

DOI: 10.5281/zenodo.12426308

A COMPARATIVE ANALYSIS OF VERTICAL GARDEN SYSTEM: TRENDS, TECHNOLOGIES AND FUTURE PATHWAYS

Ankit Kumar¹, Dr. Sharmila Jagadisan^{2*}

¹VIT University, Vellore, India.

²VIT University, Vellore, India.

Received: 13/06/2025

Accepted: 14/02/2026

Corresponding Author: Dr. Sharmila Jagadisan
(sharmila.jagadisan@vit.ac.in)

ABSTRACT

Vertical garden systems have evolved significantly from simple decorative green walls to sophisticated, sensor-enhanced vertical farms. This transformation reflects broader shifts in urban development paradigms and environmental context. The aim of the study is to trace a timeline of the vertical gardening types based on the systemic analysis of the major patents granted in past five decades (1975 to 2025) and current commercialized systems operational since 2010. Through studying technological progress in irrigation, modularity, hydroponics, smart technologies and their urban implementation, such a comparative analysis attempts to trace trends, regional competencies, and understand research directions in prominent geographical locations. The review will add an in-depth perception of the way vertical gardening has developed and can influence sustainable urban transformation further on. By aggregating innovations across time and geography, the analysis identifies key trends and intends to contribute to a deeper understanding of vertical gardening as a multidisciplinary field. The findings of the paper can further be utilized to inform future prospects by addressing gaps and emphasizing the potential of vertical gardens as integral components of green infrastructure in smart cities for policy development.

KEYWORDS: Vertical Garden, Innovation, Environmental Context, Urban Transformation.

1. INTRODUCTION

1.1 Vertical Gardening in Urban Agriculture

Vertical gardening, also called living walls, green walls, or vertical farms, is the cultivation of plants in vertical planes or vertically stratified planes, usually hydroponically or aeroponically, sometimes using soilless systems (Zareba, et al, 2021). Vertical gardens, in contrast to the horizontal ones, save a significant amount of space in densely populated cities, acting as an insulator on exterior walls by shading them from direct sunlight during hot months and retaining heat during colder periods, providing superior air quality, and a better quality of environment for human well-being (Mir et al.2022). With people in the world increasingly gathering in urban areas, the concept of vertical gardening has become an important factor in the process of urban agriculture as a way to facilitate not only food security but also social communication and ecological regeneration (Akintuyi, 2024).

1.2 Historical context

Vertical green planting is an old concept based on the inspiration of the Hanging Gardens of Babylon and the terrace farming in the cultural landscape, e.g. Aztecs and Incas (Hamidon et al.2020). The first modern green wall took the form of a patent, in 1938, by Stanley Hart White, describing a structure meant to sustain a green wall on an architectural structure (Radić et al.2019). In conjunction with a notable increase in living walls during the 1980s and a subsequent acceleration in the 1990s, it was the 1990s when innovative hydroponic wall systems were developed by Patrick Blanc, who pioneered vertical gardens in modern architecture. Vertical landscaping gained prominence through Bosco Vertical in Milan, and modern vertical farming as a movement was developed by the principles of controlled-environment agriculture (CEA) and vertical farming pioneered by Dickson Despommier in 1999 (Weerasinghe et al.2020).

The advancement of technology in the past 20 years in LED lighting, the use of IoT (internet of thing) to monitor, and closed-loop water systems, has turned vertical gardening into a low-impact, all-year-round, efficient, agricultural alternative (Van Gerrewey et al.2021). Valuable systems include Aero Farms, Sky Greens, and Infarm. Yield, water, and urban food-mile savings in these systems are dramatic, creating the paradigm of urban agriculture in the 21st century.

1.3 Objectives

The study aims to delineate the chronology of vertical gardening types based on the systematic analysis of the major patents and commercial systems in the past fifty years. Through studying technological innovations in irrigation, modularity, hydroponics, smart technologies, and their urban implementation, such a comparative analysis attempts to define technology trends, regional competencies, and research directions. The results will add to an in-depth perception of the way vertical gardening developed and can influence sustainable urban development further on.

1.4 Existing Typologies of Vertical Garden Systems

Vertical garden systems that exist in the world are several and classified depending on several typologies that are framed on the basis of construction, substrates, planting medium, and irrigation methodology. This is because through learning of such typologies, a more solid ground is developed in the analysis of the latter patent innovations.

(a) Modular Planter Box Systems:

These are systems that contain containers of potting media that are stacked or fitted together. They also occur in the tropical and subtropical regions because they are tough and simple to maintain. Planters are completely permitted to single plant subsidiary, and offer great support for the heavier species.

(b) Textile- or Felt-Based Systems:

These systems are highly used in Europe and North America and are based on the use of geotextiles (e.g., Fytotextile, Florafelt) to provide rooting substrates (Kaltsidi, 2021). They favour excellent aeration, permit the installation of light, and a thick cover of vegetation. Pre-cultivated textile panels in the temperate climates are now the trend in the industry.

(c) Pre-Cultivated Modular Panels:

Systems such as Sempergreen, LivePanel consist of prefabricated panels, which are grown in a controlled environment and are eventually assembled onsite. They are very pretty in looks, the homogeneity of vegetation cover and reliability of action. They are increasingly being used in commercial as well as big publicly installed projects.

(d) Hydroponic and Aeroponic Frames:

These are recirculating systems free of soil, working on the nutrient-rich recirculating solutions. They may be used in indoor agriculture and high-performance walls in food production. Hydroponic frames minimise the utilisation of resources, allow faster growth and can be easily combined with sensors.

(e) Biofilter Vertical Gardens:

There are biofilter systems (e.g., CityTree) that are actively applied to filter air contaminants with the assistance of mosses or M-resistant plant species (Burnham, 2022). They are used in the urban centres as climate mitigation infrastructure and combine vegetation with the IoT-enabled environmental monitoring.

