International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X

www.agronomyjournals.com
2024; 7(8): 819-831
Received: 07-06-2024
Accepted: 13-07-2024

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Enhancing vertical farming with cutting-edge automation: A comprehensive review

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DOI: https://doi.org/10.33545/2618060X.2024.v7.i8k.1389

Abstract
Vertical farming has emerged as a sustainable solution to urban food security, with automation playing a crucial role in enhancing productivity. Advanced technologies like aeroponics, hydroponics, and LED lighting have evolved traditional farming practices. Cutting-edge systems such as MACARONS, collaborative robots, AI, IoT, and machine learning automate vertical farms, optimizing temperature, nutrients, and growth conditions. These technologies not only improve operational efficiency but also significantly reduce labor costs. Environmental benefits include reduced food miles, up to 70% less water consumption, and decreased fossil fuel reliance through solar energy use. Despite challenges like high upfront costs and integration difficulties, future research in edge computing, personalized AI, and cost-effective solutions could further revolutionize vertical farming, making it a key player in achieving global food security and environmental sustainability.

Keywords: Automation, artificial intelligence, machine learning (ML), internet of things (IoT), robotics, vertical farming

Introduction

Modern cultivation techniques, namely vertical farming (VF), have gain world-wide appeal. VF is essentially the process of farming food inside of buildings, typically using anything from multiple stories within one floor to stacked levels. Most of the VF operations are in peri-urban locations, thereby reducing the distance between producer and consumer. A new concept in environment-controlled farming has been presented by VF, which is considered the front-runner in resource efficiency (Lubna *et al.*, 2022) [18].

Vertical farming is emerging as a practical approach to supplying the food requirements for a growing urban population sustainably. Vertical farming estimates a market worth $15.7 billion by 2025, taking advantage of the vertical space in urban areas and the integration of innovative technologies to cater for efficient food production. This method is in line with the push for improved agricultural systems with increasing land resources and increasing optimization of the land for urban development. Adopting smart agriculture, that includes automation, holds key to optimizing returns and decreasing wastage of resources (Saad *et al.*, 2021) [29].

Providing the perfect growing environment for crops is the main challenge of vertical farming. Automation plays a key role in overcoming this challenge through reduced dependence on the manual, and at the same time speeding up the process of farming, both in terms of magnitude and velocity. Key parts of automation include irrigation systems, climate control, soil moisture monitoring, and the use of robots or drones to apply pesticides. This technology integration increases agricultural productivity significantly and in tune, contributes to food security, bio-safety, and healing of health and environmental problems assumed to be part another syndrome of global warming (Saad *et al.*, 2021) [29].

Evolution of vertical farming with technological advances

In the evolution of vertical farming, there have been some major technological milestones

(Fig.1). The concept has evolved over thousands of years since its conceptual roots in ancient civilizations such as the Hanging Gardens of Babylon around 600 BC. The basic concepts behind vertical farming were pioneered in the 1930s by William Gericke. The idea was developed in the 1960s by Othmar Ruthner who build greenhouse towers by applying hydroponics. But the hefty energy and maintenance expenses made it unappealing. Dickson Despommier rekindled the idea in the early 2000s and presented it as a solution to food supply problems in cities. Meanwhile, Japanese inventor Toyoki Kozai developed a closed-plant production system, utilizing multiple layers. The consumer mandate for sustainability and healthy local food staples have been in large part, the catalysts driving the advancements in LED lighting, and the simple reason that vertical farming looks and operates the way it does today (Van Gerrewey *et al.*, 2022) [36].

