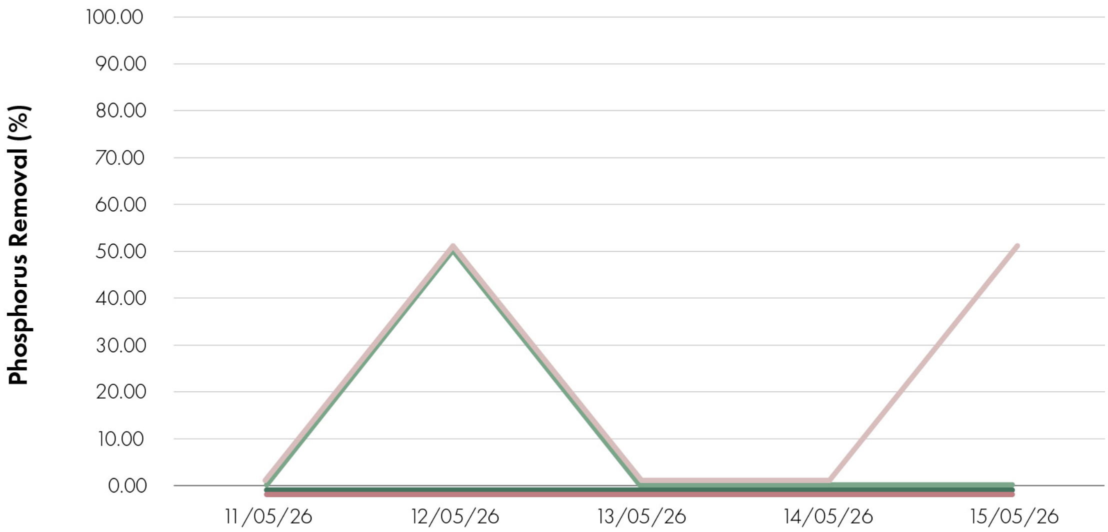
10.8 Appendix 8: Nitrite Removal Rate Results

	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26
Sample 1	100.00	0.00	0.00	0.00	100.00
Sample 2	0.00	0.00	0.00	100.00	0.00
Sample 3	100.00	0.00	100.00	100.00	100.00
Sample 4	100.00	0.00	0.00	100.00	0.00



	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26
Sample 9	0.00	100.00	0.00	100.00	100.00
Sample 10	0.00	0.00	0.00	0.00	0.00
Sample 11	0.00	100.00	100.00	100.00	100.00
Sample 12	0.00	0.00	100.00	0.00	0.00

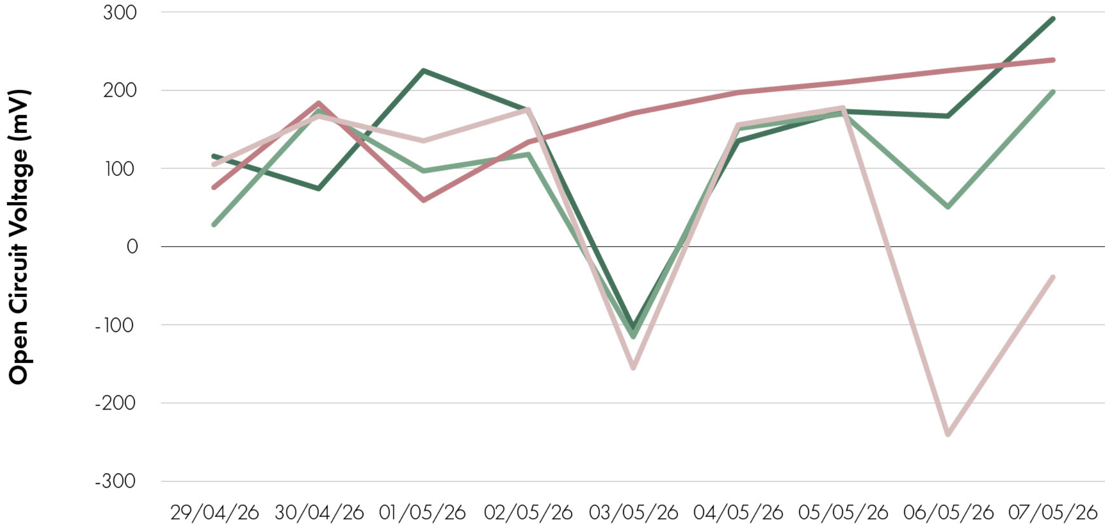
10.9 Appendix 9: Phosphorus Removal Rate Results



