Acta Structilia 2024 31(1): 43-83

Karen Botes

Dr Karen Botes, University of Pretoria, South Africa, Private Bag X20 Hatfield, Pretoria, 0028. Phone: +2782 893 4702. Email: <karen.botes@up.ac.za>, ORCID: https://orcid.org/0000-0001-8227-8716

Published by the UFS
http://journals.ufs.ac.za/index.php/as

ISSN: 1023-0564 • e-ISSN: 2415-0487

OPEN ACCESS

Received: February 2024
Peer reviewed and revised: April 2024
Published: June 2024

KEYWORDS: performance, efficiency, living walls, green walls, outdoor, modular, living wall systems

HOW TO CITE: Botes, K. 2024. Living walls: Upscaling their performance as green infrastructure. *Acta Structilia*, 31(1), pp. 43-83.

LIVING WALLS: UPSCALING THEIR PERFORMANCE AS GREEN INFRASTRUCTURE

RESEARCH ARTICLE[1]

DOI: https://doi.org/10.38140/as.v31i1.7942

ABSTRACT

Living wall systems (LWSs) can provide biophilic value and ecosystem services as part of the quest for sustainable development. Despite their benefits and potential to mitigate global challenges such as cooling, air purification, sound absorption, and human well-being, their economic feasibility, resilience, maintenance, and sustainability impact on their application and use. This article gives an overview of a pragmatic study which synthesised the factors hampering LWSs' performance as green infrastructure (GI) and analysed the performance of outdoor modular LWSs as GI. The study aims to establish criteria for selecting the most suitable LWSs as green infrastructure. Data capturing involved a mixed-method methodology. Local experts provided insight into local LWS typologies through questionnaires, which were analysed qualitatively. The six-month experimental study involved two selected LWSs of $4m^2$ each in extent on the University of Pretoria's Future Africa campus in Pretoria, in South Africa's Gauteng province. Variables included minimum and maximum daily temperatures, relative humidity, precipitation, soil temperature, water content and electrical conductivity, leaf biomass yield, and plant stress. The researcher monitored fresh and dry biomass yields with a calibrated laboratory balance as the

---

[1] DECLARATION: The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

primary performance indicator. Plant stress, the secondary performance indicator, was measured by chlorophyll fluorescence analysis. Experimental data were statistically analysed. The findings lay the groundwork for improving LWSs as GI, which can contribute to more sustainable cities. This is achieved by defining LWSs' technical characteristics to enhance their performance as GI. The results favour locally produced, low-technology, outdoor modular LWSs with limited, robust, lightweight, recycled components entailing uncomplicated assembly. Systems must involve low-technology irrigation. The LWS position should consider the plant crops' light requirements and pollution. Pots should receive limited sun exposure and have a soil volume of 3 litres and a minimum depth of 200mm.

ABSTRAK

As deel van die strewe na volhoubare ontwikkeling, kan lewende muurstelsels biofiliese waarde en ekosisteemdienste verskaf. Ten spyte van hul voordele en potensiaal om globale uitdagings krisisse aan te spreek, beperk hul ekonomiese haalbaarheid, veerkragtigheid, instandhouding en volhoubaarheid hul toepassing en gebruik. Hierdie artikel gee 'n oorsig van 'n pragmatiese studie wat die faktore wat lewende mure se prestasie as groen infrastruktuur (GI) belemmer, evalueer het, en die werkverrigting van buitemuurse modulêre lewende mure as GI ontleed het. Die doel is om 'n stel kriteria te ontwikkel om die mees geskikte LWS vir groen infrastruktuur te bepaal. Datavaslegging het 'n gemengde metode-metodologie behels. Plaaslike kundiges het deur middel van vraelyste insig gegee in plaaslike lewende mure-tipologieë. Die ses maande-lange eksperimentele studie het twee geselekteerde LWSs van 4m^2 elk in omvang op die Universiteit van Pretoria se Future Africa-kampus in Pretoria, in Suid-Afrika se Gauteng-provinsie, behels. Veranderlikes het minimum en maksimum daaglikse temperature, relatiewe humiditeit, neerslag, grondtemperatuur, waterinhoud en elektriese geleidingsvermoë, blaarbiomassa-opbrengs en plantstres ingesluit. Die navorser het vars en droë biomassa-opbrengste gemonitor met 'n gekalibreerde laboratorium skaal as die primêre prestasie-aanwyser. Plantstres, die sekondêre prestasie-aanwyser, is deur chlorofilfluoressensie-analise gemeet. Data is statisties ontleed. Die bevindinge lê die grondslag vir die verbetering van lewende mure as GI wat kan bydra tot meer volhoubare stede. Dit word bereik deur tegniese kenmerke vir lewende mure te definieer om hul werkverrigting as GI te verbeter. Die resultate bevoordeel plaaslik vervaardigde, lae-tegnologie, buitemuurse modulêre lewende mure met beperkte, robuuste, liggewig, herwonne komponente wat ongekompliseerde samestelling behels. Stelsels moet lae-tegnologie besproeiing behels. Die lewende muur-posisie moet die plantgewasse se ligvereistes en besoedeling in ag neem. Potte moet beperkte sonblootstelling kry, en 'n grondvolume van 3 liters en 'n minimum diepte van 200mm hê.

1. INTRODUCTION

Green façades, with climbing or hanging plants to cover the surface, have been expanded into living walls through technological development. In inner cities with limited ground space, the potential area for façade greenery is almost double the footprint of buildings (Köhler, 2008: 423). Green walls, therefore, have the potential to offer more environmental benefits than green roofs, in addition to their biophilic benefits. Biophilia, which entails the importance of the human tendency to connect with nature in human well-being (Lee, 2019: 141), is an important design consideration for architects, landscape architects, town planners, and urban designers.

Since the introduction of the first living wall in 1986 by Patrick Blanc, regarded as the modern inventor of living walls, the latter have been popular for their biophilia and visual appeal. Living wall benefits (to former green façades) include a more consistent growth over the entire vertical surface (Manso & Castro-Gomes, 2015: 863). Living walls' value lies much deeper than their biophilic value and aesthetical appeal, as there are many direct and indirect benefits to delivering ecosystem services. Ecosystem services are benefits from the natural environment provided to human beings through provisioning, supporting, cultural, and regulating services, in order to mitigate urbanisation impacts such as food provision, addressing climate change, water management, and air pollution (Perez & Perini, 2018: 17). Environmental benefits of LWSs include reducing indoor building environments by up to 10ºC (Radić *et al*., 2019: 1) and cooling adjacent outdoor surfaces by up to 11.5ºC (Goel, Jha & Khan, 2022: 38722; Perez *et al*., 2014: 139). Moreover, a study found that, besides fibreglass board, LWSs as green infrastructure on building façades are the most effective building material for reducing noise (Azkorra *et al*., 2015: 55; Goel *et al*., 2022: 38721). In addition to cooling and noise mitigation, plants in LWSs also improve air quality by absorbing carbon dioxide and releasing oxygen (Goel *et al*., 2022: 38721).

However, several factors hamper the performance and efficiency of living walls. Should their efficiency be enhanced, including LWSs as green infrastructure in cities, it could contribute to sustainable cities and communities (Botes, 2024: 39). Green infrastructure can be described as high-quality urban green networks that enhance biodiversity and provide ecosystem services (Dover, 2015: 747; Perez & Perini, 2018: 4). Green infrastructure is, therefore, part of the natural environment and provides human health, well-being, and restorative living (Firehock & Walker, 2015: 2). Examples of green infrastructure can include tree canopies, parks, living walls, green roofs, rain gardens, urban agriculture, permeable surfaces, and green streets (EPA, 2024). Despite the biophilic benefits of LWSs and their potential as green infrastructure to mitigate global challenges such as sustainable cities and climate change, their economic feasibility and sustainability remain questionable. This is due to high inset costs, maintenance requirements, high carbon footprints, and low resilience (Ottelé *et al*., 2011: 3419; Perini & Rosasco, 2013: 120; Larcher *et al*., 2018: 31). Thus, the current factors hampering the performance of LWSs need to be identified, in order to suggest technical guidelines that will improve their performance as green infrastructure (Mårtensson, Fransson & Emilsson, 2016: 84; Russo *et al*., 2017: 53; Ling & Chiang, 2018: 187). More efficient and resilient LWSs will equip architects and landscape architects to achieve biophilic benefits in dense urban city environments with limited horizontal space and more sustainable city environments.

This article provides an overview[2] of a six-month experimental study, which compared the performance of two outdoor modular LWSs and leafy African vegetables (AV) with conventional soil-based urban food production and a mainstream crop during the 2021/2022 growing season in Gauteng, South Africa (Botes, 2022). The study aimed to develop criteria for selecting LWSs based on their performance as green infrastructure in response to the research question: How can the technical characteristics of modular LWSs improve their performance as edible green infrastructure for growing AV in local urban conditions (Gauteng, South Africa)?

The empirical findings of this study lay the groundwork for improving LWSs as GI, which can contribute to more sustainable cities and communities. This is achieved by identifying LWSs' technical characteristics to enhance their performance as GI. This article contributes to existing knowledge of LWSs, by synthesising the factors affecting outdoor modular LWSs' efficiency as well as monitoring and analysing the performance of the selected LWSs' typologies in providing optimal growing conditions (technical characteristics) for local crops as green infrastructure in local urban environments in Gauteng, South Africa. However, the value of this study is not limited to South Africa, as the performance of LWSs is a global problem.

2. LITERATURE REVIEW

2.1 Living wall systems

Green or living walls, also referred to as vertical greenery systems (VGS) or LWSs, typically form part of building façades (Köhler, 2008: 423) and comprise vegetation in the wall structure or on the vertical surface (Vosloo, 2016: 43). Living walls are rooted in the walls or in a substrate attached to the walls itself (Francis & Lorimer, 2011: 1429), using technology or material to support the plant material (Manso & Castro-Gomes, 2015: 863). Living walls thus make use of planter boxes or plant growth facilitated through systems on interior or exterior walls that do not require rooting space at ground level (Köhler, 2008: 423) and increase the range of species that can be utilised (Vosloo, 2016: 44).

LWSs are categorised into continuous and modular systems (Manso & Castro-Gomes, 2015: 863). While modular systems incorporate substrates and consist of containers with predefined dimensions and a variety of compositions, weights, and assembly techniques, continuous systems involve lightweight screens without a substrate, with water and nutrient supply for plant development (Manso & Castro-Gomes, 2015: 863).

---

[2] This article entails an excerpt and provides an overview of the performance of LWSs following the research (Author, 2024).

Continuous systems include hydroponics, aquaponics, and aeroponics (Botes & Breed, 2021: 147).