These typologies make light of the ecological and technological reasons for creating a vertical garden and define the premises of already patented tendencies in different places.

2. METHODOLOGY***Methodological Protocol for Patent and System Selection***

A methodical pattern of protocols found and tested patents and business systems of vertical gardens. The databases of the World Intellectual Property Organisation (WIPO), Espacenet (EPO), the USPTO, and Google Patents were also searched (Majekolagbe, 2024). The reason is that the years 1975-2025 were selected, as it is a period between the introduction of modern vertical gardening in terms of the initial structure patenting involving sensor-controlled systems.

Search Strategy:

The search blocks were constructed on the basis of such words as vertical garden, green wall, hydroponic wall, modular planter, facade greening system, and IPC/CPC code (A01G, A01M, E04H, F24F, Y02A). Filtering of search by functional claims and structural innovation filters, and the irrigation technology filters were also used to narrow down the search.

Inclusion Criteria:

They would include patents and systems when they:

- Demonstrated clear technical innovation across irrigation, modular structural systems, substrate design, or intelligent monitoring technologies
- Proper documentation (claims, drawings, descriptions).

- Demonstrated to apply to the areas of vertical gardening, facade greening or soilless cultivation.

Exclusion Criteria:

- Patents with the descriptive concepts.
- Technical disclosure: Systems that are not technically disclosed.

Country Selection:

The U.S and Europe are selected because they possess excellent advancements in terms of patents and also because of their developed green infrastructure markets. Also the rise of Asian countries such as India, Japan and China, in agriculture, plant cultivation that there is an increased pace of technology regarding low-cost modular systems, smart agriculture. These countries construct natural groupings, which would be compared to one another.

This type of the selection of systems, and also considering the apprehensions of analytical rigour and scientific correctness such countries are put on priority.

Climatic and Regional Typologies of Vertical Gardens

The different climatic areas possess varied attributes and parameters of vertical garden systems due to the distinction in the temperature, rainfall, humidity, and availability of plants and maintenance of plants (Jayakody et al. 2023).

(a) Tropical Climates (India, Southeast Asia, Brazil):

Monsoons can occur aggressively, and the humidity is high, which influences system design. This favours box planters, drip sprinklers and tough plastics. Pale wills are punctuated with ferns, philodendrons, pothos and local tropical vines.

(b) Temperate Climates (Europe, North America):

Seasons are shifting, as well as the unpredictable winter weather, which makes the shift towards a textile-based system. Ready-made felt panels do give uniformity and promptness to facades. The irrigation techniques were placing pressure on frost-resistant recirculation systems.

(c) Arid and Semi-Arid Climates (Middle East, Australia):

A shortage of water is one of the causes of the use of xerophytes, slow irrigation, and greywater use. Thermal insulation is extremely beneficial because high loads of heat occur on a facade.

(d) Cold Climates (Canada, Scandinavia):

It needs to be framed by a panel of insulation, sturdy standstill and blended interior- exterior work to resist the freeze-thaw winter weather. Hydroponic walls are plants that are found indoors all year round.

This category of climatic arrangement leads to the advancement in knowledge regarding predictable variability of patented innovations by regions and the motivation of modularity, irrigation, and the choice of material.

3. TIMELINE AND GEOGRAPHIC TRENDS**3.1 The timeline of innovation frequency by decade***Table 1: Innovation frequency by decade.*

Patent	Year	Country	Title	Key innovation	Relevance	Inventor and resource
US4961284A	1990	US	Self-moisturizing plant wall	Vertical water tube having graduated openings + liner.	Old-fashioned self-watering vertical planter.	Bruce Williams, (1998)
US7516574B2	2009	US	Tower garden	Modular planters are brought up through an pump.	Semi hi-rise hydro tower.	John Gottlieb and Wendy Gottlieb (2005)
US7055282B2	2006	US	Hydroponic cultivating apparatus-	Stackable tubes, timed pump/drain, and float valve.	The aeroponic tower is represented in the commercial.	(Morris Bryan, III, Anderson, SC (US), 2004)
US8479444B2	2008-2013	US	Vertical garden assembly	Wire mesh + L -L-brackets + drain collection gutter.	Internal Drainable living wall.	(Gislene Medeiros Mesiará, São Paulo U.S. PATENT DOCUMENTS (BR), (2008)
US8919040B2	2014	US	Spiral garden	Gravity-intensities conical spiral modules.	Aesthetic pyramid of hydroponics.	(Rocquel S. Galvan, Fort Belvoir, VA, 2012)
EP2885963A1	2014	EP	Vertical garden troughs	Single-fed irrigation cascading troughs.	Hydroponic wall, Low-water.	(Josef, Nemeč CZ - 40502 Decín (CZ) (2013))
EP2983463B1	2017	EP/IN	Modular snap-in system	Expandable pots with drip trays with snap-in character.	Sized modular Green wall.	(Shah,Kumarpal 2013).
AU 2022285112 B2	2017	CN	Stackable irrigation modules	Recycling flow and little evaporation	Green columns which are efficient.	(MILLWARD, Stephen;INGRAM-TEDD, Andrew, (2022))
EP 3 970 475 A1	2022	EP	Modular vertical garden	Telescopic aluminum planters and LEDs, and irrigation.	Tool-free assembly.	(Frigerio, Alessandro Bari (BA) (IT). (2020))
US 9,032,665 B2	2013	US	Aquaponic vertical garden with integrated air channel for plant-based air filtration	Vertical Garden, Perforated backing element mounted within the support structure	its ability to combine food production with air purification, particularly in urban environments	(Christopher J. Whitney, San Francisco, CA (US), 2013)
US8774885B2	2014	United States	Device for generating a detectable signal based upon concentration of at least one substance	This has involved LED lighting techniques which can improve the efficiency of diodes.	This is important for the lighting industry.	(Marcio Marc Abreu) (Abreu, 2014)
CN103717732B	2017	China	Methods of increasing yield and stress tolerance in a plant	This has involved some agronomic characteristics which can increase the efficiency of nutrient	This is highly relevant with this for having some common barriers.	(S. Basu, J. Cohen, M. Nuccio) (Basu et al. 2017)
US20200310992A1	2021	United States	Gather-Scatter Cache Architecture For Single Program Multiple Data (SPMD) Processor	Introduced SPMD processing environment to enable skilled parallel computation.	This type of technology can give proper guidance in the smart agriculture system.	(Cook, J. J., Pearce, J. D., Srinivasan, S. T., Bheda, R. A., Sheffield, D. B., Davare, A., & Sorokin, A. A) 2021
CityTree (Green City Sols.)	2015	China	Air purification device utilizing mosses	This is the vertical biofilter which helps in purifying of air.	Relevant as this is focused on biohybrid vertical system and management of air quality.	Green City Solutions (2015).