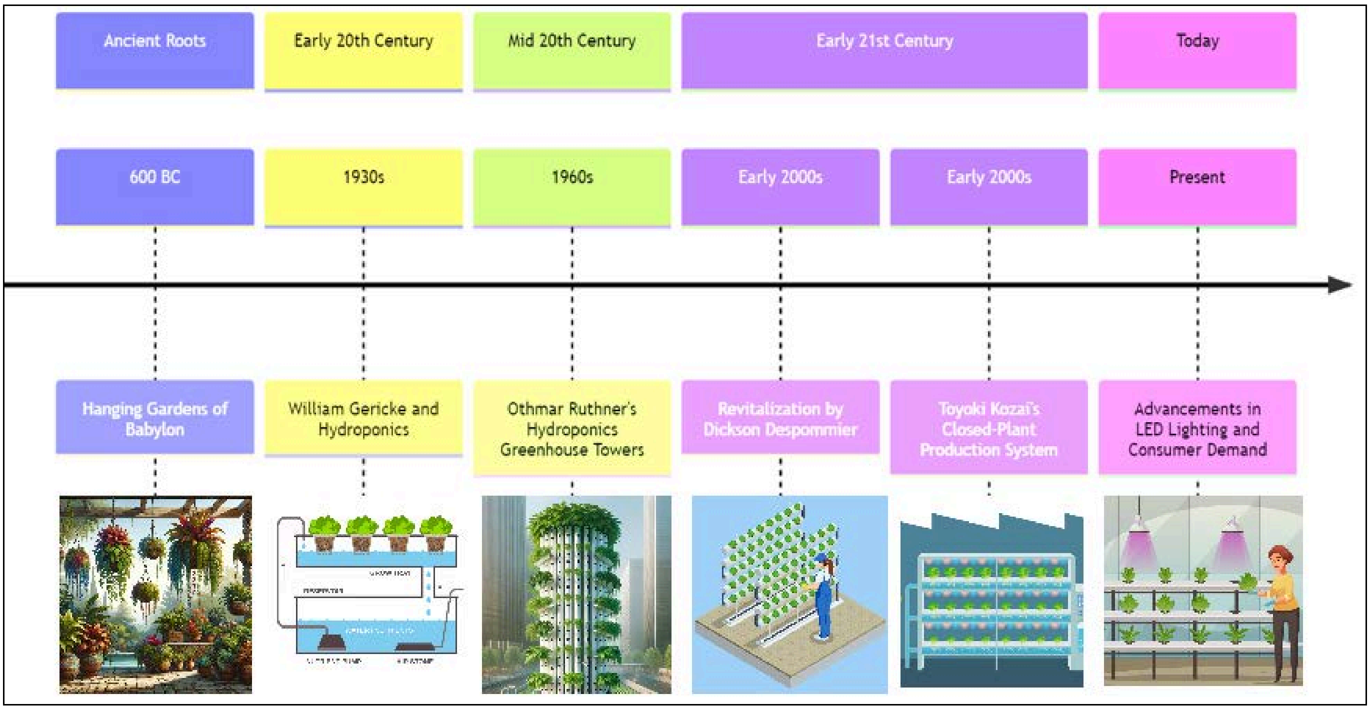

Fig 1: Technological evolution of automation in agriculture

Research has illustrated the critical significance of automation to facilitate the scaling and profitability of vertical farming initiatives. A study by Meinusch *et al.* (2021) [21] argued the importance of enclosed and artificial daylight, plant production. Autocontrol is essential to guarantee the best growing conditions for the plant. Moreover, the hybridisation of hydroponic and controlled environmental agriculture, relying on simulators in greenhouses and vertical farms, provides a solid argument for the importance of robotic automation (Meinusch *et al.*, 2021) [21] The incorporation of machine learning in agriculture and more specifically in vertical farming has led to the use of smart sensors and mechanization. As a result, there has been a continuous evolution of technology that allows the automation of agroprocesses at increasingly higher levels, leading to better productivity and increased predictability of crop production (Tageldin *et al.*, 2020) [34].

LED lighting technology has been critical for artificial lighting in precision farming and is another significant advancement in vertical gardening. Advances in this technology allow for the development of indoor vertical farming systems which can better control the quality of light leading to more productive food production (Lejeune *et al.*, 2020) [17]. Together, these developments highlight the growing importance of automation in vertical farming, using technology to better control crop growth and ultimately, crop yield.