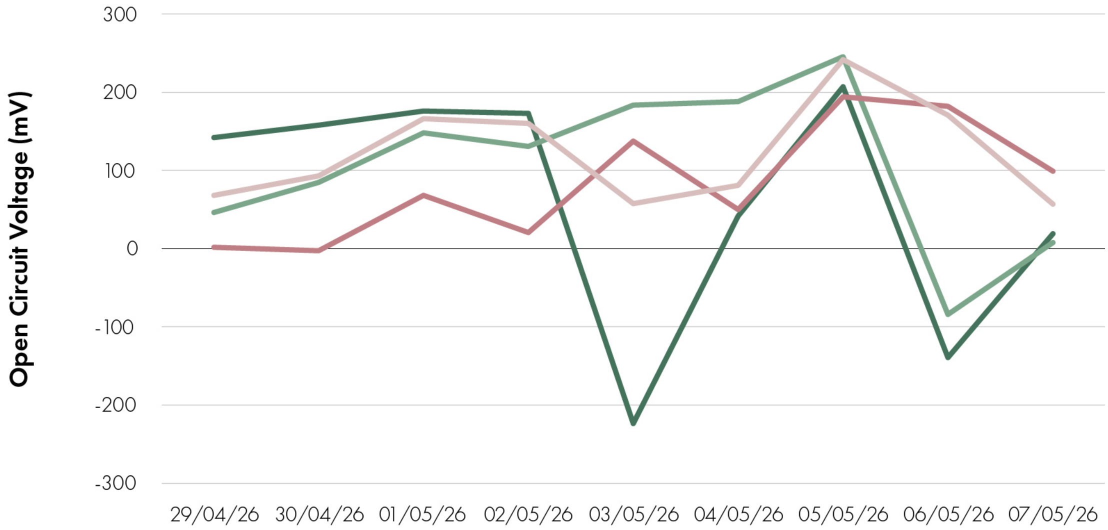
	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26
Sample 9	0.00	0.00	0.00	0.00	0.00
Sample 10	0.00	50.00	0.00	0.00	0.00
Sample 11	0.00	0.00	0.00	0.00	0.00
Sample 12	0.00	50.00	0.00	0.00	50.00

	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26
Sample 1	0.00	50.00	0.00	0.00	50.00
Sample 2	50.00	0.00	0.00	50.00	50.00
Sample 3	100.00	50.00	50.00	50.00	100.00
Sample 4	50.00	50.00	50.00	100.00	50.00

10.10 Appendix 10: Open Circuit Voltage Results

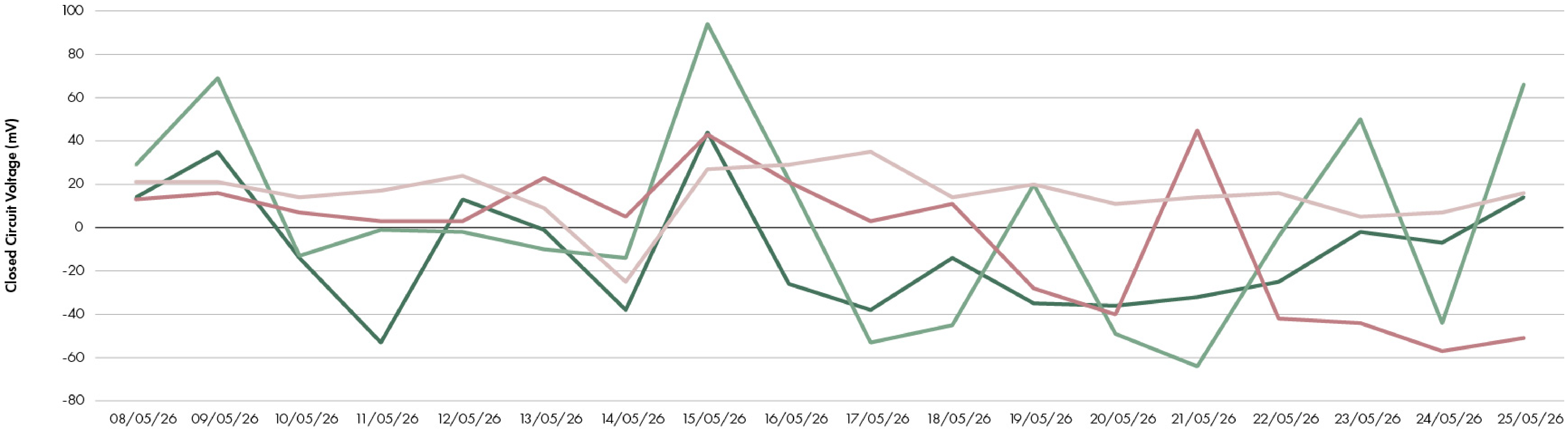


	29/04/26	30/04/26	01/05/26	02/05/26	03/05/26	04/05/26	05/05/26	06/05/26	07/05/26
Sample 5	116	74	225	174	-104	135	173	167	292
Sample 6	28	174	97	118	-115	151	170	51	198
Sample 7	76	184	59	134	171	197	210	225	239
Sample 8	105	167	135	175	-155	156	178	-240	-39