CN106572639A	2017	china	Modular container and modular irrigation system	type of vertical biofilter that uses moss to clean up the urban air	Relevant as vertical garden tower	希门尼斯·桑蒂利亚纳M·V·科沃斯·罗德里格斯, (2017)
Sky Greens A-Go-Gro	2020	United States	Controlled Agricultural Systems and Methods of Managing Agricultural Systems	Highly automated system of agriculture which has been integrated with numerous processing lines.	Supported the adaptive cultivation for getting the proper treatment.	(Bongartz, T., Olschowski, S., Haas, N., Angenendt, G., Burza, M., & Magg, N.) (Bongartz, et al. 2019)
CA2809941A1	2012	Canada	Rotating vertical racking system and method for growing plants	Introduced the vertical racking system, which can hold the plants with the help of a rounding frame.	The rotating hydroponic structure represents the innovation of low energy.	Ng, Jack. (2012).
DE202022106982U1 (Legat)	2023	Germany	Planting Module for a Hanging Garden	Gravity-fed planting system with stackable to hang the garden.	Relevant for the modular design with the irrigation technology.	Legat N Holding GmbH. (2023).
EP3691009B1	2024	Europe	Fuel cell system and fuel cell system control method	This has focused on heat management for maintaining the temperature of the fuel cell.	This technology has presented a cross-sectoral which integrates with a low amount of carbon energy for plant growth	(Tetsushi Noda, Tatsuya Yaguchi, Hayato Chikugo) (Noda et al. 2024)

(Source: Self-authored)

3.2 Country-wise contribution

United states

Vertical gardening has become a global movement currently in the phase of innovation with a few different nations dominating the contribution ability. Since the early 1990s, the United States has led the field with innovations beginning with the introduction of the self-watering plant wall (US4961284A, Williams, 1998) and the aeroponics tower garden (US7516574B2 (John Gottlieb Wendy Gottlieb)). The new patents issued at the US lately still concentrate on automation, integration of LEDs, smart data systems, such as agritech systems like US20200310992A1 that substantially allow high-performance parallel computing within the smart contexts of agriculture.

One of the earliest documented examples is the pioneer vertical gardens developed in the 1990s and 2000s in the U.S., with patents filed in the 1990s like US4961284A (Bruce Williams, 1998) having self-watering planters, and in 2010s, finally with a complete vertical garden system model (US7516574B2 (John Gottlieb Wendy Gottlieb)) having stacking hydroponic towers. The supremacy of the Americans was extended to early remote monitoring home automation systems that paved the way to the present vertical farming technology.

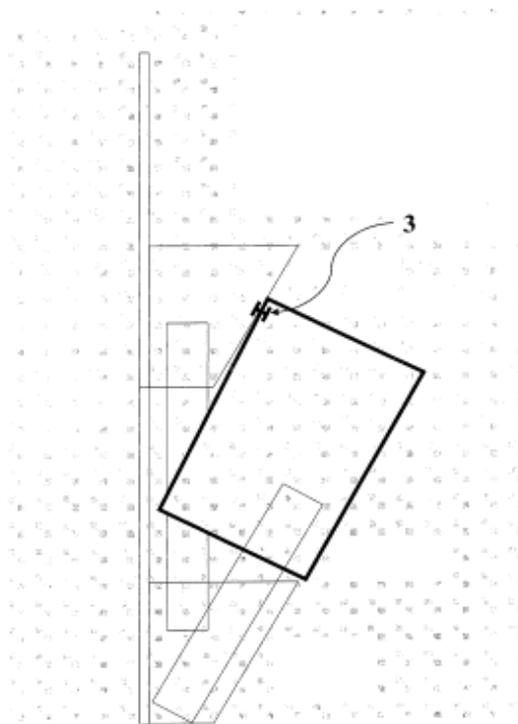


Figure 1: Josef, Nemeč, 2013, Vertical garden for exteriors and interiors EP 2 885 963 A1.

(Source: European patent application)

Europe played a great role in introducing modular and sustainable vertical green systems, especially through the EPO. Important inventions are (EP2885963A1 (Josef, Nemeč CZ - 40502 Decín (CZ) (2013)), which brought the idea of cascading trough, used to maximize water efficiency, which introduced telescopic aluminium planters with LED integration, a testament to an overall strong tradition of advanced, architecturally-incorporated green infrastructure. Europe has proved to excel in precision-engineered and modular vertical farming systems. Telling patents such as EP2885963A1 and EP3970475A1 (2022, Inventor: Alessandro Frigerio) are devoted to the sustainability of irrigation and are concentrated on rationally-designed telescopic planters and user-friendly assembly. In addition, such developments include the EP3691009B1 innovation of Noda et al. (2024), which indicates a shift towards the combination of low-carbon energy and vertical farming through the control of fuel cells.