Cutting-edge automation technologies for vertical farming

In urban settings, vertical farming is redefining agriculture processes with the help of automation technologies. These cutting edge technologies are a variety of advanced systems and ways in which to improve efficiency and productivity as well as the sustainability of the vertical farming operations. Through the scaleable and adaptable MACARONS technology; the collaborative accuracy of COBOTS; the artificial intelligence (AI) insights and the Internet of Things (IoT) the technologies work together in different ways to optimise farming conditions and outputs. Machine Learning (ML) enhances such systems by handling more complicated data analysis and decisions. This article discusses the specifics of such cutting-edge technologies and how they are utilized in vertical farming in order to illustrate how these technologies work in concert to define a new era of environmentally friendly and efficient urban agriculture.

Macarons

The MACARONS system is an open-source, scalable, and adaptable platform for vertical farming plant care monitoring and transportation. It offers customised behaviours that are programmable in Python, automated data logging of environmental parameters, and tailored dosing for particular plants. The validation process for the web-accessible system entails the attention of lettuce plants subjected to both artificial illumination and uncontrolled ambient conditions. MACARONS is scalable for larger operations, can carry payloads up to 5 kg, and is projected to complete jobs 30% faster than human operators. The system demonstrates the potential for significant labor cost reduction and operational efficiency improvements. Its ability to handle considerable payloads and scale for more extensive operations underlines the integral role of automation in developing and expanding vertical farming practices (Wichitwechkarn *et al.*, 2023) [39].

Cobots

Cobots or collaborative robots are robots that are designed to work side by side with human beings at shared work spaces. The advantages of robotics (precision, power) combined with those humans still possess (flexibility, solution creating) give systems like these the ability to improve automation of tasks that are not completely automateable. This relationship intends to increase the productivity and reduce the unfavorable conduct of workers (El Makrini *et al.*, 2018) [6]. The types of collaborative robots used in vertical farming are as follows:

a. **Monitoring and Spraying Robots:** These are task-specific robots designed to monitor crop health and spray pesticides or fertilisers. They may work either alone, or in synergy, pool their efforts to scour larger regions at lower cost (Lytridis *et al.*, 2021) [19].
b. **Harvesting Robots:** These are used to automate the harvesting of fruits and vegetables. They can help speed up the process of harvesting hand in hand with human laborers or robots, assisting in labor shortage during harvest peak times (Legun & Burch, 2021) [16].
c. **Swarm Robotics:** This consists of many robots that work together to perform agricultural activities. Swarm robotics are intrinsically flexible, scalable, and resilient, thus making them apt to deal with weed control and large scale monitoring (Albani *et al.*, 2017) [1].
d. **Dual-Arm Manipulative Robots:** These robots wield two arms that allow them to perform human-like actions such as picking and placing. For example, they are useful in tasks that need fine manipulation (e.g., in harvesting fruits or vegetables without damaging them) (Sepúlveda *et al.*, 2020) [30].
e. **Collaborative Robotic Swarms for Precision Agriculture:** These use ground robots as well as Unmanned Aerial Vehicles (UAV) to carry out task be that optimized path routing, crop sensing or selective weeding (Botteghi *et al.*, 2020) [2].
f. **Human-Centered Collaborative Robots:** These are based on the concept of the human-robot collaboration where Robots can work with or not parts of the working group and production, and do heavy lifting, tedious, repetitive work for people. These developed are conceived with the task of advocating safety and ergonomics to increase the working conditions of the agricultural workforce (Gualtieri *et al.*, 2020) [8].
g. **Multi-Agent Systems:** These systems include a number of robots and devices which communicate and collaborate to carry out farming operations better. For full field management, this can be on the basis of ground-based robots along with aerial drones (Lytridis *et al.*, 2022) [19].

Collaborative robots (Fig. 2) in containerized vertical farming will greatly increase efficiency of the workers in limited space.