In addition to their aesthetic value, outdoor living walls provide numerous functional direct and indirect benefits to deliver ecosystem services and increase the sustainability of cities and human health and well-being (Collins, Schaafsma & Hudson, 2017:114; Ling & Chiang, 2018: 187). These primarily include regulating ecosystem services, which involve improving environmental conditions and cultural ecosystem services entailing psychological and recreational benefits (Ode Sang, Thorpert & Fransson, 2022: 3, 11). Living walls mitigate noise and insulate sound (Davis *et al*., 2017: 62). Studies show that LWSs with increased plant cover and leaf area index in narrow streets are the most effective in mitigating noise (Ode Sang *et al*., 2022: 11). Moreover, depending on the plant palette, LWSs can potentially attract birds and add positive sounds to an area (Ode Sang *et al*., 2022: 11). LWSs provide improved thermal cooling to direct adjacent environments, with high-density planting, well-saturated, deeper substrates, and certain vegetation traits such as leaf area index and leaf morphology, leading to more effective cooling through evapotranspiration (Köhler, 2008: 423; Price, Jones & Jefferson, 2015; Davis & Hirmer, 2015: 135; Coma *et al*., 2017: 228; Yang *et al*., 2018: 43; Ode Sang *et al*., 2022: 9). Besides cooling through evapotranspiration, LWSs can also provide cooling through wind or sun screening (Cameron, Taylor & Emmett, 2014: 198). Similarly to noise reduction and cooling, LWSs with a high vegetation density, leaf area index, and leaf morphology were found to be more effective in reducing particulate matter and gaseous pollutants such as nitrogen and sulphur oxides and carbon dioxide close to the pollution source (Francis & Lorimer, 2011: 1429; Ode Sang *et al*., 2022: 11). Although increased biodiversity (Collins *et al*., 2017: 114) is considered a benefit, the variety and quality of habitats are questioned (Mayrand & Clergeau, 2018: 1), requiring more research on integrating LWSs and green roofs into natural systems, in order to enhance ecosystem services (Bartesaghi Koc, Osmond & Peters, 2017:15). Another recent area of interest is urban small-scale, vertical outdoor food production (Nagle, Echols & Tamminga, 2017: 23; Botes & Breed, 2021: 165; Botes & Breed, 2022: 1). Localised food production holds significant benefits in terms of contributing to ecosystem services and decreasing greenhouse gas (GHG) emissions, due to the reduced transportation of food from remote areas (Lee, 2019: 1; Russo *et al*., 2017: 53). Edible green infrastructure (EGI) provides ecosystem services integral to sustainable cities (Russo *et al*., 2017: 53; Ling & Chiang, 2018: 187; Russo & Cirella, 2019: 1).

A life cycle analysis of LWSs in Delft, The Netherlands, found that their environmental burden exceeds their cooling benefits (Ottelé *et al*., 2011: 3419). Another cost-benefit analysis, which compared the installation, maintenance, and disposal costs to the social benefits (including real estate value, energy demand reduction, durability and air quality improvement) over the life cycle of the analysed systems, confirmed that LWSs are not economically feasible (Perini & Rosasco, 2013: 110).

2.2 Factors hampering the performance of LWSs

LWSs should be viewed as integrated units or systems, including increasing crop performance by addressing the suitability of the plant palette (Russo & Cirella, 2019: 1; Russo *et al*., 2017: 53), increasing the social benefits (Perini & Rosasco, 2013: 110), and reducing irrigation and energy usage (Beacham, Vickers & Monaghan, 2019: 277; Natarajan *et al*., 2015: 1) as equally important factors in the system's performance. The literature highlights four main factors hampering the performance of LWSs globally. These include the cost efficiency of LWSs, low resilience, high maintenance, and carbon footprint (Botes & Breed, 2022: 1).

2.2.1 Cost efficiency

Despite their benefits in delivering ecosystem services, living walls are still underutilised as green infrastructure globally, due to the high financial output (Liberalesso *et al*., 2020: 1). Imported systems with complicated assembly, requiring specialised skills and technology, impact on the installation and maintenance costs of LWSs (Botes, 2024: 46).

Increasing social benefits and improving environmental conditions for cities through ecosystem services could lead to government incentives to improve the economic feasibility of LWSs (Perini & Rosasco, 2013: 110; Medl, Stangl & Florineth, 2017: 227; Botes & Breed, 2022: 1). Few countries have government incentives for green infrastructure, with the biophilic value only visible in occupancy rates (Liberalesso *et al*., 2020: 1) and decision-making in the hospitality sector (Lee, 2019: 141). However, although the value of biophilic benefits (Mårtensson *et al*., 2016: 84; Ling & Chiang, 2018: 187), biodiversity and noise reduction (Collins *et al*., 2017: 114) are recognised, these benefits are difficult to monetise and include in cost-benefit analyses. A study testing 500 Tokyo residents' perceptions of green infrastructure, where the installation of LWSs and green roofs have been mandatory since 2001, found that residents appreciated thermal comfort, air quality, and biophilic value (Jim, Hui & Rupprecht, 2022: 35). However, high installation and maintenance costs are among the negative experiences of LWSs, as well as the government policy enforcing the installation of green infrastructure, with more appreciation from pro-environmental citizenry (Jim *et al*., 2022: 39).

2.2.2 Resilience

Resilience refers to a system's ability to adapt to changes such as climate change and recover to a balanced state while retaining its operation (Panagopoulus, Jankovska & Dan, 2018: 56). Resilient systems are less vulnerable and can recover more easily from disturbances. This is especially relevant in living walls with intensified stresses, due to their shallow and limited soil conditions and specific light, wind, and water requirements, as limited plant species can adapt to these requirements. Therefore, the resilience of LWSs depends on selecting suitable plant species. Plants found to perform best in LWSs include hemicryptophytes, which are perennials with renewal buds located near the soil surface and annuals, which are plants that complete their life cycle in one growing season (Van Mechelen, Dutoit & Hermy, 2014: 88; Yalcinalp & Meral, 2017: 1). Another study found that indigenous succulent cremnophytes, plants growing on cliff faces, are successful in LWSs (Vosloo, 2016: 42).

Fundamental design flaws and the system's resilience can result in failures of LWSs (Gunawardena & Steemers, 2020: 526). A simplistic, robust system, with limited parts comprising a low-technology irrigation system improves the resilience of living walls.

2.2.3 Maintenance

Perceptions of LWSs' installation and maintenance costs were found to impact on the incorporation of skyrise greenery projects in Singapore in 2016, despite Green Building rating system initiatives (Huang *et al*., 2019b: 437). Their maintenance was found to contribute to the highest expenditure (Huang *et al*., 2019b: 437). Maintenance challenges were identified as unequal water provision on all plant levels, insufficient light availability, and accessibility for maintenance if systems are too high above ground level (Beacham *et al*., 2019: 277). Moreover, Natarajan *et al*. (2015: 1) suggest that irrigation and plant selection lead to high water usage during the operational phase of LWSs, increasing their life-cycle energy usage and GHG emissions.

A study assessing maintenance challenges in eight outdoor and two indoor European LWSs listed plant stress management, due to local climate extremes and light exposure, as a significant maintenance consideration, with the high maintenance costs listed as a secondary concern (Gunawardena & Steemers, 2020: 526). Moreover, other maintenance issues were identified, including irrigation. Modular systems were found to require lower maintenance than hydroponic systems (Gunawardena & Steemers, 2020: 526). Higher systems result in higher wastage, with waterlogging leading to water stress. Other maintenance issues involved nutrient supply in the form of nitrogen (N), phosphorous (P), and potassium (K) and washing of leaves in high-pollution areas to mitigate particulate matter (PM), minerals and sulphur dioxide, and nitrogen oxides. Trimming of plants is necessary to mitigate overshadowing, especially in the case of high planting densities. Pests, diseases, and weed control, although limited, are required, with infrastructure maintenance of the system listed as a maintenance factor to be considered.

2.2.4 Carbon footprint

Hydroponic felt-based systems require more energy and water than modular systems and more plant material replacement (Gunawardena & Steemers, 2020: 526). Manufacturing, with the type of materials used, location of production, and assembly of the system, including transportation and end-of-life disposal, impact on the carbon footprint (Natarajan, 2015: 1; Botes & Breed, 2022: 4), although the operational phase of LWSs has the highest impact on the total life-cycle burden due to water and energy use (Natarajan *et al.*, 2015: 1). Measures such as water harvesting, drip irrigation, a pumpless gravity-fed watering system, and drought-tolerant plant species are required, in order to reduce their carbon emissions (Natarajan *et al.*, 2015: 1; Botes & Breed, 2022: 4).

3. STUDY SITE

The City of Tshwane Metropolitan Municipality (Tshwane) was regarded as a good study area, due to the area's urbanisation, poverty, unemployment, poor education, and health problems (see Figure 1).

Figure 1: Location of the Gauteng province and Tshwane area, including Pretoria

Source: OrangeSmile Tours B.V., 2024

Tshwane falls within the monsoon-influenced humid subtropical climate area (Cwa), according to the Köppen-Geiger climate classification (Engelbrecht & Engelbrecht, 2016: 247). Tshwane's annual precipitation is approximately 580mm. Mean minimum temperatures range between 5ºC and 7ºC and mean maximum temperatures between 28ºC and 30ºCbased on 1991 to 2020 data (SA Weather Service, 2022: 12).

Following the funding of the experiment construction through Innovation Africa, the University of Pretoria's Future Africa campus (25.7515° S, 28.2608° E) in the Tshwane area was selected as the study site. Moreover, the study site fits in well with the theme of the Future Africa campus, which entails urban food gardens. The site was also chosen due to its characteristics, representing a typical urban area, as it consists of 50% built-up cover, including buildings, paved surfaces, and roads (Schneider, Friedl & Potere, 2010: 1733). It was essential to select a full-sun area to provide for the microclimatic requirements of traditional African vegetables. The north-facing kitchen yard wall of the campus was selected for the experiment (see Figure 2), as it entailed a 12m^2 area with no shade interference. Further selection criteria included water and electrical supply, easy access for construction, maintenance and data collection, minimal chances of interference with the LWSs' irrigation and maintenance, and legal and campus facility compliance. The University's Department of Facilities Management Permission approved the study site based on the aesthetics, functionality, and maintenance requirements of the proposed living walls.

Figure 2: The north-facing kitchen yard wall at the Future Africa campus that was selected as the experimental study site

Source: Author, 2024.

4. MATERIAL AND METHODS

4.1 Research design

This research is positioned in the pragmatist paradigm, involving a real-world field experiment (Falk & Heckman, 2009: 535) and a realistic problem-solving approach (Frey, 2018). The study involved a literature review followed by a purposeful, carefully selected mixed-method methodology sequence to select the LWS typologies qualitatively and a quantitative experimental study to measure the LWS performance. The mixed-method approach combines qualitative and quantitative investigation, enabling a more comprehensive, in-depth analysis of, and insight into the research problem, combining the strengths of each method to inform theory and practice (Almalki, 2016: 293). It also allows for using descriptive data analysis to identify patterns and summarise data, show frequencies, and use inferential data analysis to gain insight into the trends and relationships between variables (Migiro & Magangi, 2011: 3762). The six-month experimental study measured the performance of two selected LWS typologies to compare the preset criteria. Data collection entailed primary and secondary data, which were statistically analysed. The reason for selecting a mixed method study was to enable the researcher to elaborate on specific findings from the breakdown of the questionnaire responses and cross-check this data against the dataset from the experiment, such as similarities in the technical specifications for LWS (Creswell & Plano-Clark, 2018: 27).