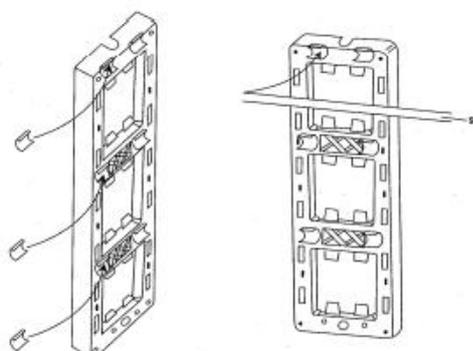


Figure - 9 A

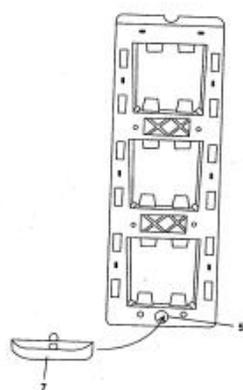


Figure 2: Shah, Kumarpal, 2013 vertical garden system, EP2983463B1.

(Source: European patent application)

The contribution made by India became prominent after 2015, which includes patents, such as EP2983463B1 in 2013, Shah, Kumarpal cantered on modular systems and scalable drip-fed

frameworks that could be implemented at a lower cost in urban settings such as Mumbai and Bengaluru.

Japan

Smart-sensor integration and small-scale hydroponic systems have been the priorities of Japanese innovators. Patents such as US 10,619,353 B1 (2017, Inventor : Stephen J. Scharr , Kennett Square , PA) with drip-fed greening on the facade level expounded on by Japan due to the culture of efficiency and high-density population, and so did the series with automated, rotating hydroponic towers being ideal systems to employ in urban homes. The contributions by each region highlight the world's move into the creation of intelligent, sustainable, and scalable vertical garden ecosystems by combining all of their parts. Japan remains interested in sensor-based compact systems of smart agriculture. Its level of patenting in this sector is low in comparison, but it is the accuracy of technologies such as vertical drip-fed building greening that is having an impact on designing within the confines of a city.

China

China has vertically branched into air purification design and water-saving patterns. However, notable new inventions are CN106572639A (2017), which inflated the idea of stackable modules of irrigation, and CityTree (2015)-a type of vertical biofilter that uses moss to clean up the urban air. The technologies exhibit the hybrid nature of China in environmental and agricultural innovations in urbanism.

Other new entrants are the countries of Germany, which has donated modular planting systems (patent: DE202022106982U1, e.g., Legat 2023), and Canada, where CA2809941A1, Jack Ng has proposed a rotating hydroponic racking system, an innovative low-power, efficient urban farming. The country-specific trend in the allocation of innovations corresponds to a trend worldwide in the urban agriculture model being modular, sustainable and highly digitized. Underlying the issue of automation are other technological advantages with Three countries playing to their advantages, Europe with modular architecture, China with hybrid environmental systems, and India with low cost, high-value, scalable designs.

3.3 Recent surge post of India

The path of innovation of India on vertical gardening has been considerably escalated after

2015, thanks to the prolific necessity of sustainable agrarian practices, optimization of the urban space, and designing against climate change. This would require consideration of cost effective and modular solutions that are context-sensitive and would best fit in dense urban ecosystems, provided by innovative minds in India. The system will especially be useful in the cities in India where space and water are scarce. Its construction allows intensive planting with little plant input that aids food security in cities.

Also vertical garden system patented by Kumarpal SHAH with case no EP2983463B1 (2013) as well as WO2014167576A1 (2013). The snap in pot with drip feed trays design presents a ready scalable framework suitable to both home and business settings. Its cheap manufacturing cost and user-friendly design has made it to be popular among urban farming projects, community farms, and household gardeners in India cities. As more people continue to embrace digital in India, this technology is adapting this demand of convenience and self-contained green spaces by the customers. It is convenient in terms of living in the contemporary era of smart homes and ecosystems: the expansion enables observing the nutrient levels and environmental conditions through a smartphone.

India is majorly contributing after technical novelty; it is the business model of functionality, as well as a social and environmental model, which is educative and welcomes everyone. This type of systems can be utilized in school, community rooftops as well as some urban slums in aid of environmental awareness. The innovations boom in India makes a contribution to international climate-friendly agro-discussions. Indian systems focus on energy independence and the local sourcing operations of materials the qualities of which are critical to making it replicable in other developing countries, with comparable resource shortages.

4. COMPARATIVE ANALYSIS OF INNOVATIONS

4.1 Watering and irrigation techniques

Evolution of irrigation systems

Invented in the 1970s, the first types of vertical garden irrigation were the passive systems that rely on gravity to operate. Years later, irrigation systems have advanced to highly efficient and programmable ones that contain recirculating flows and smart sensing. Early implementations included self-watering planters, in which portable self-watering planters or water reservoirs were used

(Angelakts et al.2020). Due to the increasing need for more significant installations, the irrigation system advanced as well, beginning with daily water applications using runoff, to the completely regulated systems that preserve almost all the water put into them.