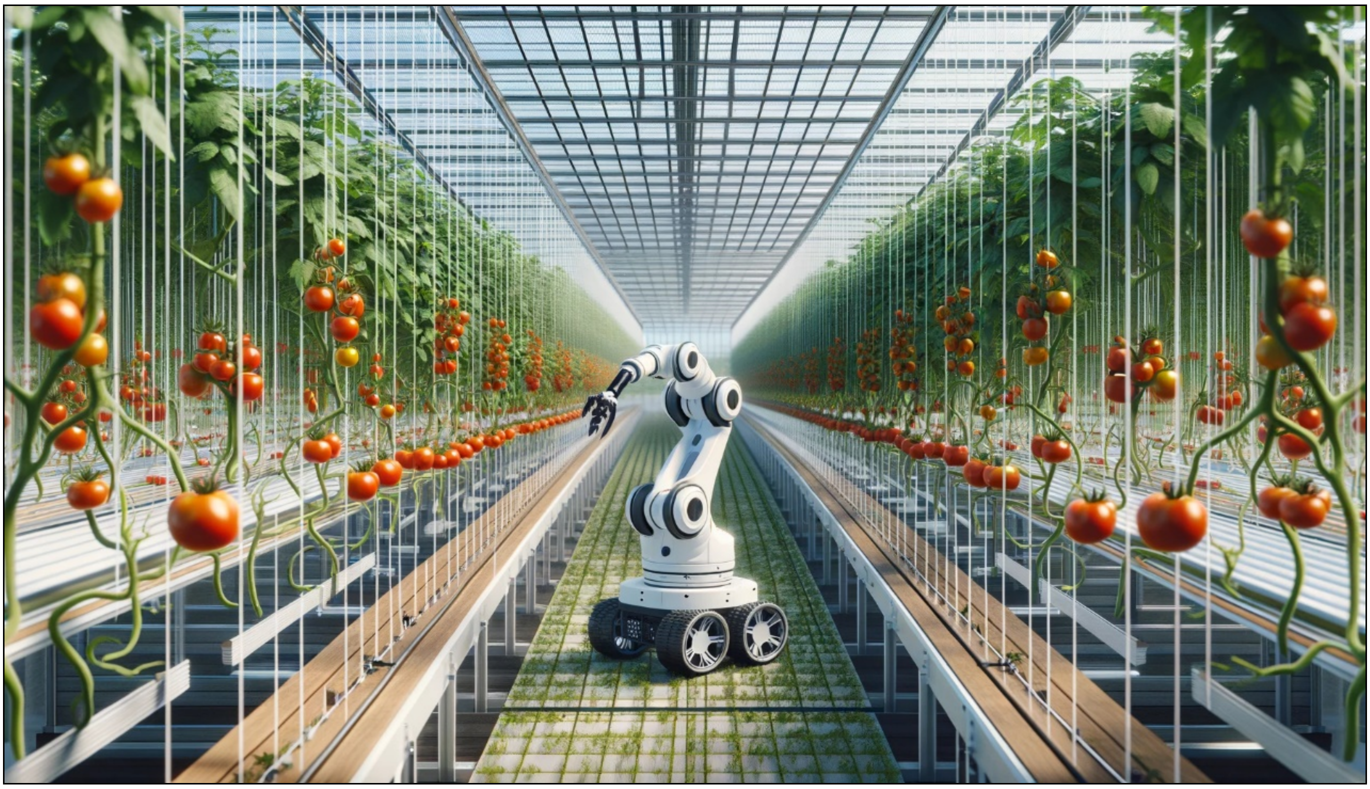

Fig 2: Advanced robotics in precision agriculture - collaborative robots equipped with RGBD camera systems automate critical tasks such as tomato harvesting

Important factors involve the automation of sapling transplantation and mature plant harvesting inside shipping containers. One interesting aspect is the use of RGBD camera imaging, which, when combined with learning from just one demonstration, makes programming for these tasks much easier. This approach is crucial for maximizing space in vertical farming and provides practical solutions for sustainable agriculture technologies (Mahalingam *et al.*, 2023) [20].