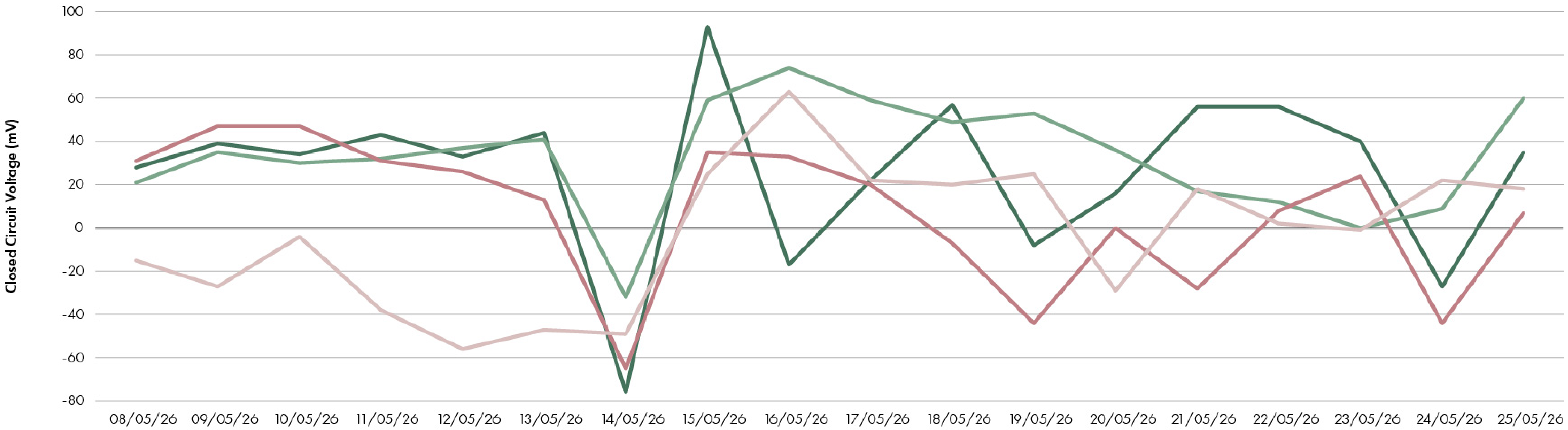


	29/04/26	30/04/26	01/05/26	02/05/26	03/05/26	04/05/26	05/05/26	06/05/26	07/05/26
Sample 1	142	158	176	173	-224	42	207	-139	19
Sample 2	46	85	148	131	184	188	246	-84	8
Sample 3	2	-3	68	21	138	50	194	182	99
Sample 4	68	93	166	160	58	81	242	171	57

10.11 Appendix 11: Closed Circuit Voltage Results

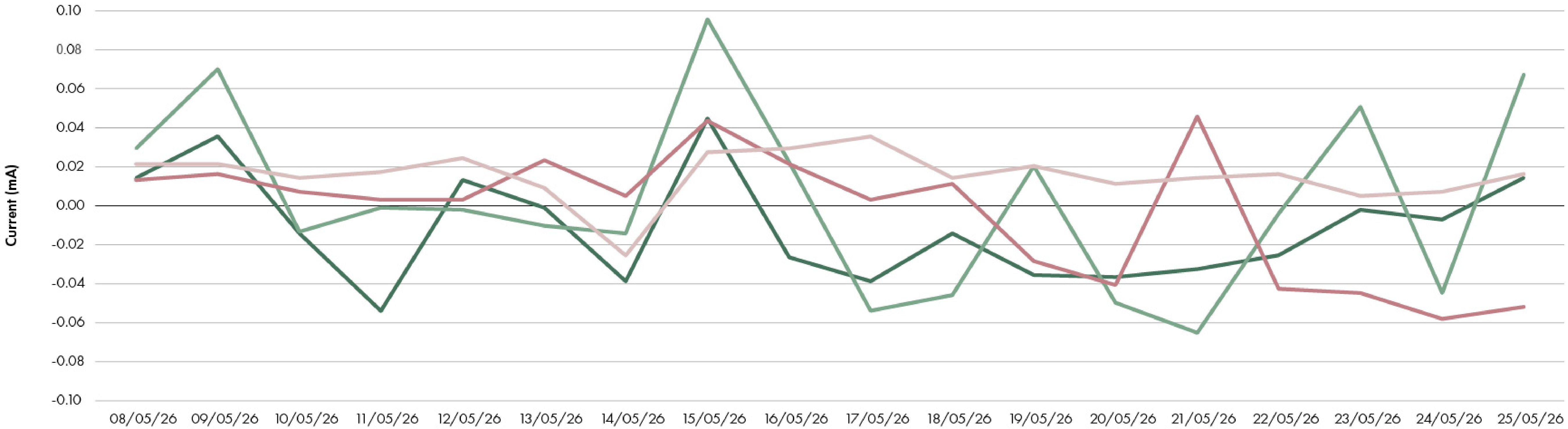


	08/05/26	09/05/26	10/05/26	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26	16/05/26	17/05/26	18/05/26	19/05/26	20/05/26	21/05/26	22/05/26	23/05/26	24/05/26	25/05/26
Sample 1	14	35	-14	-53	13	-1	-38	44	-26	-38	-14	-35	-36	-32	-25	-2	-7	14
Sample 2	29	69	-13	-1	-2	-10	-14	94	22	-53	-45	20	-49	-64	-4	50	-44	66
Sample 3	13	16	7	3	3	23	5	43	21	3	11	-28	-40	45	-42	-44	-57	-51
Sample 4	21	21	14	17	24	9	-25	27	29	35	14	20	11	14	16	5	7	16