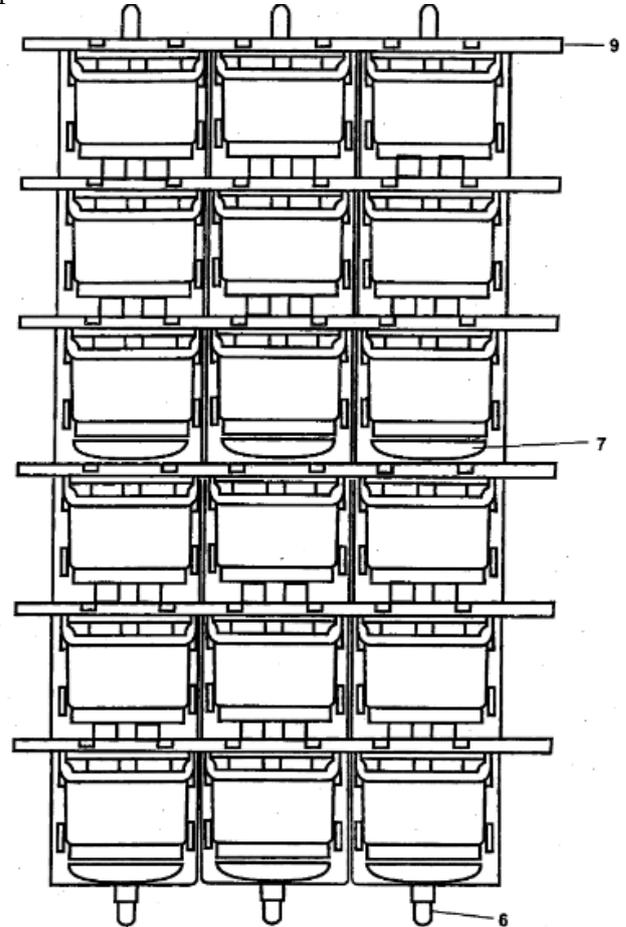


Figure 3: Shah Kumarpal, (2013) the frames of vertical garden system fixed to the wall to create a green living wall EP 2 983 463 B1.

(Source: European patent application)

Passive and gravity-driven systems

Innovative systems aimed at making maintenance much easier through passive water delivery. A good case in point is the US4961284A (Bruce Williams, 1998) that came out with a vertical-water-tube topped with a series of outlets that were graduated and additionally had a removable liner mechanism that created equal watering without external pumps through gravity. These initial models fitted small household applications and were a necessary way forward to automatic irrigation.

Drip-fed and recirculating mechanisms

By the 2000s, the innovations had made a move

to drip-fed irrigation to deliver specific water. Records such as EP2885963A1 had cascading troughs with single-feed recirculating hydroponic systems that had the capacity of refilling every 14 days and decreased water wastage by a great deal (Bakirov, k et al.2024). Rain Bird and the other companies emphasize the capacity of the drip systems to minimize evaporation and fungal disease by sending water directly to the root zone.

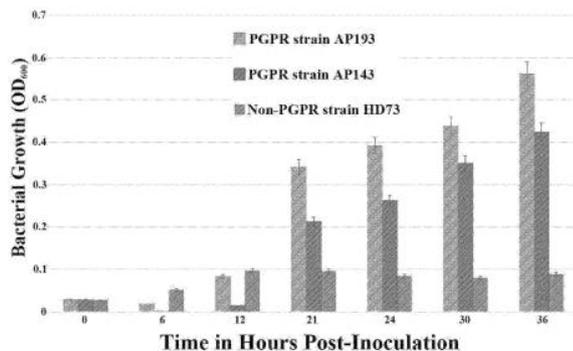


Figure 4: Lilies and Kloeppe, 2024, Patent US12089598B2 From 17.10.2024 on Comparative analysis.

(Source: US Patent office)

Inoculation mechanisms

The bar graph (Fig-4) indicates how the bacteria grew (OD 600) in 2 different strains of PGPR (Plant Growth-Promoting Rhizobacteria) (AP193, AP143) and different strains the non-PGPR strain (HD73) over the course of time after inoculation. It proves that the PGPR strains have a high growth in comparison with the non-PGPR strain. The graph helps to understand the aim of this study that compares the colonization capacity of beneficial vs. non-beneficial strains of the bacteria. Since vertical gardens often use compact or artificial soil media (e.g., cocopeat, perlite), introducing efficient colonizing PGPRs ensures better root development and nutrient uptake in constrained setup.

Hydroponic aerologic towers

Recycling of water is also efficient in compact hydroponic towers. US7516574B2 invented a closed-looped aeroponic tower that is driven by a water pump to permit continuous circulation of the nutrient solution, consuming 90- 98% less water than conventional farming and recycling all of its nutrients (Pucher et al.2022). Consumers have experienced an accelerated turnover of crops and a decrease in the area occupied by land, a situation that catapulted vertical farming into the center stage of environmentally friendly city farming for selected

few plants and vegetables.

IoT-enabled smart irrigation

The latest innovation is based on autonomous irrigation panels fitted with moisture, humidity, and nutrient sensors that allow real-time water control in line with the specific needs of the plant being grown. The possibility to avoid overutilization of water with the help of predictive algorithms is implied by connections with AI, which can be witnessed in recent agricultural projects.

4.2 Modularity and Structure

In the vertical garden systems focus on setting up a system that is modular, stackable and telescopic in nature, one that can be set up and scaled easily. This development is provided with features that overcome the spatial and maintenance limitations experienced in the city setting. The modular design with clamped-in trays was created by Kumarpal SHAH, (EP2983463B1, 2013) which permits the convenience of expansion and configuration. The patent of Paltrinieri (EP3970475A1, 2022) made a step further in this direction, introducing telescopic aluminum planters, which allow being assembled without using a tool, minimizing energy consumption (using LEDs) and working both indoors and outdoors.

Easy variation of disposition--in vertical columns, in pyramidal layers, or in removable racks, is a power of beauty as well as of utility. As the need to have gardening systems that are user-friendly in the high-density housing increases, modularity has emerged as one of the characteristics that favor its widespread implementation in all gardening environments both in amateur and professional gardens.