4.2 Population and sampling

4.2.1 Population and sample size for the LWS questionnaires

The study entailed purposive non-probability followed by snowball sampling, as the study aimed to identify experts best suited in the field of LWSs and involved limited knowledge sources who were challenging to identify (Nikolopoulou, 2023a). The researcher focused on including experts who have completed at least three LWS projects in Gauteng, South Africa. Experts are professionals regarded by their peers as authorities in a field based on qualifications, skills, and experience. For the study population, Gauteng members of the Institute of Landscape Architecture South Africa (ILASA) (membership n = 63) and South African Landscapers Institute (SALI) (membership n = 90), regarded as experts, were approached. A total of six experts were identified in the first round. Based on the initial consultation, the researcher visited at least 15 LWS projects in Pretoria and Johannesburg, Gauteng, in 2019, extending the sample population (n = 9). The researcher is confident that all known commercial projects with edible LWSs in Gauteng were identified and visited. Following referrals from the initial panel of experts through snowball sampling, the sample was further extended (n =11) in the third and final rounds. Of the population of 11 experts identified in Gauteng, seven respondents participated in the study. The researcher considered the small respondent sample group sufficient and representative of experts in LWSs, as snowball sampling was implemented through three rounds. The expertise of the participants/experts was diverse, covering the supply, design, and construction of LWSs. All participants/experts on the referral lists were included in the population.

4.2.2 Sample size for the experimental phase

There were two LWS typologies, and natural soil was used as the control, with nine AV crops and a commercial crop as the control. The AV crops were selected through a literature review and expert input prior to the experimental stage of the research study (Botes, 2024: 99).

Two living walls, namely the Eco Green and the Vicinity Walls, were installed as part of the experiment with nine AV species. The LWSs were selected based on an analysis of five systems identified by the experts through the questionnaires. The five systems were compared based on the selection criteria developed from the literature and questionnaire findings. Two walls were considered sufficient for this study, as one typology represented low technology, and the other represented an all-in-one high technology system.

Furthermore, funding and the study site's space capacity were considerations and limitations in the selection and quantity of LWSs. The sample size for each living wall comprised 80 plants, covering ten species (eight plants per species). The experimental study was limited to nine AV species, with one mainstream leafy dark green vegetable crop as control, to accommodate the study site's area and the researcher's capacity. The natural soil area, which serves as the control for the experiment, included 30 plants, three plants per species of each selected AV and the mainstream crop. The top three rows of each LWS were included in the data collection, with a plant from each species positioned in a randomised pattern in each row, amounting to 90 plants comprising ten species, including 30 plant crops per LWS typology and 30 plant crops in the control, the natural soil area. The mean and standard errors were calculated from three plants for all measurements.

4.3 Data collection

4.3.1 Literature review

To develop LWS selection criteria, an integrative literature review process was followed because the researcher collected data to combine different perspectives and fields of research rather than cover all published information on the performance of LWSs (Snyder, 2019: 333). The review process entailed the following steps: problem identification, literature search, data evaluation, selection of studies for inclusion, data analysis, and presentation in line with a framework (Whittemore & Knafl, 2005: 546). An initial search involved publications between 2017 and 2021 using the Scopus and ScienceDirect databases and Google Scholar with keywords on living walls with food plants.

4.3.2 Questionnaires on living wall systems

In addition to the literature review, data were collected between June 2019 and March 2020 from the sample expert group through a questionnaire electronically via email (Lavrakas, 2008). Emails included an introductory explanation of the project, and a self-completion questionnaire was attached. The questionnaire was designed to capture expert opinions on LWSs currently used for projects in South Africa. The questionnaire consisted of six open-ended questions on specific qualities that are important to use as selection criteria for LWS. These included types of LWSs, maintenance, challenges, dimensions, orientation, and technical specifications. The open-ended questions allow for more detailed and in-depth responses to LWS selection criteria than closed-ended questions (McCombes, 2023).

4.3.3 Experimental design data collection

The experimental stage involved the construction of the two selected systems. The first system, the Vicinity Wall, represents a high-technology system, and the second system, the Eco Green Wall, is a low-technology system. The control was a natural soil area in which the crops were planted in conventional agricultural conditions for comparison with the two LWS typologies.

The LWSs were constructed in October 2020, with nine AV crops and one mainstream crop established between October 2020 and September 2021. Crops were planted as plugs, rooted seedlings or seeds, and one plug per pot was planted. Randomisation is critical for comparing groups to ensure maximum validity for statistical tests (Kang, Ragan & Park, 2008: 215). Therefore, using a complex algorithm, the AV crops were randomised in each LWS through a pseudo-random number generator (Urbaniak & Plous, 2013). The researcher positioned one plant per species in each row according to the randomised pattern.

The pots of each system were filled with a soil mixture comprising potting soil, river sand, and perlite (ratio 1:4:1) to ensure sufficient aeration, optimal pH and nutrient levels. The soil mixture was slightly alkaline, with a pH of 7.6. A granular slow-release nitrogen fertiliser comprising four macro-nutrients, nitrogen, phosphate, potassium and carbon, was added at the onset of the experimental study in October 2020, and a slow-release nitrogen fertiliser comprising three macro-elements, nitrogen, phosphate and potassium, was applied a year later.

The Future Africa gardens involve automated and manual irrigation areas fed by harvested water stored in a retention dam on the campus; therefore, minimal potable water is used only in the case of the harvesting system's failure. The experiment's control (natural soil area) falls in a manual irrigation area and is watered thrice weekly for 15 minutes by the campus maintenance team. The Vicinity system was connected to a digital programmable timer and watered four times weekly. The Eco Green Wall system was watered daily by an automated battery-operated controller for the data-collection period.

Data were collected from the top three rows in each system for six months, from 1 November 2021 to 30 April 2022, after all crops were established. The variables included minimum and maximum daily temperatures, relative humidity, precipitation, soil temperature, water content and electrical conductivity, leaf biomass yield, and plant stress.

The researcher monitored fresh and dry biomass yields as the first performance indicator. Biomass yield, as the primary attribute of crops, indicates the productivity and profitability of the LWS/ natural soil area. Plant weight is an essential indicator of crop performance and yield (Wei-Tai *et al*., 2016: 256; Huang *et al*., 2019a). Crops were harvested once a month to determine the biomass. The researcher separated leaves from stems with a hand pruner, placed them in labelled brown bags, and weighed the fresh mass within three hours of harvesting to ensure consistent data. As performance indicators, crop yields (g FW plant−1) were monitored at harvest with a calibrated laboratory Mettler 4400 balance with a 5 to 4400g weight capacity and a measurement accuracy of 0.01g readability. After measuring the fresh weight of the leaves, they were dried in the University of Pretoria laboratory on the experimental farm. Similar to the weighing and recording of the fresh weight, the dry leaves of each plant per species per typology were measured using the electric balance after drying the plants at a constant temperature of 60°C for 72 hours in the laboratory drying ovens. The monthly fresh and dry weights of three plants per species per typology were recorded manually in a notebook and carried over to Excel.

For plant stress, the second performance indicator, measuring chlorophyll fluorescence with a portable fluorimeter, has been reported as an effective measuring tool of chlorophyll fluorescence to indicate plant adaptation and stress (Little & Rolando, 2003: 5; Kalaji *et al.*, 2014: 121). The researcher harvested one leaf per plant, three replicates per species per LWS typology and three per natural soil control area monthly for the empirical research period. Leaves were adapted to dark conditions for two hours, after which three readings each (nine readings per AV species per LWS typology or natural soil) were taken with a plant efficiency analyser.

Two parameters were measured. The first parameter, the quantum efficiency of the pigment-protein complex, Photosystem II (PSII) (F_v/F_m), has been reported as an indicator of water stress (Little & Rolando, 2003: 5; Ceusters *et al*., 2019: 1). The maximum quantum yield of photosystem II declines under most stress conditions and is, therefore, regarded as a critical plant stress indicator (Kim *et al*., 2019). To address technical errors, the researcher removed inconsistent F_v/F_m values from the readings downloaded in Microsoft Excel before finalising the datasets for statistical analysis based on the fast chlorophyll a-fluorescence induction (OJIP transient). The second parameter, the performance index, PI_{total}, is an indicator linked to plant and drought stress. The PI_{total} is a photosynthetic performance indicator that combines biophysical parameters and strongly correlates with plant growth, health, and survival rate (Yusuf *et al.*, 2010: 1428; Berner, Cloete & Shuuya, 2021: 1; Maliba, Inbaraj & Berner, 2019: 4).

4.4 Data analysis and how to interpret the results

4.4.1 Literature

A list of eight books and 115 articles were selected for the study after titles and abstracts of the peer-reviewed publications were screened for content on outdoor living walls and modular walls involving a growth medium. For analysis, these primary sources were divided into subgroups, including the efficiency of LWSs, outdoor edible LWS benefits, and ecosystem service provisioning of LWSs. The author selected only the literature categorised in living walls for this article, resulting in 51 journal articles that were included in the core review. Using thematic analysis based on frequency of appearance, nine categories (see Table 1) as criteria for selecting LWS typologies were identified (Braun & Clarke, 2006: 79)

4.4.2 Questionnaire

Data from the open-ended responses in the questionnaire were analysed through a qualitative thematic method (Braun & Clarke, 2006: 79). The researcher reduced data to the core categories by identifying and reporting specific phrases to achieve the aim of obtaining an understanding of LWS characteristics, efficiency, and typologies (Tetnowski, 2015: 43; Coffey, 2014: 370). Based on the frequency of occurrence, nine categories were identified for the technical characteristics as criteria for selecting the LWS typologies. These included the system, production, technology, material, installation, cost, plants, soil, and water.

The researcher developed the final system criteria for the LWS typology selection by combining phrases within these themes following the data analysis of the questionnaire findings with the literature review findings. These criteria, shown in Table 1, included that the system must be locally produced; contain recycled or recyclable material components to limit the carbon footprint; have an adequate soil volume of a minimum of 1,5 litres to support optimal growth; must include a drip irrigation system to minimise potable water consumption; must be cost-effective; must involve uncomplicated assembly and technology; must have a lightweight structure; must have a structure to support plant density for full vegetation cover and vegetation continuity (easy replacement of plants), and must be flexible for different scale installations.

The researcher analysed the LWSs listed by respondents in the questionnaire responses based on the nine system criteria to guide the selection of systems for the experimental stage of the study. Scores for each system were calculated by adding a score of one point for each criterion complied with and two for strong compliance with the criterion (see Figure 3).