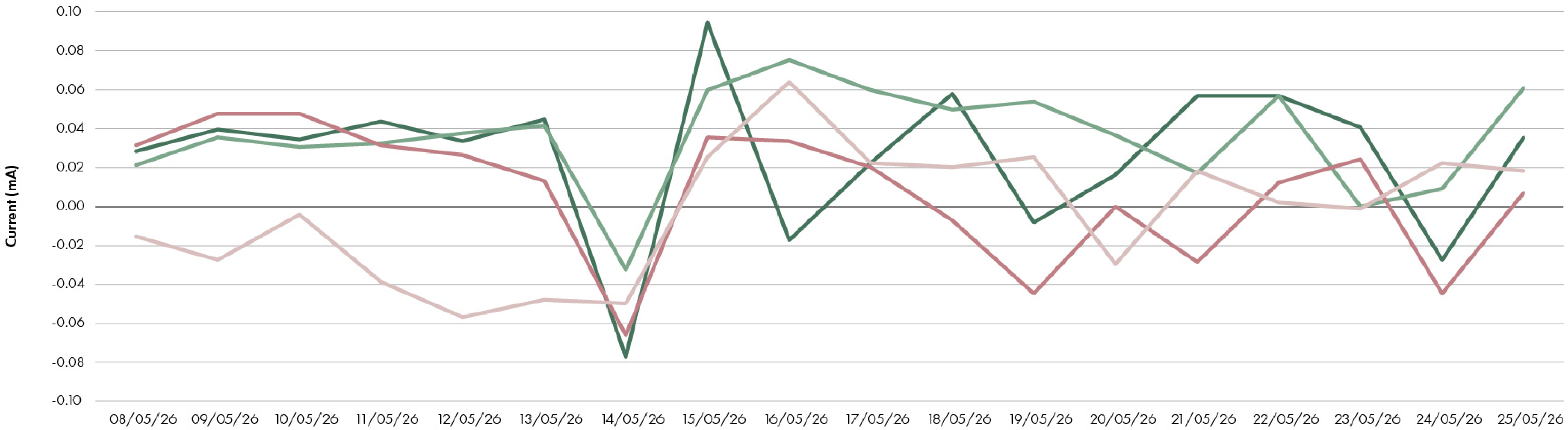


	08/05/26	09/05/26	10/05/26	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26	16/05/26	17/05/26	18/05/26	19/05/26	20/05/26	21/05/26	22/05/26	23/05/26	24/05/26	25/05/26
Sample 5	28	39	34	43	33	44	-76	93	-17	22	57	-8	16	56	56	40	-27	35
Sample 6	21	35	30	32	37	41	-32	59	74	59	49	53	36	17	12	0	9	60
Sample 7	31	47	47	31	26	13	-65	35	33	20	-7	-44	0	-28	8	24	-44	7
Sample 8	-15	-27	-4	-38	-56	-47	-49	25	63	22	20	25	-29	18	2	-1	22	18