Artificial Intelligence (AI)

In vertical farms, Artificial Intelligence (AI) is used to control the environmental conditions for the best growth of the crops. We control temperature, humidity, light, and nutrients specifically to satisfy the diverse needs of every plant in-house. AI systems take in data obtained from diverse set of sensors and adjust latest conditions as per the stored information optimized on farm lands, resulting on high agricultural productivity at the cost of low resource utilization.

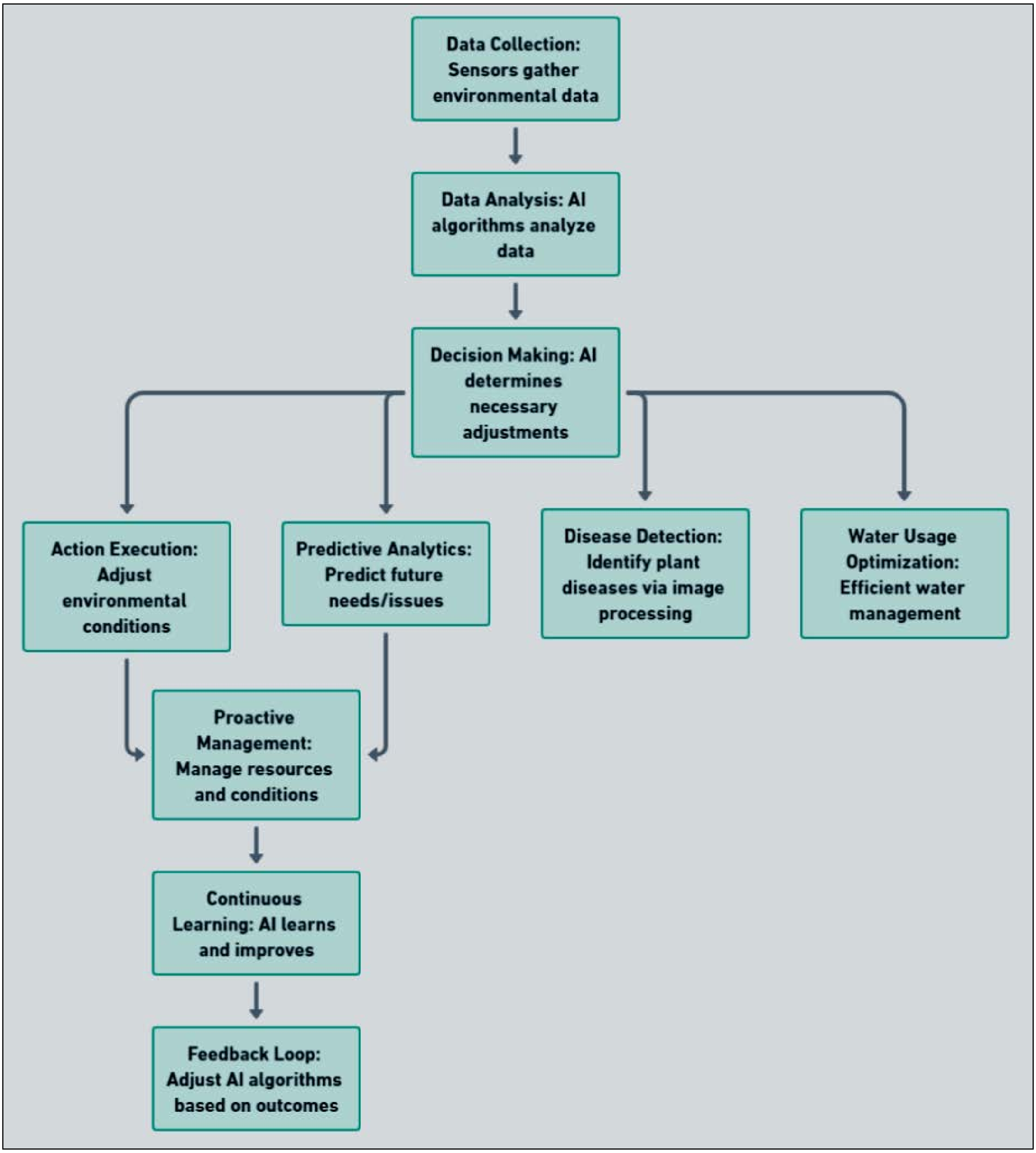

Fig 3: AI Integration in Vertical Farming Workflow. Illustrates the flow from environmental data collection to AI-driven adjustments, predictive analytics, and continuous improvement for sustainable crop growth