4.4.3 Experiment

The study compared the biomass and plant stress for the living wall typologies, the natural soil as control, and the AV and control crops. The natural soil was selected as control to represent conventional agricultural practices. The local maximum temperatures, relative humidity, soil water content, soil temperature, soil electrical conductivity, and plant stress were compared to identify any external influences on the crop performance.

Biomass data were tested for uniform distribution using the numerical method, the Shapiro-Wilk test, before analysis, which showed that data came from a normally distributed population. Therefore, the one-way analysis of variance (ANOVA) and linear regression analysis tests were employed for the inferential statistics. Descriptive analysis was carried out for all numeric variables in the dataset. The pairwise Tukey's multiple comparison post-hoc tests were performed to compare crops and LWS typologies. Significance was set at a threshold of $p < 0.05$ between all genotypes. Concerning the post-hoc test results, effect size, which indicates the size of the association between two variables, is important for statistically significant combinations, as it indicates whether an effect is large enough to have practical significance (Bhandari, 2022). Hedge's g and Cohen's d are two measures of effect sizes with similar interpretations, although Hedge's g is unbiased and preferable for small sample groups below 20 (NIST, 2018: 1). Therefore, this study's effect sizes are categorised using Cohen's (1988) rule of thumb, where effect sizes of 0.20 are considered small, 0.50 medium, and 0.80 represent a large effect size.

The plant stress analysis was performed using IBM SPSS (version 28) software. Microsoft Excel and IBM SPSS (version 28) were used to produce graphs. The one-way Analysis of Variance (ANOVA) and the Pearson correlation coefficient tests were employed for the inferential statistics to compare groups and to assess relationships between climatic and soil data and plant stress. Descriptive analyses were carried out for all numeric variables in the dataset. Independent-sample T-tests and pairwise Tukey's multiple comparison post-hoc tests were performed to compare plant stress, crops, and LWS typologies. Significant differences were calculated at a threshold of $p < 0.05$ between all genotypes. Correlations were analysed by reporting on the type and strength of the relationship, measured by the correlation coefficient or r coefficient (Taylor, 1990:35), using the Pearson correlation coefficient. A direct relationship between variables is positive, where both variables increase in accordance with each other. By contrast, a negative correlation coefficient indicates an inverse relationship, with one variable decreasing following the increase of the other (Taylor, 1990: 35). Concerning the correlation strength, r coefficients equal to or below 0.35 are considered weak, 0.36 to 0.67 moderate, 0.68 to 1.0 strong, and equal to or above 0.90 very strong (Taylor, 1990: 35).

Findings related to productivity, installation, costs, and maintenance were analysed based on the researcher's observations and calculations. Area and footprint findings were calculated based on the plant's monthly yield per square meter per typology. These were compared to a benchmark average of fresh produce weight of 244g/m^2, based on the average mixed-crop small-scale conventional production rates of 2.44 kg/m^2 at the Rutgers Agricultural Experiment Station (Rabin *et al*., 2012 in Nagle *et al.*, 2017: 34).

4.5 Study limitations

The limited sample for the questionnaires to select LWSs [n=7] could be considered a study limitation. However, there are few experts on LWSs in South Africa, as this is a niche market. However, the criteria for expert selection and qualifications were well-defined. Moreover, the snowball sampling assisted the researcher in composing the expert panel based on the researcher's selection and expert input. This increased the sample size and extended the expert panel to a well-balanced group of professionals from different backgrounds to ensure an unbiased selection of LWSs.

The experimental study was conducted during a growing season in Pretoria (Gauteng province, South Africa), and the results apply to the monsoon-influenced humid subtropical (Cwa) Köppen-Geiger climate classification. Findings might, therefore, not be generalisable to other climatic regions in South Africa or the world, but are only applicable to areas with similar conditions (temperature, precipitation, water, humidity, wind, aspect, height, as well as soil volume, composition, and nutrient replenishment of soil cells). The results are limited to the selected and similar LWSs and AV species tested. Technical and efficiency recommendations can be applied to LWSs using matching technologies. External factors beyond the researcher's control impacted on the planned data-collection period. These included species loss due to consumption by local dassies (rock hyrax) and a faulty main irrigation system that interrupted the water supply in November 2021 and January 2022. The water shortage during this period impacted on the soil volumetric water content and electrical conductivity. Some of the initially planted species were incompatible with the system.

5. RESULTS

5.1 LWS selection criteria

The researcher developed the final criteria for selecting the LWS typologies by combining the findings from the literature review and the questionnaire findings. The criteria selection was finalised based on the similarities between the literature and the questionnaire findings in Table 1.

Table 1: LWS selection criteria

Main criteria	*Questionnaire*		*Literature review*	*Similarity between literature review and questionnaire*
	Freq (n=7)	*Expert response*		
System	7	The system must be soil-based	Modular LWSs with individual pots are more efficient (Huang *et al.*, 2019b: 450; Botes & Breed, 2022: 3)	Modular system must have a structure to support plant density for full vegetation cover and vegetation continuity (easy replacement of plants)
	5 2	The Vicinity and Eco Green Wall are the preferred local systems		
	2	Modiwall, Mobilane, and Growall systems are proposed as the second option		
Production	7	The system must be locally manufactured	The system must be locally produced (Botes & Breed, 2022: 2; Akinwolemiwa *et al.*, 2018: 277; Perini & Rosasco, 2013: 113)	Locally produced
Technology	7	The system must be easy to install	The system must involve low-skilled, non-specialised workmanship (Akinwolemiwa *et al.*, 2018: 277; Botes & Breed, 2021: 143) Recycled materials increase the feasibility (Ottelé *et al.*, 2011: 3424)	Uncomplicated assembly and technology
Material	5	Recycled or recyclable and robust material for the LWS components	Recycled materials increase the feasibility (Ottelé *et al.*, 2011: 3424)	Contain recycled or recyclable material components

Main criteria	*Questionnaire*		*Literature review*	*Similarity between literature review and questionnaire*
	Freq (n=7)	*Expert response*		
Installation	5	The system must be lightweight (structure and pots)		Flexible/adjustable installation
	5	The system must have modular expandable components to be flexible for different-scale installations		
	1	The system should be able to function on a free-standing basis without relying on walls and building façades		
	5	The system's height and size should ensure sufficient yields, while ensuring accessibility for harvesting and maintenance		
	1	Public safety through the secure fastening of the system is required		
	1	The system should have good insulation properties		
Cost	5	The system must have a low installation cost	The installation and maintenance costs must be reduced (Botes & Breed, 2021: 164; Huang *et al*., 2019b: 452; Akinwolemiwa *et al*., 2018: 287)	Be cost-effective
Plants	7	Plants should be grouped and positioned according to water and light requirements	Plant selection to integrate benefits increases resilience and performance (Russo & Cirella, 2019: 7; Russo *et al*., 2017: 62; Beacham *et al*., 2019: 1; Natarajan *et al*., 2015: 8)	Plant selection
	5	Plants with non-spreading, small, compact roots and above-ground parts used as vegetables should be selected		
	7	Plant species without limiting factors must be selected		

Main criteria	*Questionnaire*		*Literature review*	*Similarity between literature review and questionnaire*
	Freq (n=7)	*Expert response*		
Soil	7	A lightweight soil mixture should be used, considering water and nutrient-holding capacity, aeration and nutrient content, and the inclusion of water-retention agents		An adequate soil volume of a minimum of 1.5 litres to support optimal growth.
	5	The system must include plant containers with a sufficient growth-medium capacity		
Water	3	The irrigation system must provide for the low water requirements of AV, with manual irrigation added as an option	Reduced potable water usage during the operational phase through water harvesting, drip irrigation, and plant selection is essential (Natarajan *et al.*, 2015: 8)	A drip irrigation system must be included to minimise potable water consumption
	4	An automated irrigation system with water harvesting is required		
	7	Maintenance of the irrigation system and plants is required		

Source: Author, 2024

Based on Table 1, five LWSs are successfully used for growing crops. Five respondents proposed the Vicinity system, widely used for LWS projects in South Africa, while two suggested a newly patented system, the Eco Green Wall. Two respondents also listed the Modiwall, Mobilane, and Atlantis Growall systems. The Atlantis GroWall and Mobilane are supplied in South Africa, although they are manufactured in Australia and The Netherlands, respectively. Both systems are used for commercial and residential scale projects in South Africa. The Vicinity and Modiwall are locally manufactured systems comprising recyclable plastic pots for plants and growing mediums. In the Modiwall system, the growing medium is placed directly in modules. By contrast, in the Vicinity Wall, geotextile bags in hexagonal pots contain the growing medium, comprising three litres. The Modiwall system includes wall panels fixed to the building structure of the façade, to which pots with a growing medium capacity of almost one litre are clipped in. The Eco Green Wall system is locally manufactured in South Africa. It is a low-technology outdoor system comprising interlocking, lightweight recycled polystyrene aggregate, and cement mixture blocks stacked onto each other with seed trays as plant pots.

Relating to the system's qualities and technical specifications for optimal growing conditions, cost-effectiveness and uncomplicated installation were listed by five respondents as a critical performance consideration. Other considerations included modular expandable components that are flexible for different-scale installations, systems that can function on a free-standing basis without relying on walls and building facades, and systems with good insulation properties.

Local production and recycled or recyclable and robust material for the LWS components were listed as considerations to limit the system's ecological footprint. Systems with bigger capacity plant containers were proposed, although the selection of lightweight systems (pots and soil) was emphasised.

Although this article focuses on the LWS performance, plant selection should be considered, as systems should be viewed holistically. All the participants (7) recommended that the positioning of plants should consider grouping species with similar water and light requirements. Root size should be considered, and plants with spreading root systems should be avoided.

In response to the question on the required maintenance of these systems, respondents were unanimous in the view that maintenance is mainly focused on the irrigation system and planting, as the systems themselves need limited maintenance, due to the basic assembly and robust materials used. Concerning water and irrigation, participants reported that maintenance would require checking that the pump does not run dry, cleaning filters, and clearing drippers of blockages as needed. Regarding the plants, weeding, the fast growth rate of AV species, which requires regular harvesting, the health of the plants, selecting an appropriate growth medium, nutrients, and irrigation for the planting palette were raised as essential considerations. There were suggestions for addressing diseases and pests through companion planting strategies to increase the system's efficiency.

All the participants (7) identified the most critical challenges associated with LWSs as the limiting factors of plants, including soil, water, light, and aspect. Concerning soil, lighter soil mixtures and the inclusion of water retention agents as well as aeration and nutrient content were proposed. Regarding water, participants suggested the importance of automated irrigation systems and water harvesting. The vast majority of the participants agreed that the installation cost of systems was a significant challenge. One participant raised the challenge of ensuring public safety through the secure fastening of systems.

Concerning developing an understanding of the LWS size required to ensure sufficient yields, while ensuring accessibility for maintenance, suggestions included that crops' nutritional value and user requirements should guide the LWS size. Another critical factor raised is the accessibility for maintenance.