10.12 Appendix 12: Current Results

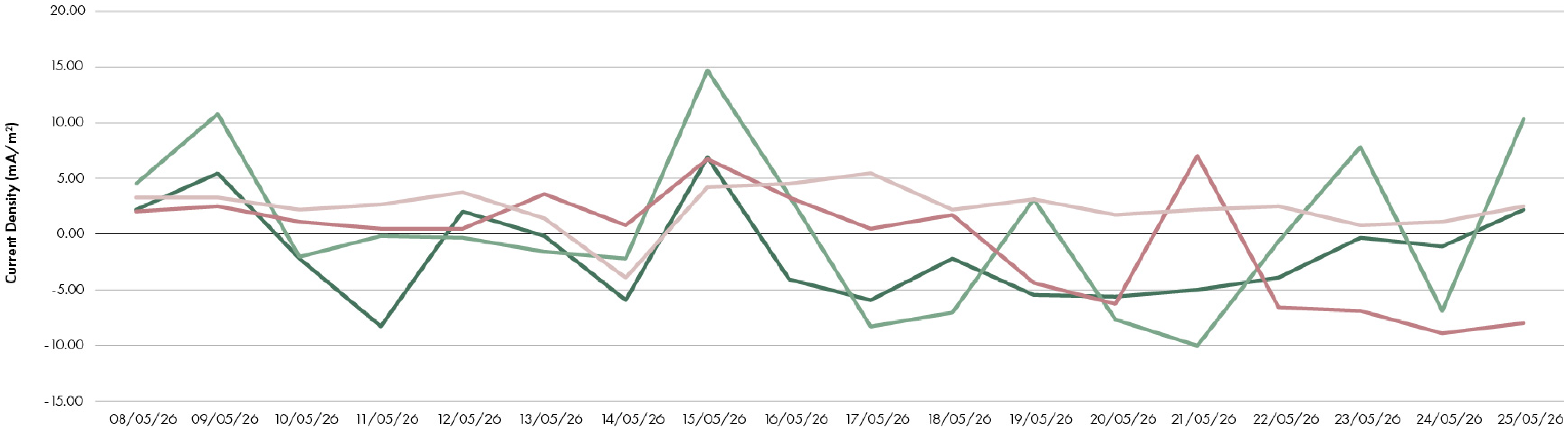


	08/05/26	09/05/26	10/05/26	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26	16/05/26	17/05/26	18/05/26	19/05/26	20/05/26	21/05/26	22/05/26	23/05/26	24/05/26	25/05/26
Sample 1	0.01	0.04	-0.01	-0.05	0.01	0.00	-0.04	0.04	-0.03	-0.04	-0.01	-0.04	-0.04	-0.03	-0.03	0.00	-0.01	0.01
Sample 2	0.03	0.07	-0.01	0.00	0.00	-0.01	-0.01	0.10	0.02	-0.05	-0.05	0.02	-0.05	-0.07	0.00	0.05	-0.04	0.07
Sample 3	0.01	0.02	0.01	0.00	0.00	0.02	0.01	0.04	0.02	0.00	0.01	-0.03	-0.04	0.05	-0.04	-0.04	-0.06	-0.05
Sample 4	0.02	0.02	0.01	0.02	0.02	0.01	-0.03	0.03	0.03	0.04	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.02

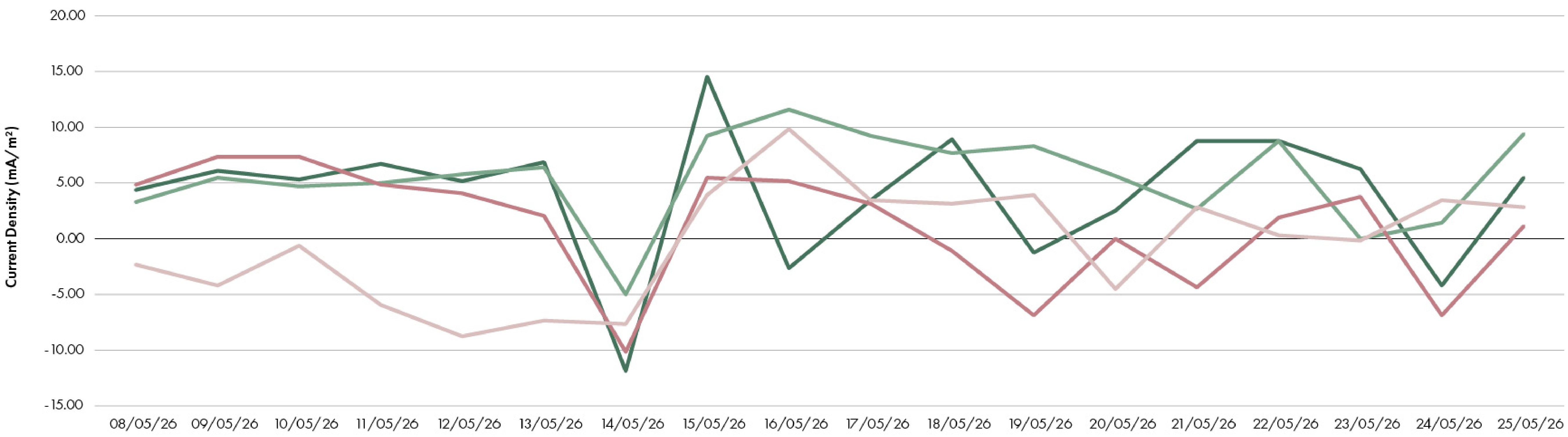


	08/05/26	09/05/26	10/05/26	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26	16/05/26	17/05/26	18/05/26	19/05/26	20/05/26	21/05/26	22/05/26	23/05/26	24/05/26	25/05/26
Sample 5	0.03	0.04	0.03	0.04	0.03	0.04	-0.08	0.09	-0.02	0.02	0.06	-0.01	0.02	0.06	0.06	0.04	-0.03	0.04
Sample 6	0.02	0.04	0.03	0.03	0.04	0.04	-0.03	0.06	0.08	0.06	0.05	0.05	0.04	0.02	0.06	0.00	0.01	0.06
Sample 7	0.03	0.05	0.05	0.03	0.03	0.01	-0.07	0.04	0.03	0.02	-0.01	-0.04	0.00	-0.03	0.01	0.02	-0.04	0.01
Sample 8	-0.02	-0.03	0.00	-0.04	-0.06	-0.05	-0.05	0.03	0.06	0.02	0.02	0.03	-0.03	0.02	0.00	0.00	0.02	0.02