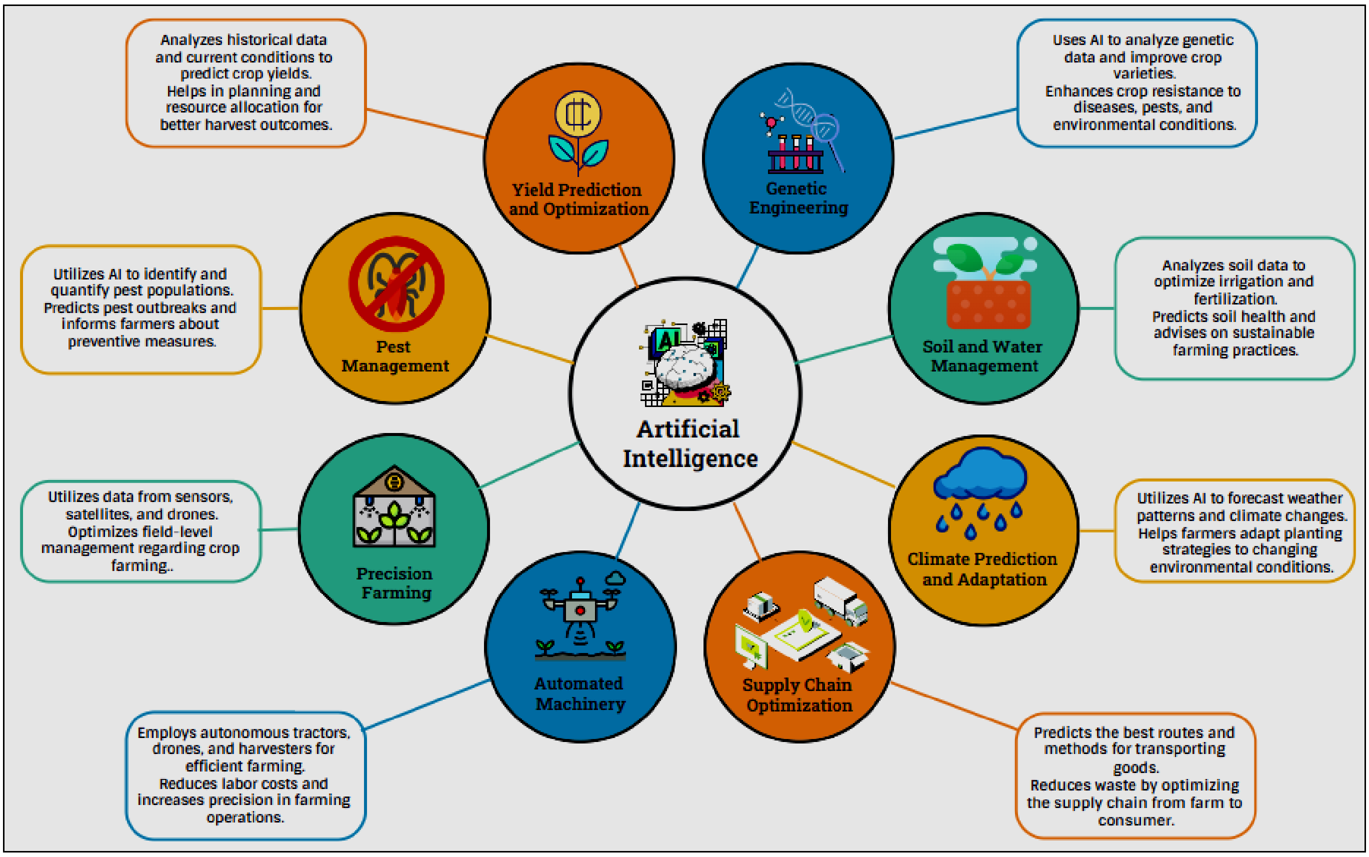

Fig 4: Integration of AI in vertical farming

Moreover, AI supported Predictive analytics will anticipate what a plant needs or where it could possibly go wrong, enabling a proactive approach to managing vertical farming infrastructure. The inclusion of Artificial Intelligence (AI) in vertical farming (Fig. 3) is a big step in adopting sustainable and high productive agricultural practices. In vertical farms, AI systems manage a different set of assignments right from the simple ones to detect plant diseases based on image processing techniques to optimize water usage with predictive analytics AI systems are meant to be self-learning and adaptive, which also enable improvements on the farm operations (Fig.5) (Krishnan *et al.*, 2020) [15].

IOTs and Machine Learning

The Internet of Things (IoT) refers to a system of interrelated devices like smartphones, cars, computers, or wearables that are connected to each other through the ability of them to transfer data over a network such as the internet. This network allows the collection of data and the sharing of data for targeted service delivery (Muzammal *et al.