5.2 LWSs' analysis

The researcher analysed all LWSs listed by the respondents in the questionnaire responses based on the system criteria. These systems included the locally manufactured 1) Vicinity Wall, 2) Modiwall, 3) Eco Green Wall, and the imported 4) Growall, and 5) Mobilane systems. Considering uncomplicated assembly, low technology and cost efficiency, the Eco Green Wall's assembly skills, technology requirements, and installation cost were half or less than half of the other typologies. Figure 3 depicts the scores for each typology, with the Eco Green Wall and Vicinity Wall the only two systems that complied with all criteria.

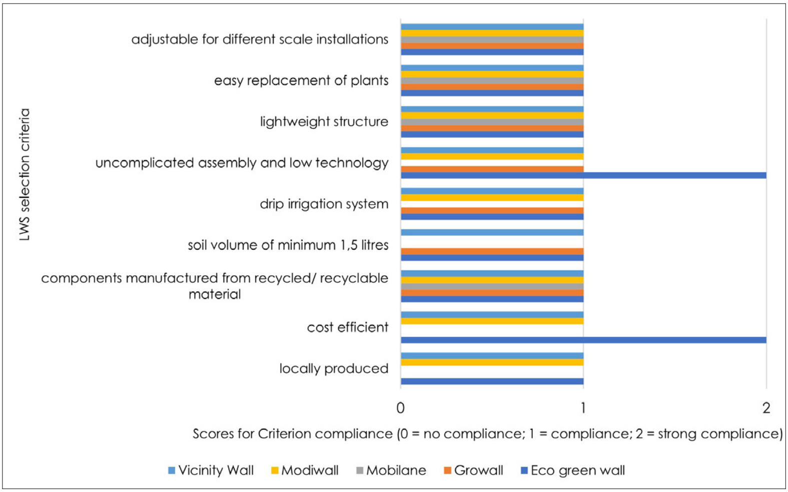

Figure 3: Comparison of the Eco Green Wall, GroWall, Mobilane, Modiwall, and Vicinity systems' compliance with the selection criteria

Source: Author, 2024

5.3 Selection of LWSs for the experimental study

Based on the analysis in Figure 3, the Eco Green Wall and Vicinity systems comply with the selection criteria and are deemed sufficient to analyse the performance of LWSs. The Vicinity system represents a high-technology system, and the Eco Green Wall represents a low-technology system. Furthermore, the space of the study area and the funding budget made the selection of only two systems possible. As the control, a natural soil area in which the crops were planted in traditional agricultural conditions for comparison with the two LWS typologies was selected as the third option for the growing needs of the AV species.

5.3.1 Eco Green Wall system

The Eco Green Wall is a local low-technology outdoor system developed to address the economic feasibility and sustainability challenges experienced with modular LWSs. The Eco Green Wall system comprises interlocking, lightweight, recycled polystyrene aggregate, and cement mixture blocks (Van der Walt, 2019). These blocks are stacked onto each other and can be fixed onto a building structure or façade with stainless steel brackets or placed back-to-back as a free-standing element. The pots comprise black seed trays containing the growth medium and the plants. The system aims to limit exposure of the growth medium for enhanced moisture retention by limiting the majority area of the seed tray's sun exposure (Van der Walt, 2019). The growth medium retains moisture for more prolonged periods, protected by the blocks in which the seed trays fit. Seed trays have almost half the capacity of the Vicinity system, with a volume of 1.59 litres for the growth medium and plants.

The system offers two alternatives for irrigation: trunking with a wick or a drip irrigation system (Van der Walt, 2019). An irrigation line irrigates each planter row, and the trays drain into each other. Figure 4 illustrates the Eco Green Wall.

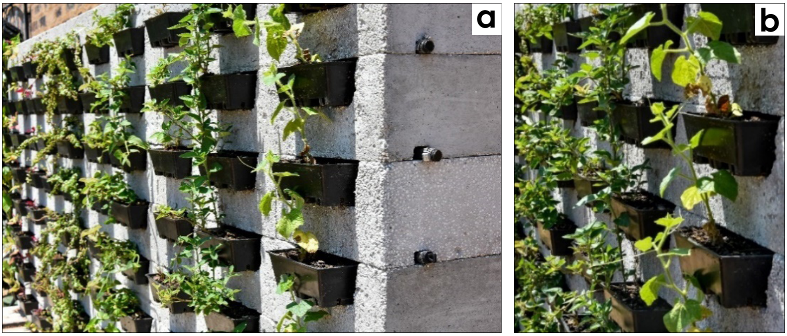

Figure 4a: The Eco Green Wall system, installed at the Future Africa campus of the University of Pretoria

Figure 4b: The black seed trays, with dimensions of 150 x 230 x 50mm are fitted into the blocks

Figure 4c: The interlocking, lightweight recycled polystyrene aggregate and cement mixture blocks stacked onto each other with the drip irrigation feeder line

Source: Author, 2024

5.3.2 Vicinity system

The Vicinity system comprises an all-in-one system, with water reservoir tanks at the bottom, a pump and filter, drip irrigation for the top row of pots, gravitating into each row, and circulating back to the top row (Vicinity, 2022). The Vicinity pots are clipped onto an aluminium rail fixed to the building structure or façade and comprise geotextile planter bags with a 3-litre capacity (Vicinity, 2022). Figures 5 and 6 provide a diagram and photos of the Vicinity system.

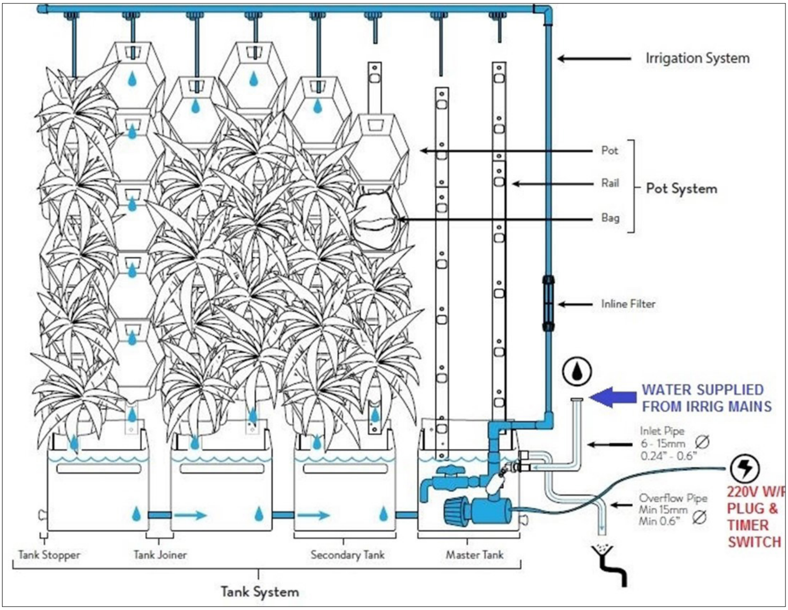

Figure 5: Diagram of the Vicinity system

Source: Vicinity, 2022

Figure 6a: The Vicinity system, with hexagonal pots containing geotextile bags, the growth medium, plants, and water-reservoir tanks at the bottom feeding the drip irrigation line.

Source: Image by author, 2020

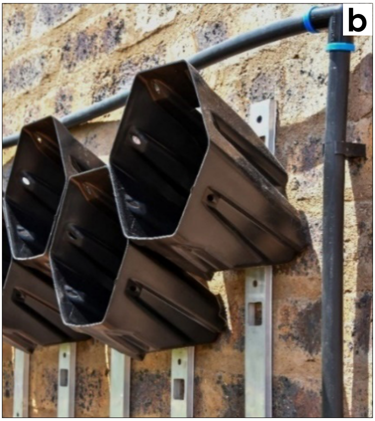

Figure 6b: The pots clip onto aluminium rails, that are fixed to the Future Africa campus kitchen yard wall

Source: Image by author, 2020

5.4 Experimental study

5.4.1 Biomass

The total crop biomass yields for each LWS were compared to the control (natural soil) to test the efficiency of the LWSs. Regarding fresh leaf mass results over the 6-month data-collection period, the natural soil area produced a higher yield than the two LWSs (total = 5278.62g, mean = 29.33g, sd = 52.77, var = 2785.17). The Vicinity Wall (total = 1140.99g, mean = 6.34g, sd = 11.61, var 134.73) produced a higher yield than the Eco Green Wall (1042.77g, mean = 5,79g, sd = 9.19, var 84.43).

The dry mass figures confirm these correlations, with the natural soil (total = 693.34g, mean = 3.85g, sd = 6.28, var = 39.34), Vicinity Wall (total = 147.73g, mean = 0.82g, sd = 1.75, var 3.07), and Eco Green Wall (total = 137.55g, mean = 0.76g, sd = 0.96, var 0.92). Considering the vertical area occupied by the LWSs versus the horizontal area of the natural soil area, the natural soil produced the highest yield per m^2 (see Table 2).

Table 2: Comparison of typologies' fresh yield per area to average conventional mixed-stand, small-scale agriculture production benchmark of 244 kg/m^2

System	*Plants per m^2 in typology*	*Mean fresh monthly mass per plant (g)*	*Fresh yield in grams/m^2 per month (g)*	*Benchmark in grams per m^2 (average conventional small-scale agriculture production rate = 244g/m^2)*	*Difference between typology fresh yield and benchmark*
Eco Green Wall	22	5,793	127,446	244	-116,554
Vicinity Wall	33	6,339	209,187	244	-34,813
Natural soil	9	29,326	263,934	244	19,934

Source: Author, 2024

The Eco Green Wall and Vicinity Wall produced lower yields per square meter than the average conventional small-scale, mixed-use agricultural production benchmark weight of 244g/m^2 (Rabin *et al*., 2021, in Nagle *et al*., 2017: 34).

However, considering the footprint, the typologies produced more than the benchmark average fresh produce weight of 244g/m^2 (Rabin *et al*., 2021, in Nagle *et al*., 2017: 34). Table 3 compares typologies concerning the fresh monthly yield performance per m^2 horizontal footprint. The Vicinity Wall (1304,58g) was the most productive, producing over five times the yield of the natural soil area (263,93g). The Eco Green Wall was over two times (594,75g) more productive than the natural soil area (263,93g) per m^2 in footprint.

Table 3: Comparison of typologies' fresh yield per horizontal footprint

System	*Area planted*	*Horizontal footprint*	*Fresh yield/m² per month (g)*	*Total fresh yield per wall per month based on g/m² yield*	*Total monthly yield per m² fresh footprint*
Natural soil	12	12	127,446	1529,352	263,93
Eco Green Wall	4,2	0,9	209,187	878,5854	594,75
Vicinity Wall	4	0,6	263,934	1055,736	1 394,58

Source: Author, 2024

5.4.2 Installation, cost and maintenance

In addition to biomass, the researcher observed the installation cost, labour, skills, and maintenance during the experimental study period to measure the performance of the two LWSs. Table 4 compares the two LWSs relating to all actions required during the study period. Costs are based on the construction time of the experiment, October 2020, and indicated in South African Rand (ZAR). The Eco Green Wall costs less and requires less installation time, skills, and maintenance than the Vicinity Wall. The Vicinity Wall's maintenance mainly involved the irrigation system components.