10.13 Appendix 13: Current Density Results

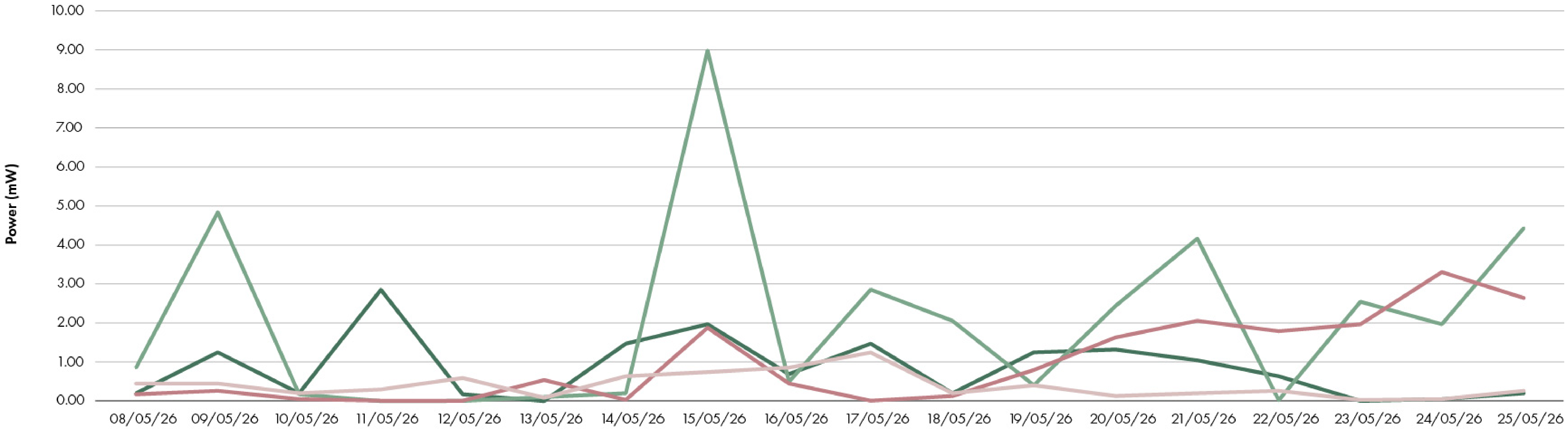


	08/05/26	09/05/26	10/05/26	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26	16/05/26	17/05/26	18/05/26	19/05/26	20/05/26	21/05/26	22/05/26	23/05/26	24/05/26	25/05/26
Sample 1	2.19	5.47	-2.19	-8.29	2.03	-0.16	-5.94	6.88	-4.07	-5.94	-2.19	-5.47	-5.63	-5.00	-3.91	-0.31	-1.09	2.19
Sample 2	4.53	10.79	-2.03	-0.16	-0.31	-1.56	-2.19	14.70	3.44	-8.29	-7.04	3.13	-7.66	-10.01	-0.63	7.82	-6.88	10.32
Sample 3	2.03	2.50	1.09	0.47	0.47	3.60	0.78	6.72	3.28	0.47	1.72	-4.38	-6.25	7.04	-6.57	-6.88	-8.91	-7.97
Sample 4	3.28	3.28	2.19	2.66	3.75	1.41	-3.91	4.22	4.53	5.47	2.19	3.13	1.72	2.19	2.50	0.78	1.09	2.50