*, 2021) [23]. Internet-of-Things (IoT) and Machine Learning (ML) in vertical urban farming systems have been accepted as a significant advancement of intelligent farming systems. IoT is used for collecting big data and monitoring purpose and machine learning algorithm is used to optimize different parameters for profitable farming. This causes increase in crop productivity and proper resource management (Rajendiran *et al.*, 2023) [27]. The amalgamation has improved efficiency, output, and sustainability in the long run. This system is one that manages resources well enough for vertical hydroponic systems to consume as little as 30% of the water required and nothing more than 10% of the original land. Thereby, this strategy utilizes water effectively and reduces affairs of land use for crop production (Shrivastava *et al.*, 2023) [31]. These technologies can be combined with one another to optimise vertical farming systems, in addition to aquaponics, hydroponics, aeroponics, and fogponics.

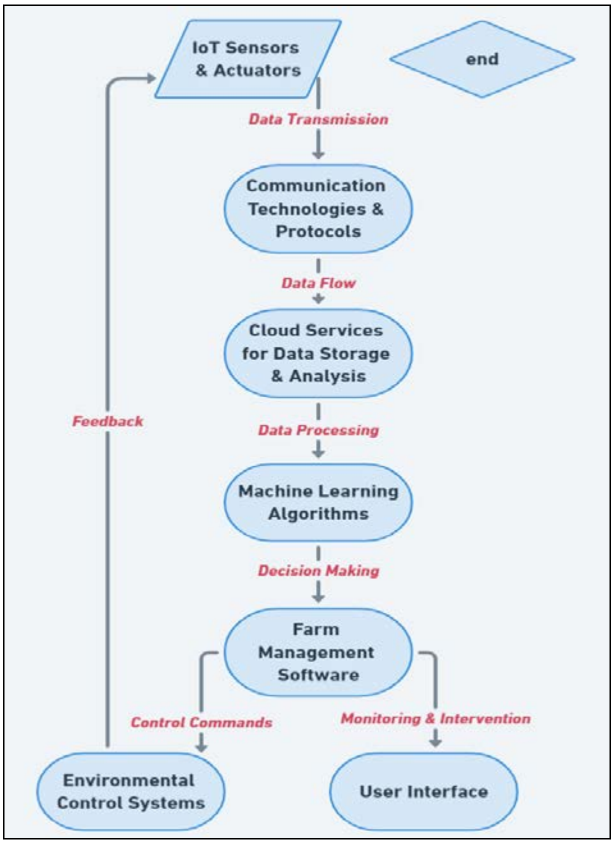

Fig 5: IoT and ML Integration in Urban Vertical Farming System Architecture. This diagram depicts the structured integration of IoT sensors and ML algorithms across four layers - Perception, Network, Processing, and Application - highlighting the seamless data flow from environmental monitoring to actionable insights for optimized farming operations