Table 4: Comparison of the Eco Green and Vicinity Walls' installation and maintenance actions

Criteria	*Eco Green Wall (number of times during six months indicated in brackets)*	*Vicinity Wall (number of times during six months indicated in brackets)*
Installation cost	ZAR7931,75	ZAR10094,00
Installation tools and equipment	Drill, level, measuring tape	Level, measuring tape
Installation labour	4 hours	8 hours
Installation specialised skills	Basic (low technology) The installation guide provides sufficient guidance for installation.	Medium to specialised (high technology) The installation guide provides sufficient guidance to a skilled person. Installation requires a submersible pump.

Criteria	*Eco Green Wall (number of times during six months indicated in brackets)*	*Vicinity Wall (number of times during six months indicated in brackets)*
Maintenance required	A slow-release fertiliser (Culterra Vitaflora 5:1:5) is applied to both LWSs Plants are treated for mealybug with Koinor (1) Minor weeding (1)	A slow-release fertiliser (Culterra Vitaflora 5:1:5) is applied to both LWSs Plants are treated for mealybug with Koinor (1) Minor weeding (1) Clean the water reservoirs (2) Clean the water filter (2) Clean the drip emitters when malfunctioning (1) Clear rope ties at the top of planters that block drainage into pots positioned in bottom rows (2) Repositioning drippers in the top row to enter the drainage opening (3) Clipping pots back onto the aluminium rail, due to bypassers removing/ repositioning them (2)
Water (Irrigation)	Regulated drip irrigation is provided for each row. A battery-operated irrigation controller is installed. The battery needed replacement in October 2021.	Only the top row is irrigated, with the gravitation of water to the bottom pots. A digital timer is installed. The timer needed a reset in January 2022.
Other requirements	The contractor repaired the faulty irrigation	The contractor repaired the faulty irrigation

Source: Author, 2024

5.4.3 Plant stress

Considering the total performance index, the crops in the natural soil area had the highest mean in PI_{total} values (mean = 1.709974, sd = 0.9560993). Unlike the maximum quantum yield, the crops in the Eco Green Wall (mean = 1.626365, sd =1.0263101) had a higher PI_{total} mean value than the crops in the Vicinity Wall (mean = 1.395481, sd = 0.8686037). Statistically significant differences, evident in each typology's crops, are discussed below.

The one-way ANOVA showed statistically significant differences in the maximum quantum yield (Fv/Fm) of crops between the typologies ($F(2,1168) = 4.165$, $p = 0.016$, $np^2 = 0.007$) and the total performance index of crops ($F(2,1168) = 11.852$, $p < 0.001$, $np^2 = 0.020$). Where statistically significant differences were evident ($p < 0.05$), Tukey multi-comparison post-hoc procedures and independent samples T-tests were performed to assess pairwise differences in the maximum quantum yield and total performance index of crops among the typologies. Table 5 shows the post-hoc results of pairwise F_v/F_m comparisons between the three typologies.

Table 5: Post-hoc results of typology combinations concerning the crops' mean maximum quantum yield

Typology A	*Typology B*	*Mean difference (A-B)*	*Standard error*	*Significance*
Natural soil (F_v/F_m = 0.81448)	Eco Green Wall (F_v/F_m = 0.80860)	0.005885	0.002151	0.017*
Natural soil (F_v/F_m = 0.81448)	Vicinity Wall (F_v/F_m = 0.81329)	0.001195	0.002095	0.836
Vicinity Wall (F_v/F_m = 0.81329)	Eco Green Wall (F_v/F_m = 0.80860)	0.004690	0.002124	0.070

*Significant $p < 0.05$

There were no statistically significant differences in the maximum quantum yield between the crops that were grown in the Vicinity Wall and the Eco Green Wall ($p = 0.070$) and those that were grown in the natural soil compared to the Vicinity Wall ($p = 0.836$). The post-hoc tests for the mean maximum quantum yield between the natural soil ($F_v/F_m = 0.81448$) and the Eco Green Wall ($F_v/F_m = 0.80860$) reveal a statistically significant ($p = 0.017$) difference between the natural soil and the Eco Green Wall.

Table 6 presents the crops' total performance index (PI_{total}) post-hoc results of all typology combinations.

Table 6: Post-hoc results of typology combinations concerning the crops' mean total performance index

Typology A	*Typology B*	*Mean difference (A – B)*	*Standard error*	*Significance*
Eco Green Wall PI_{total} = 1.626365)	Vicinity Wall (PI_{total} = 1.395481	0.2308844	0.0679350	0.002*
Natural soil (PI_{total} = 1.709974	Vicinity Wall (PI_{total} = 1.395481	0.3142928	0.0670120	0.001*
Natural soil (PI_{total} = 1.709974	Eco Green Wall PI_{total} = 1.626365)	0.0834085	0.0687960	0.446

*Significant $p < 0.05$

The post-hoc test for the total performance index (PI_{total}) reveals a statistically significant difference between the crops in the Eco Green Wall and the Vicinity Wall ($p = 0.002$), and the Vicinity Wall also showed statistically significant lower PI_{total} values than the natural soil ($p < 0.001$).

6. DISCUSSION

6.1 Biomass

LWSs are more effective in space-saving of a horizontal footprint than traditional soil-based food production on a household scale, as the natural soil area produced the lowest yield per m^2 considering footprint. The Vicinity Wall was the most productive, considering the horizontal footprint area occupied in terms of yield per m^2. The Vicinity Wall produced over four times the yield of the natural soil area, with the Eco Green Wall over three times more productive than the natural soil area. The soil volume explains the higher yields in the natural soil and the yields in the Vicinity Wall, with a soil volume double the volume of the Eco Green Wall containers.

6.2 Installation cost and maintenance

Considering the installation cost, the Eco Green Wall's installation was 21% more cost-effective than the Vicinity Wall's cost. The Eco Green Wall required fewer skills, specialised tools, and labour for installation and maintenance. Low technology, limited and robust components, and uncomplicated assembly are essential to reduce maintenance. Table 7 summarises the technical characteristics of LWSs proposed by this study for improved performance as GI for growing AV in local urban conditions (Gauteng, South Africa).

Table 7: The technical characteristics of LWSs proposed by this study

Criteria	*Characteristic*
System	Free-standing or fixed
	2000mm height for ease of maintenance and harvesting
	Varying width
	Uncomplicated assembly
	Recycled
	North aspect (in the southern hemisphere)
	No shade interference
	Prevent polluted areas, water and soils
Production	Locally manufactured
Technology	Low technology
Material	Lightweight
Material (Pots)	Recycled
	Removable
	Soil depth > 200mm
	One drainage hole
	No lose fittings
Plants	Specified AV

Criteria	*Characteristic*
Soil	Potting soil, river sand and perlite (1:4:1)
	3-litre capacity
	Sufficient nutrients according to plant requirements
	PH to meet plant requirements
	Loose texture, aerated
	Lightweight
Water (Irrigation)	Drip/wick system
	Non-exposed or no reservoir
	Harvested water
	Equal irrigation per row

Source: Author, 2024

6.3 Plant stress

The mean maximum quantum yield of photosystem II (F_v/F_m) between the crops grown in the Eco Green Wall shows a statistically significant difference with those grown in the natural soil. This implies that the crops in the Eco Green Wall experienced stress compared to the crops in the natural soil. Plant stress can be linked to temperature extremes or dry spells. However, the literature argues that the maximum quantum yield of photosystem II is associated with high-temperature stress, leaf senescence, and only extended drought stress periods (Kalaji *et al*., 2017: 13; Lu *et al*., 2002: 1173; Kotakis, Kyzeridou & Manetas, 2014: 413). The lowest maximum quantum yield of photosystem II (F_v/F_m) values were measured in the Eco Green Wall between January and March 2022, affecting between three and five crops. These levels can be explained by an irrigation malfunction of the Future Africa campus' main irrigation system in January. However, January had high rainfall and lower maximum temperatures, which might have assisted in the crops' survival. This assumption is strengthened by the Eco Green Wall's significantly low soil electrical conductivity levels, indicating low soil nutrient uptake and moisture content. Therefore, it can be assumed that the plant stress of crops in the Eco Green Wall, depicted by the low maximum quantum yield of photosystem II mean values, results from the irrigation malfunction in January 2022, leading to available water content stress. Although the Eco Green Wall's crops experienced stress compared to other typologies, the plants still coped with their environmental conditions and stresses, and their photosynthetic apparatuses were not damaged.

As the total performance index (PI_{total}) strongly correlates with plant growth, health, and survival rate (Yusuf *et al*., 2010: 1428; Berner *et al*., 2021:1; Maliba *et al*., 2019: 1), the trend in PI_{total} values over a period is a good indicator of plant vitality. The statistically significant difference in the total performance index (PI_{total}) between the crops in the Vicinity Wall with the

Eco Green Wall and the natural soil shows that the Vicinity Wall's crops experienced more stress than the other typologies. Investigating the periods of the highest plant stress, January 2022 showed the lowest PI_{total} values in five crops. The plant stress in January 2022 is also visible in the low soil electrical conductivity and the volumetric water content levels, which indicates the soil nutrient uptake and moisture content. These levels can be explained by the irrigation malfunction in January. Therefore, it can be assumed that the plant stress of the Vicinity Wall's crops, depicted by the low PI_{total} mean values, due to the irrigation malfunction in January 2022, leading to available water content stress. However, although the Vicinity Wall's crops experienced more stress than crops in the Eco Green Wall and natural soil, the plants still coped with their environmental conditions and stresses, and their photosynthetic apparatuses were not damaged.

7. CONCLUSIONS AND RECOMMENDATIONS

Although LWSs provide ecosystem services, the current sustainability and feasibility of living walls are debatable and need considerable improvement as green infrastructure in compact urban environments. The study's proposed technical characteristics expand on the research by Perini and Rosasco (2013), which stressed the importance of cost-effective installation. Moreover, the findings expand on the research by Huang *et al*. (2019a), suggesting that maintenance costs should be reduced.The potential of LWSs can be improved by implementing the technical characteristics listed in Table 7, which all impact on the system's performance. Cost-effectiveness and sustainability can be enhanced using locally produced structures with recycled or recyclable materials. The system design should be simplistic, with limited, robust, lightweight components entailing uncomplicated assembly, allowing flexibility to accommodate varying sizes. The system's maximum height must allow accessibility for maintenance and harvesting. The systems' positioning should consider polluted environments to address possible contamination of crops. The orientation of the LWS must provide efficient sun exposure for the plant palette and consider any structures that might affect the light quality and quantity of the LWS.