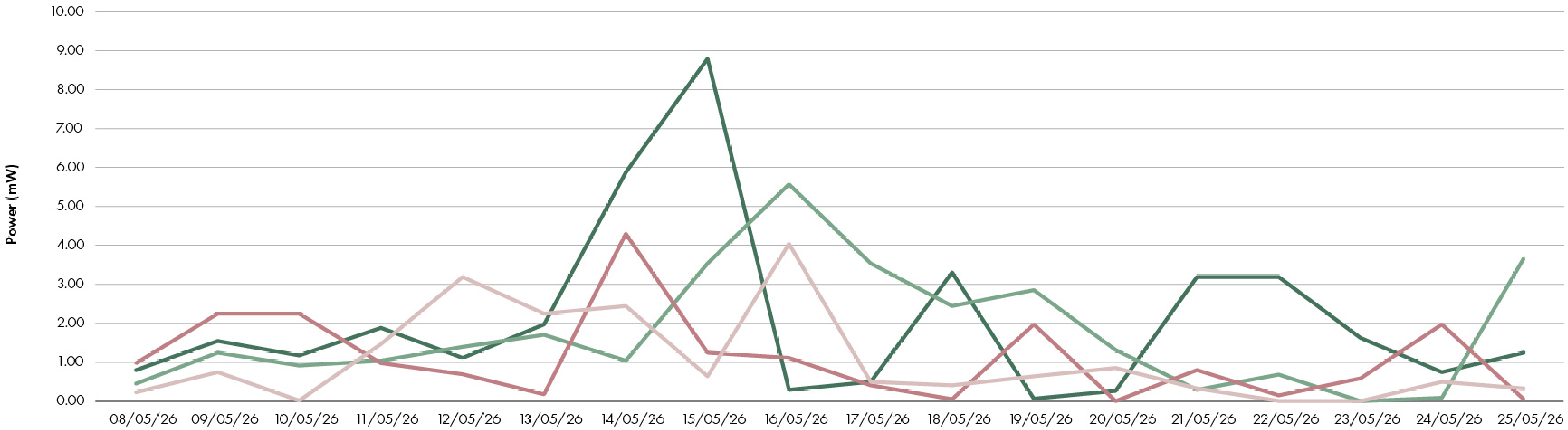


	08/05/26	09/05/26	10/05/26	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26	16/05/26	17/05/26	18/05/26	19/05/26	20/05/26	21/05/26	22/05/26	23/05/26	24/05/26	25/05/26
Sample 5	4.38	6.10	5.32	6.72	5.16	6.88	-11.88	14.54	-2.66	3.44	8.91	-1.25	2.50	8.76	8.76	6.25	-4.22	5.47
Sample 6	3.28	5.47	4.69	5.00	5.78	6.41	-5.00	9.22	11.57	9.22	7.66	8.29	5.63	2.66	8.76	0.00	1.41	9.38
Sample 7	4.85	7.35	7.35	4.85	4.07	2.03	-10.16	5.47	5.16	3.13	-1.09	-6.88	0.00	-4.38	1.88	3.75	-6.88	1.09
Sample 8	-2.35	-4.22	-0.63	-5.94	-8.76	-7.35	-7.66	3.91	9.85	3.44	3.13	3.91	-4.53	2.81	0.31	-0.16	3.44	2.81

10.14 Appendix 14: Power Results

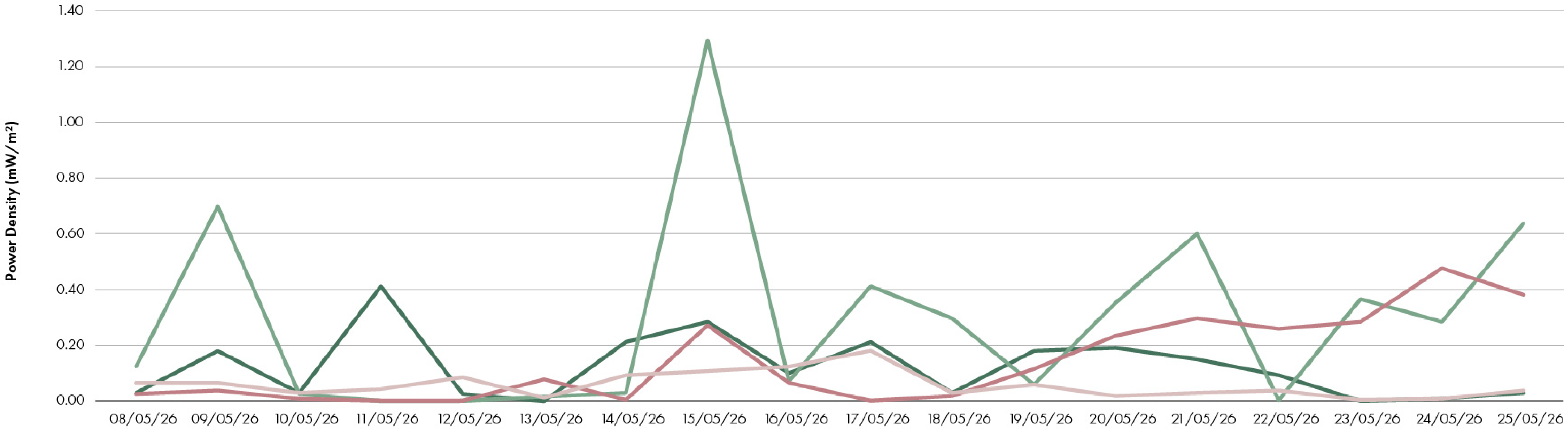


	08/05/26	09/05/26	10/05/26	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26	16/05/26	17/05/26	18/05/26	19/05/26	20/05/26	21/05/26	22/05/26	23/05/26	24/05/26	25/05/26
Sample 1	0.20	1.24	0.20	2.85	0.17	0.00	1.47	1.97	0.69	1.47	0.20	1.24	1.32	1.04	0.64	0.00	0.05	0.20
Sample 2	0.85	4.84	0.17	0.00	0.00	0.10	0.20	8.98	0.49	2.85	2.06	0.41	2.44	4.16	0.02	2.54	1.97	4.43
Sample 3	0.17	0.26	0.05	0.01	0.01	0.54	0.03	1.88	0.45	0.01	0.12	0.80	1.63	2.06	1.79	1.97	3.30	2.64
Sample 4	0.45	0.45	0.20	0.29	0.59	0.08	0.64	0.74	0.85	1.24	0.20	0.41	0.12	0.20	0.26	0.03	0.05	0.26