4.3 Soil-less Cultivation and Hydroponics

Vertical farming has become focused on the use of hydroponic and aeroponic systems, which provide ample efficiency, extreme use efficiency, and do not rely on conventional soil. Closed-loop hydroponic designs are also found in commercial systems because they negate the use of resources that would occur in open-loop systems (Sky Greens A-Go-Gro, 2010), Another practical use of the soil-free technique is linked to a smallhold (2020) where the vertical spaces allow incorporating hydroponics into an efficient mushroom growing strategy. Such innovations are suited to contemporary urban farming since they can eliminate soil-borne pests, minimize the wastage of water, and allow nutrient delivery to be controlled spot-on. Moreover,

automation is better suited to soil-less systems, and they are compatible with digital farming platforms. With the increasing populations of the urban areas and a reduction in the arable land, the Hydroponic and aeroponic systems can be considered as a sustainable as well as scalable method of food production in urban regions across the world.

4.4 Smart and IoT Integration

Vertical gardening was reinvented after the adoption of smart technologies and IoT, with features of real-time monitoring, automation, and remote control. Likewise, Gardyn Home (2021) implements hydroponic towers with AI to control nutrients and moisture conditions and allow growing plenty of produce indoors throughout the entire year. New technology available through the smart vertical gardening will render the latter affordable. Hexagro Clovy (2020) is a software-

prediction-sensor product integration that optimizes plant well-being and minimizes user interaction (Dsouza et al. 2023). Such systems have automated responses with moisture, pH, light, and temperature sensors and, as such, they minimize waste and maximize yield. Also, a significant number of them are now equipped with diagnostics that use AI and inform the user about the deficiencies or threats.

4.5 Urban context and Interior Applications

Vertical gardens systems are progressively designed to fit cities, where there is little space and green infrastructures are important in resilience to climate. Such developments as CityTree (2015), which integrates biofiltration with moss and a vertical housing system to clean the air of cities, confirm this tendency due to the integration of nature with a related vertical structure, and acting as a vertical garden and environmental monitor.



Figure 5. Kelly Bergevin, CityTree - reducing urban air pollution, one bench at a time 2015 on biofiltration. (Source: worldatlas News portal)

Lechuza (2023) is a gravity-based, modular hanging garden that fits well in balconies and small houses, focused on a small footprint and simplicity of assembly. Agritecture (2017) and its likes implement intermediate steps between interior design and practical farming, with some decorative, eye-pleasing, and nutritious tastes from vertical planters in offices and homes

SOCIO-ECONOMIC BARRIERS & POLICY CHALLENGES

Socio-Economic Barriers and Implementation Challenges

Despite their high values with respect to their environmental standards, vertical gardens have a grave socio-economic constraint that limits their

application in various cities. It is too expensive to install and maintain, and therefore cannot be used within low-income areas. Maintenance of irrigation, pruning, and pest control also might require skilled labour that contributes to the long-term cost of operation.

It also has diverse policy and regulatory frameworks. Some cities also enforce some incentives to facade-greening (e.g. Germany, Singapore), but others fail to specify the parts of the structure that should be integrated, the security of irrigation or the type of plant that is to be used. The acceptability of the concept of vertical garden among the people who may consider it expensive, straining in terms of maintenance or simply ornamental also differs. All this socio-economic environment has a significant impact on the implementation of vertical gardens' scopes and accomplishment.

INDIA'S INNOVATION FOOTPRINT

India has become a potentially successful member of the vertical gardens innovations, whose design boasts cost-effectiveness, modularization, and adjustability to a wide range of climates. Important innovations include the EP2983463B1 in 2013, Shah, Kumarpal modular vertical garden with snap-in pots, fixed drainage trays, and drip-feed irrigation designed by Shah, Kumarpal that is maximized to be scalable, whether in a public or domestic residence area. It is simple, and one can easily make it, and hence they can be used educationally, at home, as well as in the commercial world.

An Indian smart vertical herb nursery known as Vigga Grow (2019) automates the process of nutrient dosing using the control of nursery processes via a mobile phone app, meeting the level of automation and convenience demanded by the user (Reddy, R et al.2022). These systems suggest the rise of India as one of the contributors to the vertical garden democratization with the help of technologically humble but situationally and locally responsive responses to fresh, decor, and sustainability.

INNOVATION GAPS AND FUTURE PROSPECTS

7.1 Necessities for Irrigation

Although the development of the vertical gardens is fast-paced, there is no standardization of irrigation technologies in models and regions. They include gravity-fed tubes, drip-fed systems fully powered by electrical systems, but there is no

standard procedure or recommended practice for domestic, commercial use. This leads to a discrepancy in water economy, particularly in low-cost or (DIY) do-it-yourself installations. Scalability and maintenance are still issues when there are no flow rates or pressure levels. This can be enhanced by the determination of international standards to define the supply components of the system -like those of the traditional agriculture- to enhance interoperability of the systems, lower cost and enhance efficiency of the same, considering countries that are catching up with the inner markets adopt the sustainable vertical gardening activities without sacrificing resource management.

7.2 Lack of nutrients optimization based on AI application

Artificial intelligence in the form of nutrient management is an innovation of the lower-level large corporation's vertical farms but is not adopted in mid-level consumer and education facilities in general. This is an inefficient way of getting the plant to a healthy state and also causes frustration to the user because of over or overdosing. The best way to bridge this gap is by developing lightweight AI tools, which may be integrated into cheaper systems using smartphone solutions and open-source systems. Large-scale AI-based nutrient management would bring precision agriculture to the masses, making it available to both amateur gardeners and educational establishments, letting those gain access to the power of higher plant diagnostics and autonomous resourcing.

7.3 Prospects for the development of modular greenery

Vast majority of vertical garden systems is tuned to temperate areas, and in tropical regions the gap in innovations is massive. The modular green facades built in tropical conditions (such as Mumbai, Bangkok, or Lagos) should use rain-harvesting systems. The possibilities are to come up with climate-adaptive innovations that allow the growth of native plants and greenhouse that helps to reduce the absorption of heat inside the buildings. Megacities would also enhance by these systems, decreasing urban heat islands, as well as biodiversity. The adaptation of modular facade to tropical climates has the potential to create new business by opening up markets in new locations, and opening up possibilities of vertical greening in the areas where the climate change is most concerning.