Moreover, to confirm the research by Huang *et al*. (2019a), the system should be modular, comprising individual and removable pots to ease the installation and replacement of plants and their maintenance. Pot sizes must preferably have a capacity of at least 3 litres with a minimum soil depth of 200mm, in concurrence with Passioura (2006), as this soil volume produces higher resilience than smaller pots of 1.5 litres. The soil should be lightweight and meet the crop requirements, ensuring sufficient aeration, texture, and drainage. The research found that one drainage hole is adequate, although the drainage hole's position must ensure drainage and limit any blockages. Although the pots' colour did not impact on their performance in the six-month experimental study, the pots' sun exposure should be limited to mitigate extreme maximum and minimum soil temperatures. Limited exposure can be achieved through the system design, with the Eco Green Wall system as an example of pots with limited sun exposure and crop protection by the structure.

The irrigation system must entail low technology, comprising either a drip or wick system, with harvested water as a source and equal irrigation per row or level of the LWS. This is also confirmed by Natarajan *et al*. (2015). Water reservoirs must be covered to prevent particles from entering and clogging drip emitters. There is a need for systems with the technical requirements recommended by this study. Manufacturing of such systems would contribute to the discourse on edible urbanism and guide future LWS designs.

Existing LWSs still require significant improvement to achieve optimal performance as green infrastructure in compact city environments, and more empirical research is needed to develop systems with the above characteristics.

REFERENCES

Akinwolemiwa, O.H., Bleil de Souza, C., De Luca, L.M. & Gwilliam, J. 2018. Building community-driven vertical greening systems for people living on less than £1 a day: A case study in Nigeria. *Building and Environment*, 131, pp. 277-287. https://doi.org/10.1016/j.buildenv.2018.01.022

Almalki, S. 2016. Integrating quantitative and qualitative data in mixed methods research – Challenges and benefits. *Journal of Education and Learning*, 5, pp. 288-296. https://doi.org/10.5539/jel.v5n3p288

Azkorra, Z., Pérez, G., Coma, J., Cabeza, L.F., Bures, S., Álvaro, J.E., Erkoreka, A. & Urrestarazu, M. 2015. Evaluation of green walls as a passive acoustic insulation system for buildings. *Applied Acoustics*, 89, pp. 46-56. https://doi.org/10.1016/j.apacoust.2014.09.010

Bartesaghi Koc, C., Osmond, P. & Peters, A. 2017. Towards a comprehensive green infrastructure typology: A systematic review of approaches, methods and typologies. *Urban Ecosystems*, 20, pp. 15-35. DOI: 10.1007/s11252-016-0578-5

Beacham, A. Vickers, L. & Monaghan, J. 2019. Vertical farming: A summary of approaches to growing skywards. *The Journal of Horticultural Science and Biotechnology*, 94, pp. 277-283. https://doi.org/10.1080/14620316.2019.1574214

Berner, J.M., Cloete, H. & Shuuya, T. 2021. A baseline assessment of the photosynthetic potential of Welwitschia mirabilis using the JIP-test for monitoring and conservation proposes. *Bothalia*, 51(1), pp. 1-9. https://doi.org/10.38201/btha.abc.v51.i1.9

Bhandari, P. 2022. What is effect size and why does it matter? [Online]. Available at: https://www.scribbr.com/statistics/effect-size/ [Accessed 11 January 2023].

Bhandari, P. 2023. Questionnaire design: Methods, question types and examples. [Online]. Available at: https://www.scribbr.com/methodology/questionnaire/ [Accessed 3 June 2023].

Botes, K.L. 2022. Traditional African vegetables: Living walls. *African Journal for Landscape Architecture*. [Online]. Available at: https://www.ajlajournal.org/articles/traditional-african-vegetables-living-walls [Accessed 10 December 2023].

Botes, K.L. 2024. The performance of traditional African vegetables in urban outdoor modular living wall systems for food security in Gauteng, South Africa. Unpublished PhD, University of Pretoria.

Botes, K.L. & Breed, C.A. 2021. Outdoor living wall systems in a developing economy: A prospect for supplementary urban food production? *Acta Structilia*, 28(2), pp. 143-169. https://doi.org/10.18820/24150487/as28i2.6

Botes, K.L. & Breed, C.A. 2022. Traditional African vegetables in modular living walls: A novel approach towards smart cities. IOP Conference Series: *Earth and Environmental Science*, 1101. DOI: 10.1088/1755-1315/1101/2/022051

Braun, V. & Clarke, V. 2006. Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2), pp. 77-101. https://doi.org/10.1191/1478088706qp063oa

Cameron, R.W., Taylor, J.E. & Emmett, M.R. 2014. What's 'cool' in the world of green façades? How plant choice influences the cooling properties of green walls. *Building and Environment*, 73, pp. 198-207. https://doi.org/10.1016/j.buildenv.2013.12.005

Ceusters, N., Valcke, R., Frans, M., Claes, J.E. & Van den Ende, W. 2019. Performance index and PSII connectivity under drought and contrasting light regimes in the CAM Orchid Phalaenopsis. *Frontiers in Plant Science*, 10, article 1012, pp. 1-15. DOI: 10.3389/fpls.2019.01012

Coffey, A. 2014. Analysing documents. In: Flick, U. (Ed.). *The Sage handbook of qualitative data analysis*. Los Angeles: SAGE, pp. 367-379. https://doi.org/10.4135/9781446282243

Cohen, J. 1988. *Statistical power analysis for the behavioral sciences*. 2nd edition. London: Routledge. https://doi.org/10.4324/9780203771587

Collins, R., Schaafsma, M. & Hudson, M.D. 2017. The value of green walls to urban biodiversity. *Land Use Policy,* 64, pp. 114-123. https://doi.org/10.1016/j.landusepol.2017.02.025

Coma, J., Pérez, G., Gracia, A., Burés, S., Urrestarazu, M. & Cabeza, L. 2017. Vertical greenery systems for energy savings in buildings: A comparative study between green walls and green façades. *Building and Environment,* 111, pp. 228-237. https://doi.org/10.1016/j.buildenv.2016.11.014

Creswell, J.W. & Plano Clark, V.L. 2018. *Designing and conducting mixed methods research*. 3rd edition. Thousand Oaks, California: SAGE.

Davis, M.M. & Hirmer, S. 2015. The potential for vertical gardens as evaporative coolers: An adaptation of the 'Penman Monteith Equation'. *Building and Environment*, 92, pp. 135-141. https://doi.org/10.1016/j.buildenv.2015.03.033

Davis, M., Tenpierik, M.J., Ramírez, F.R. & Pérez, M.E. 2017. More than just a green façade: The sound absorption properties of a vertical garden with and without plants. *Building and Environment*, 116, pp. 64-72. https://doi.org/10.1016/j.buildenv.2017.01.010

Dover, J.W. 2015. *Green infrastructure: Incorporating plants and enhancing biodiversity in buildings and urban environments*. London: Routledge. https://doi.org/10.4324/9780203121993

Engelbrecht, C.J. & Engelbrecht, F.A. 2016. Shifts in Köppen-Geiger climate zones over southern Africa in relation to key global temperature goals. *Theoretical and Applied Climatology*, 123, pp. 247-261. https://doi.org/10.1007/s00704-014-1354-1

EPA (United States Environmental Protection Agency). 2024. What is green infrastructure? [Online]. Available at: https://www.epa.gov/green-infrastructure/what-green-infrastructure [Accessed 28 April 2024].

Falk, A. & Heckman, J. 2009. Lab experiments are a major source of knowledge in the social sciences. *Science*, 326 (5952), pp. 535-538. DOI: 10.1126/science.1168244

Firehock, K. & Walker, R.A. 2015. *Strategic green infrastructure planning: A multi-scale approach*. Washington, DC: Island Press (Bibliovault). https://doi.org/10.5822/978-1-61091-693-6

Francis, R.A. & Lorimer, J. 2011. Urban reconciliation ecology: The potential of living roofs and walls. *Journal of Environmental Management*, vol. 92, pp. 1429-1437. https://doi.org/10.1016/j.jenvman.2011.01.012

Frey, B.B. 2018. *The Sage encyclopedia of educational research, measurement, and evaluation*. Thousand Oaks, California: SAGE Publications. 10.4135/9781506326139

Goel, M., Jha, B. & Khan, S. 2022. Living walls enhancing the urban realm: A review. *Environmental Science and Pollution Research*, 29, pp. 38715-38734. https://doi.org/10.1007/s11356-022-19501-7

Gunawardena, K. & Steemers, K. 2020. Urban living walls: reporting on maintenance challenges from a review of European installations. *Architectural Science Review*, 63, pp. 526-535. https://doi.org/10.1080/00038628.2020.1738209

Huang, W., Ratkowsky, D., Hui, C., Wang, P., Su, J. & Shi, P. 2019a. Leaf fresh weight versus dry weight: Which is better for describing the scaling relationship between leaf biomass and leaf area for broadleaved plants? *Forests*, 10(3) 256, pp. 1-19. https://doi.org/10.3390/f10030256

Huang, Z., Lu, Y., Wong, N.H. & Poh, C.H. 2019b. The true cost of “greening” a building: Life cycle cost analysis of vertical greenery systems (VGS) in tropical climate. *Journal of Cleaner Production*, 228, pp. 437-454. https://doi.org/10.1016/j.jclepro.2019.04.275

Jim, C.Y., Hui, L.C. & Rupprecht, C.D.D. 2022. Public perceptions of green roofs and green walls in Tokyo, Japan: A call to heighten awareness. *Environmental Management,* 70, pp. 35-53. https://doi.org/10.1007/s00267-022-01625-8

Kalaji, H.M., Schansker, G., Brestic, M., Bussotti, F., Calatayud, A. *et al*. 2017. Frequently asked questions about chlorophyll fluorescence, the sequel. *Photosynthesis Research*, 132, pp. 13-66. https://doi.org/10.1007/s11120-016-0318-y

Kalaji, H.M., Schansker, G., Ladle, R.J., Goltsev, V., Bosa, K. *et al*. 2014. Frequently asked questions about *in vivo* chlorophyll fluorescence: Practical issues. *Photosynthesis Research*, 122, pp. 121-158. https://doi.org/10.1007/s11120-014-0024-6

Kang, M., Ragan, B.G. & Park, J. 2008. Issues in outcomes research: An overview of randomization techniques for clinical trials. *Journal of Athletic Training*, 43, pp. 215-221. DOI 10.4085/1062-6050-43.2.215

Kim, J.H., Bhandari, S.R., Chae, S.Y., Cho, M.C. & Lee, J.G. 2019. Application of maximum quantum yield, a parameter of chlorophyll fluorescence, for early determination of bacterial wilt in tomato seedlings.