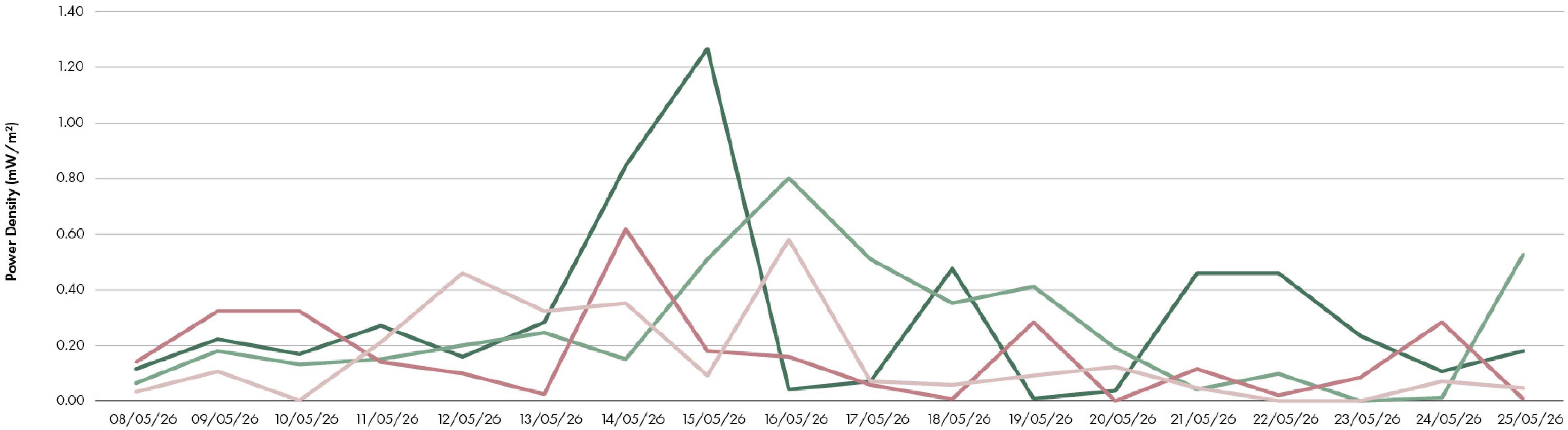


	08/05/26	09/05/26	10/05/26	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26	16/05/26	17/05/26	18/05/26	19/05/26	20/05/26	21/05/26	22/05/26	23/05/26	24/05/26	25/05/26
Sample 5	0.80	1.55	1.17	1.88	1.11	1.97	5.87	8.79	0.29	0.49	3.30	0.07	0.26	3.19	3.19	1.63	0.74	1.24
Sample 6	0.45	1.24	0.91	1.04	1.39	1.71	1.04	3.54	5.57	3.54	2.44	2.85	1.32	0.29	0.68	0.00	0.08	3.66
Sample 7	0.98	2.24	2.24	0.98	0.69	0.17	4.29	1.24	1.11	0.41	0.05	1.97	0.00	0.80	0.15	0.59	1.97	0.05
Sample 8	0.23	0.74	0.02	1.47	3.19	2.24	2.44	0.64	4.03	0.49	0.41	0.64	0.85	0.33	0.00	0.00	0.49	0.33

10.15 Appendix 15: Power Density Results



	08/05/26	09/05/26	10/05/26	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26	16/05/26	17/05/26	18/05/26	19/05/26	20/05/26	21/05/26	22/05/26	23/05/26	24/05/26	25/05/26
Sample 1	0.03	0.18	0.03	0.41	0.02	0.00	0.21	0.28	0.10	0.21	0.03	0.18	0.19	0.15	0.09	0.00	0.01	0.03
Sample 2	0.12	0.70	0.02	0.00	0.00	0.01	0.03	1.29	0.07	0.41	0.30	0.06	0.35	0.60	0.00	0.37	0.28	0.64
Sample 3	0.02	0.04	0.01	0.00	0.00	0.08	0.00	0.27	0.06	0.00	0.02	0.11	0.23	0.30	0.26	0.28	0.48	0.38
Sample 4	0.06	0.06	0.03	0.04	0.08	0.01	0.09	0.11	0.12	0.18	0.03	0.06	0.02	0.03	0.04	0.00	0.01	0.04



	08/05/26	09/05/26	10/05/26	11/05/26	12/05/26	13/05/26	14/05/26	15/05/26	16/05/26	17/05/26	18/05/26	19/05/26	20/05/26	21/05/26	22/05/26	23/05/26	24/05/26	25/05/26
Sample 5	0.11	0.22	0.17	0.27	0.16	0.28	0.85	1.27	0.04	0.07	0.48	0.01	0.04	0.46	0.46	0.23	0.11	0.18
Sample 6	0.06	0.18	0.13	0.15	0.20	0.25	0.15	0.51	0.80	0.51	0.35	0.41	0.19	0.04	0.10	0.00	0.01	0.53
Sample 7	0.14	0.32	0.32	0.14	0.10	0.02	0.62	0.18	0.16	0.06	0.01	0.28	0.00	0.11	0.02	0.08	0.28	0.01
Sample 8	0.03	0.11	0.00	0.21	0.46	0.32	0.35	0.09	0.58	0.07	0.06	0.09	0.12	0.05	0.00	0.00	0.07	0.05