7.4 Community & Social Impact

Community and Social Dimensions of Vertical Gardens .Although vertical gardens differ in their technical features, they have many social and societal benefits. The vertical farms in the communities assist in establishing food security in the locality and provide educational opportunities to schools and neighbourhoods.

The more urban residents become attracted to the vertical gardens and their use as the common areas, which can trigger the process of socialisation, eco-friendliness, and climate accountability (Zaręba et al. 2021). These are also the same dimensions of the social spectrum, rendering vertical gardens to be more appealing to a wider range of audience in the context of architecture and engineering, their use in the spheres of sustainability, community health and community development.

6. CONCLUSION

The vertical garden systems have evolved over the past fifty years and are evolving not only to be simple decoration designs, but also modernised to be highly developed hydroponic systems, capable

Author Contributions: The first author, Ankit Kumar conceptualized the work, wrote the original draft, framed the methodology and comparative analysis.

The corresponding author, Dr. Sharmila Jagadisan supervised, reviewed and edited the final manuscript.

Both the authors have read and approved of the work.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in [Google patents and European patents repository]

REFERENCES

- Morris Bryan, III, Anderson, SC (US), 2004. Hydroponic plant cultivating apparatus (U.S. Patent No. 7,055,282 B2).
- Frigerio, Alessandro Bari (BA) (IT). (2020). MODULAR SYSTEM FOR VERTICAL GARDEN No. EP 3 970 475 A1).
- Rocquel S. Galvan, Fort Belvoir, VA, 2012 Spiral garden (U.S. Patent No. 8,919,040 B2).
- John Gottlieb and Wendy Gottlieb (2005). Vertical garden (U.S. Patent No. 7,516,574 B2).
- Kumarparl S. (2013). frames of vertical garden system fixed to the wall to create a green living wall (EP. Patent No. EP 2 983 463 B1).
- Gislene Medeiros Mesiara, São Paulo U.S. PATENT DOCUMENTS (BR), (2008). Vertical garden assembly (U.S. Patent No. 8,479,444 B2).
- Stephen J. Scharr , Kennett Square , PA, 2017). INTEGRATED WALL ASSEMBLY(U.S. Patent Application Publication No. US 10,619,353 B1).
- Josef, Nemeč CZ - 40502 Decín (CZ) (2013) European patent application: Vertical garden system (EP Patent Application No. EP 2 885 963 A1).
- MILLWARD, Stephen;INGRAM-TEDD, Andrew, (2022). MODULAR GROWTH UNIT FOR A VERTICAL FARMING SYSTEM (A.U. Patent No. AU 2022285112 B2).

of detecting the surroundings and relaying the information to the control device. A wide variety of technologies like irrigation, modularity, substrates and smart-integration are conditioned very highly by the climatic factors, which include regional design cultures and socio-economic environments.

The research provides a more comprehensive and scientifically informed conception of global vertical gardens development, as it suggests a systematic approach, geographical typology, system types, and socio-economic interpretation of that concept. The discovery of the difference between the systems comprising the textiles in the temperate regions, modular planters systems in the tropical regions, and the combinations of these systems with bi-filters in the densely populated areas is useful in increasing the relative weight of the study.

The future should be based on climate-adaptive material, low-cost modular buildings, automated food, and universal communal constructions. The vertical gardens will use these innovations to expand their operations in regards to sustainable, resilient, and socially responsive cities as an aspect of the green infrastructure.