Horticulture, Environment, and Biotechnology, 60, pp. 821-829. https://doi.org/10.1007/s13580-019-00182-0

Köhler, M. 2008. Green facades – A view back and some visions. *UrbanEcosystems*, 11, pp. 423-436. https://doi.org/10.1007/s11252-008-0063-x

Kotakis, C., Kyzeridou, A. & Manetas, Y. 2014. Photosynthetic electron flow during leaf senescence: Evidence for a preferential maintenance of photosystem I activity and increased cyclic electron flow. *Photosynthetica*, *52*(3), pp. 413-420. DOI: 10.1007/s11099-014-0046-5

Larcher, F., Battisti, L., Bianco, L., Giordano, R., Montacchini, E. *et al*. 2018. Sustainability of living wall systems through an ecosystem services lens. In: Nandwani, D. (Ed.). *Urban horticulture: Sustainability for the future*. Cham: Springer, pp. 31-51. https://dx.doi.org/10.1007/978-3-319-67017-1_2

Lavrakas, P.J. 2008. *Encyclopedia of survey research methods*. Thousand Oaks, California: SAGE Publications. https://doi.org/10.4135/9781412963947

Lee, S.H. 2019. Effects of biophilic design on consumer responses in the lodging industry. *International Journal of Hospitality Management*, 83, pp. 141-150. https://doi.org/10.1016/j.ijhm.2019.05.006

Liberalesso, T., Mutevuie Júnior, R., Oliveira Cruz, C., Matos Silva, C. & Manso, M. 2020. Users' perceptions of green roofs and green walls: An analysis of youth hostels in Lisbon, Portugal. *Sustainability*, 12(3) article10136. https://doi.org/10.3390/su122310136

Ling, T.-Y. & Chiang, Y.-C. 2018. Well-being, health and urban coherence – Advancing vertical greening approach toward resilience: A design practice consideration. *Journal of Cleaner Production*, 182, pp. 187-197. https://doi.org/10.1016/j.jclepro.2017.12.207

Little, K.M. & Rolando, C.A. 2003. Using chlorophyll fluorescence to determine stress in eucalyptus grandis seedlings: Scientific paper. *Southern African Forestry Journal*, 197, pp. 5-12. https://doi.org/10.1080/20702620.2003.10431716

Lu, Q., Lu, C., Zhang, J. & Kuang, T. 2002. Photosynthesis and chlorophyll a fluorescence during flag leaf senescence of field-grown wheat plants. *Journal of Plant Physiology*, 159, pp. 1173-1178. https://doi.org/10.1078/0176-1617-00727

Maliba, B.G., Inbaraj, P.M. & Berner, J.M. 2019. Photosynthetic responses of canola and wheat to elevated levels of CO2, O3 and water deficit in open-top chambers. *Plants*, 8(6), pp. 1-17. DOI: 10.3390/plants8060171

Manso, M. & Castro-Gomes, J. 2015. Green wall systems: A review of their characteristics. *Renewable and Sustainable Energy Reviews*, 41, pp. 863-871. https://doi.org/10.1016/j.rser.2014.07.203

Mårtensson, L.M., Fransson, A.M. & Emilsson, T. 2016. Exploring the use of edible and evergreen perennials in living wall systems in the Scandinavian climate. *Urban Forestry & Urban Greening*, 15, pp. 84-88. https://doi.org/10.1016/j.ufug.2015.12.001

Mayrand, F. & Clergeau, P. 2018. Green roofs and green walls for biodiversity conservation: A contribution to urban connectivity? *Sustainability*, 10(4), 985, pp. 1-13. https://doi.org/10.3390/su10040985

McCombes, S. 2023. Survey research: Definition, examples and methods. Scribbr. [Online]. Available at: https://www.scribbr.com/methodology/survey-research/ [Accessed: 29 February 2024].

Medl, A., Stangl, R. & Florineth, F. 2017. Vertical greening systems – A review on recent technologies and research advancement. *Building and Environment*, 125, pp. 227-239. https://doi.org/10.1016/j.buildenv.2017.08.054

Migiro, S.O. & Magangi, B.A. 2011. Mixed methods: A review of literature and the future of the new research paradigm. *African Journal of Business Management*, 5(10), pp. 3757-3764. DOI: 10.5897/AJBM09.082

Nagle, L., Echols, S. & Tamminga, K. 2017. Food production on a living wall: Pilot study. *Journal of Green Building*, 12(3), pp. 23-38. DOI: 10.3992/1943-4618.12.3.23

Natarajan, M., Rahimi, M., Sen, S., Mackenzie, N. & Imanbayev, Y. 2015. Living wall systems: Evaluating life-cycle energy, water and carbon impacts. *Urban Ecosystems*, 18, pp. 1-11. https://doi.org/10.1007/s11252-014-0378-8

Nikolopoulou, K. 2023a. What Is purposive sampling? Definition and examples. Scribbr. [Online]. Available at: https://www.scribbr.com/methodology/purposive-sampling/ [Accessed 29 February 2024].

Nikolopoulou, K. 2023b. What is snowball sampling? Definition and examples. Scribbr. [Online]. Available at: https://www.scribbr.com/methodology/snowball-sampling/ [Accessed 29 February 2024].

NIST. 2018. Hedge's g statistic. [Online]. Available at: https://www.itl.nist.gov/div898/software/dataplot/refman2/auxillar/hedgeg.htm [Accessed 14 January 2023].

Ode Sang, Å., Thorpert, P. & Fransson, A. 2022. Planning, designing, and managing green roofs and green walls for public health – An ecosystem services approach. *Frontiers in Ecology and Evolution,* 10, article 804500. https://doi.org/10.3389/fevo.2022.804500

OrangeSmile Tours B.V. 2024. Country maps. [Online]. Available at: https://www.orangesmile.com/common/img_country_maps_provinces/south-africa-map-provinces-1.jpg [Accessed 12 December 2022].

Ottelé, M., Perini, K., Fraaij, A., Haas, E.M. & Raiteri, R. 2011. Comparative life cycle analysis for green façades and living wall systems. *Energy & Buildings*, 43, pp. 3419-3429. https://doi.org/10.1016/j.enbuild.2011.09.010

Panagopoulus, T., Jankovska, I. & Dan, M. 2018. Urban green infrastructure: The role of urban agriculture in city resilience. *Urbanism. Arhitectura. Constructii*, 9(1), pp. 56-70.

Passioura, J. 2006. The perils of pot experiments. *Functional Plant Biology,* 33, pp. 1075-1079. DOI: 10.1071/FP06223

Perez, G. & Perini, K. 2018. Nature-based strategies for urban and building sustainability. Oxford, UK: Butterworth-Heinemann. https://doi.org/10.1016/C2016-0-03181-9

Pérez, G., Coma, J., Martorell, I. & Cabeza, L. 2014. Vertical greenery systems (VGS) for energy saving in buildings: A review. *Renewable and Sustainable Energy Reviews*, 39, pp. 139-165. https://doi.org/10.1016/j.rser.2014.07.055

Perini, K. & Rosasco, P. 2013. Cost-benefit analysis for green façades and living wall systems. *Building and Environment*, 70, pp. 110-121. https://doi.org/10.1016/j.buildenv.2013.08.012

Price, A., Jones, E. & Jefferson, F. 2015. Vertical greenery systems as a strategy in urban heat island mitigation. *Water, Air, and Soil Pollution: An International Journal of Environmental Pollution*, 226(247), pp. 1-11. https://doi.org/10.1007/s11270-015-2464-9

Radić, M., Brković Dodig, M. & Auer, T. 2019. Green façades and living walls – A review establishing the classification of construction types and mapping the benefits. *Sustainability*, 1(17), article 4579. https://doi.org/10.3390/su11174579

Russo, A. & Cirella, G. 2019. Edible urbanism 5.0. *Palgrave Communications*, 163 pp. 1-9. https://doi.org/10.1057/s41599-019-0377-8

Russo, A., Escobedo, F., Cirella, G. & Zerbe, S. 2017. Edible green infrastructure: An approach and review of provisioning ecosystem services and disservices in urban environments. *Agriculture, Ecosystems and Environment*, 242, pp. 53-66. https://doi.org/10.1016/j.agee.2017.03.026

SA Weather Service, 2022. Annual state of the climate of South Africa 2021. Pretoria, South Africa.

Schneider, A., Friedl, M. & Potere, D. 2010. Mapping global urban areas using MODIS 500-m data: New methods and datasets based on urban ecoregions. *Remote Sensing of Environment*, 114(8), pp. 1733-1746. https://doi.org/10.1016/j.rse.2010.03.003

Snyder, H. 2019. Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104, pp. 333-339. https://doi.org/10.1016/j.jbusres.2019.07.039

Taylor, R. 1990. Interpretation of the correlation coefficient: A basic review. *Journal of Diagnostic Medical Sonography*, 6(1), pp. 35-39. https://doi.org/10.1177/875647939000600106

Tetnowski, J. 2015. Qualitative case study research design. *Perspectives on Fluency and Fluency Disorders*, 25(1), pp. 39-45. https://doi.org/10.1044/ffd25.1.39

Urbaniak, G. & Plous, S. 2013. Research randomizer (Version 4.0) [Computer software] [Online]. Available at: http://www.randomizer.org/ [Accessed 26 July 2021].

Van der Walt, I. 2019. RE: (Owner of Abrus Enterprise). Personal communication on Eco Green Wall.

Van Mechelen, C., Dutoit, T. & Hermy, M. 2014. Mediterranean open habitat vegetation offers great potential for extensive green roof design. *Landscape and Urban Planning*, 21, pp. 81-91. https://doi.org/10.1016/j.landurbplan.2013.09.010

Vicinity. 2022. Modular vertical garden. Vicinity. [Online]. Available at: https://vicinity.za.com/ [Accessed 7 November 2022].

Vosloo, P. 2016. Living walls and green façades: A case study of the UP plant sciences. *ArchSA*, 80, pp. 42-55. https://saia.org.za/assets/docs/archsa/ASA80.pdf

Wei-Tai, E., Yu-Hui Flora, Y., Ting-Yu, E. & Ta-Te, E. 2016. An automated and continuous plant weight measurement system for plant factory. *Frontiers in Plant Science*, 7, article 392. https://doi.org/10.3389/fpls.2016.00392

Whittemore, R. & Knafl, K. 2005. The integrative review: Updated methodology. *Journal of Advanced Nursing*, 52(5), pp. 546-553. DOI: 10.1111/j.1365-2648.2005.03621.x

Yalcinalp, E. & Meral, A. 2017. Wall vegetation characteristics of urban and suburban areas. *Sustainability*, 9(10), article 1691. https://doi.org/10.3390/su9101691

Yang, F., Yuan, F., Qian, F., Zhuang, Z. & Yao, J. 2018. Summertime thermal and energy performance of a double-skin green façade: A case study in Shanghai. *Sustainable Cities and Society*, 39, pp. 43-51. https://doi.org/10.1016/j.scs.2018.01.049

Yusuf, M., Kumar, D., Rajwanshi, R., Strasser, R., Merope, T. *et al*. 2010. Overexpression of Y-tocopherol methyl transferase gene in transgenic brassica juncea plants alleviates abiotic stress: Physiological and chlorophyll. *Biochinlica et Biophysica Acta*, 1797(8), pp. 1428-1438. https://doi.org/10.1016/j.bbabio.2010.02.002