- Bruce Williams, (1998). Vertical garden assembly (U.S. Patent No. 4,961,284).
- Christopher J. Whitney, San Francisco, CA (US), (2013). Aquaponic vertical garden with integrated air channel for plant-based air filtration (U.S. Patent Application Publication No. US 9,032,665 B2).
- Abreu, M. M. (2014). Device for generating a detectable signal based upon concentration of At least one substance (U.S. Patent No. US8774885B2).
- Basu, S., Cohen, J., & Nuccio, M. (2017). Methods of increasing yield and stress tolerance in a plant (Chinese Patent No. CN103717732B).
- Noda, T., Yaguchi, T., & Chikugo, H. (2024). Fuel cell system and fuel cell system control method (European Patent No. EP3691009B1).
- Cook, J. J., Pearce, J. D., Srinivasan, S. T., Bheda, R. A., Sheffield, D. B., Davare, A., & Sorokin, A. A. (2021). Gather-scatter cache architecture for single program multiple data (SPMD) processor (U.S. Patent No. US10896141B2).
- Green City Solutions (Inventor). (2015). Air purification device utilizing mosses (Chinese Patent No. CN103316584B).
- Bongartz, T., Olschowski, S., Haas, N., Angenendt, G., Burza, M., & Magg, N. (2020). Controlled agricultural systems and methods of managing agricultural systems (U.S. Patent Application No. US20200134741A1).
- Ng, J. (2012). Rotating vertical racking system and method for growing plants (Canadian Patent Application No. CA2809941A1).
- Legat N Holding GmbH. (2023). Planting module for a hanging garden (German Utility Model No. DE202022106982U1).
- Shah, Kumarpal (2013). Vertical garden system in modular form (European Patent No. EP2983463B1).
- Mark R. Liles, Joseph Kloepper, (2024), Use of pectin or pectin-related saccharides to enhance efficacy of plant growth-promoting rhizobacteria (PGPR) strains for promoting growth and health in plants and animals Patent (US12089598B2)
- Akintuyi, O. B. (2024). Vertical farming in urban environments: a review of architectural integration and food security. *Open Access Research Journal of Biology and Pharmacy*, 10(2), 114-126. , <https://oarjbp.com/content/vertical-farming-urban-environments-review-architectural-integration-and-food-security>
- Angelakis, A. N., Zaccaria, D., Krasilnikoff, J., Salgot, M., Bazza, M., Roccaro, P., ... & Fereres, E. (2020). Irrigation of world agricultural lands: Evolution through the millennia. *Water*, 12(5), 1285. <https://www.mdpi.com/2073-4441/12/5/1285>
- Bakirov, K., Tussupov, J., Tultabayeva, T., Makangali, K., Abdikerimova, G., & Yessenova, M. (2024). Advances in the design and optimization of smart irrigation systems for sustainable urban vertical farming. *Scientific Journal of Astana IT University*, 76-90. <http://journal.astanait.edu.kz/index.php/ojs/article/view/654>
- Dsouza, A., Newman, L., Graham, T., & Fraser, E. D. (2023). Exploring the landscape of controlled environment agriculture research: A systematic scoping review of trends and topics. *Agricultural Systems*, 209, 103673. <https://www.sciencedirect.com/science/article/abs/pii/S0308521X23000781>
- Hamidon, M. H., Abd Aziz, S., Ahamed, T., & Mahadi, M. R. (2020). Design and development of smart vertical garden system for urban agriculture initiative in Malaysia. *Jurnal Teknologi (Sciences & Engineering)*, 82(1). <https://journals.utm.my/jurnalteknologi/article/view/13931>
- Hong, K. P., & LEE, H. J. (2019). Analysis on Indoor Garden Technology Trends Based on Patent Search. *International Journal of Advanced Culture Technology*, 7(4), 40-48. <https://koreascience.kr/article/JAKO201909055503731.page>
- Mir, M. S., Naikoo, N. B., Kanth, R. H., Bahar, F. A., Bhat, M. A., Nazir, A., ... & Ahngar, T. A. (2022). Vertical farming: The future of agriculture: A review. *The Pharma Innovation Journal*, 11(2), 1175-1195. https://www.researchgate.net/profile/Zakir-Amin/publication/358749034_Vertical_farming_The_future_of_agriculture_A_review/links/6213b0604be28e145ca7aab5/Vertical-farming-The-future-of-agriculture-A-review.pdf
- Pucher, B., Zluwa, I., Spörl, P., Pitha, U., & Langergraber, G. (2022). Evaluation of the multifunctionality of a vertical greening system using different irrigation strategies on cooling, plant development and greywater use. *Science of the Total Environment*, 849, 157842. <https://www.sciencedirect.com/science/article/pii/S0048969722049415>

- Radić, M., Brković Dodig, M., & Auer, T. (2019). Green facades and living walls – a review establishing the classification of construction types and mapping the benefits. *Sustainability*, 11(17), 4579. <https://www.mdpi.com/2071-1050/11/17/4579>
- Reddy, R.V.S.K., Omprasad, J. and Janakiram, T., 2022. Technological innovations in commercial high tech horticulture, vertical farming and landscaping. *International Journal of Innovative Horticulture*, 11(1), pp.78-91. <https://www.indianjournals.com/ijor.aspx?target=ijor:ijih&volume=11&issue=1&article=008>
- Van Gerrewey, T., Boon, N., & Geelen, D. (2021). Vertical farming: The only way is up?. *Agronomy*, 12(1), 2. <https://www.mdpi.com/2073-4395/12/1/2>
- Weerasinghe, K. G. N. H., Jayasinghe, K. G. D. N., & Halwatura, R. U. (2020). Development of Edible Vertical Gardening System and Societal Impact of Vertical Gardening through a Systematic Literature Review. 2020 From Innovation to Impact (FITI), 1, 1-5. <https://ieeexplore.ieee.org/abstract/document/9424890/>
- Ankit Kumar (2017), Vertical Gardens for India Social, Architecture Acceptance & Practice- *International Journal on Emerging Technologies*, 2017, <https://www.researchtrend.net/ijet/pdf/4%20ANKIT%20KUMAR.pdf>
- Kaltsidi, M. P. (2021). Assessment and optimization of felt living walls in terms of water retention performance and artificial lighting (Doctoral dissertation, University of Cordoba and University of Seville). <https://idus.us.es/bitstreams/abe198ed-037b-4bab-8b82-147e3db0e9b2/download>
- Burnham, S., 2022. Nature~ Enabled Urban Design. *Earth Island Journal*, 37(3), pp.48-52. https://www.jstor.org/stable/27370333?casa_token=zq15KTs5LcgAAAAA:QT3kOHH8xkh36dYusrNHZcpXj86Gf_06Xkno_5AUdLU2oK3ax29PT4osJB7sxKbjQEnVIVLQMm9I4eVnEvv_x5mOVfFPLHX-tyJI4pS_Xkwzkmlyg
- Jayakody, G. D. C., Weerasinghe, K. G. N. H., Jayasinghe, G. Y., & Halwatura, R. U. (2023). Economical sustainability of vertical greeneries in tropical climate. *Energy and Buildings*, 299, 113580. https://www.sciencedirect.com/science/article/pii/S0378778823008101?casa_token=AthT3WRC9IUAAAAA:bz3fHAEHIXcNTZxfAd_J-Rearat3FuVILF8oC26COisllGuA8jcnLPIMCm0C7UcotJwcvRwJ
- Zaręba, A., Krzemińska, A., & Kozik, R. (2021). Urban vertical farming as an example of nature-based solutions supporting a healthy society living in the urban environment. *Resources*, 10(11), 109. <https://www.mdpi.com/2079-9276/10/11/109>
- Kelly Bergevin, 2015 CityTree - reducing urban air pollution, one bench at a time, worldatlas News portal (Source: <https://www.worldatlas.com/news/citytree-reducing-urban-air-pollution-one-bench-at-a-time.html>)