Integrating IoT and ML into vertical farming (Fig. 5) brings about numerous advantages. The precision of pH, light, and temperature can be monitored using IoT sensors, enabling a meticulous control of environmental factors. In addition, ML algorithms are used to optimize nutrient delivery as well as climate settings for better crop growth. Resource management efficiency is achieved through IoT monitoring water, energy, and nutrients thus reducing wastage. Furthermore, automation of farming activities such as crop monitoring and prediction of yields is made easier with the help of machine learning which consequently increases productivity levels while improving decision-making processes.

What is more, smart farming practice is enhanced by IoT and ML technologies in that they help to tailor lighting for different types of plants besides facilitating early disease detection thereby allowing for prompt intervention whenever necessary. In general, this kind of synergy leads to better cultivation results and maximum operational efficiency within systems.

Some examples of successful vertical farming projects that have integrated IoT and ML technologies include:

a. In the case of a hydroponic system, IoT sensors monitored the levels of nutrients and pH, while AI algorithms forecasted the need for nutrients and what quantity to provide this resulted in higher crop production (Fig.6).

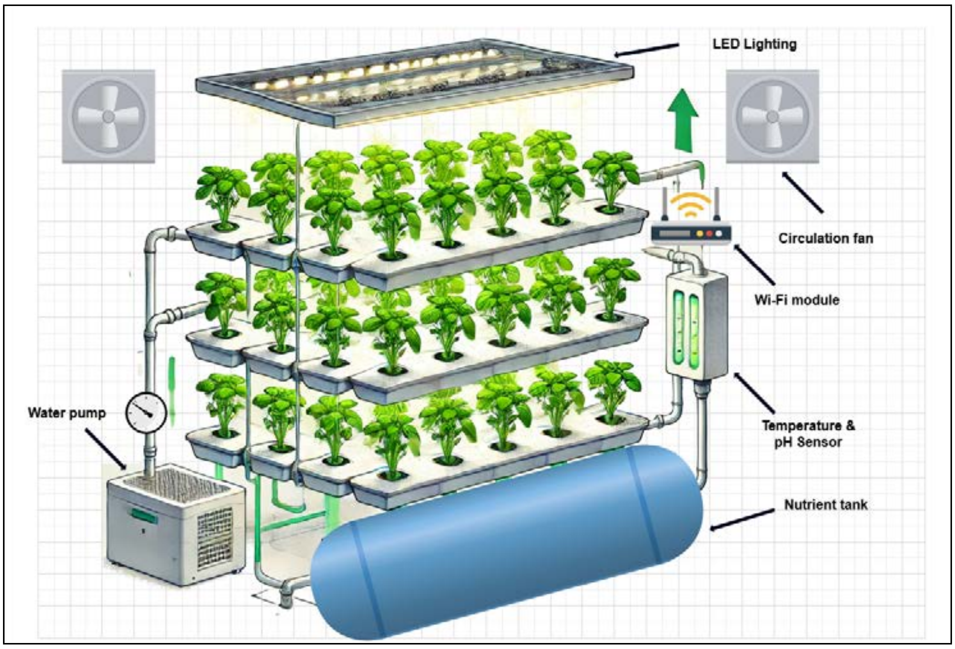

Fig 6: Hydroponics using IOT sensors

b. An aquaponic system with IoT sensors to monitor fish health and water quality. Utilizing machine learning algorithms to predict fish mortality rates and regulate feeding, which will result in healthier fish and better crops (Fig.7).

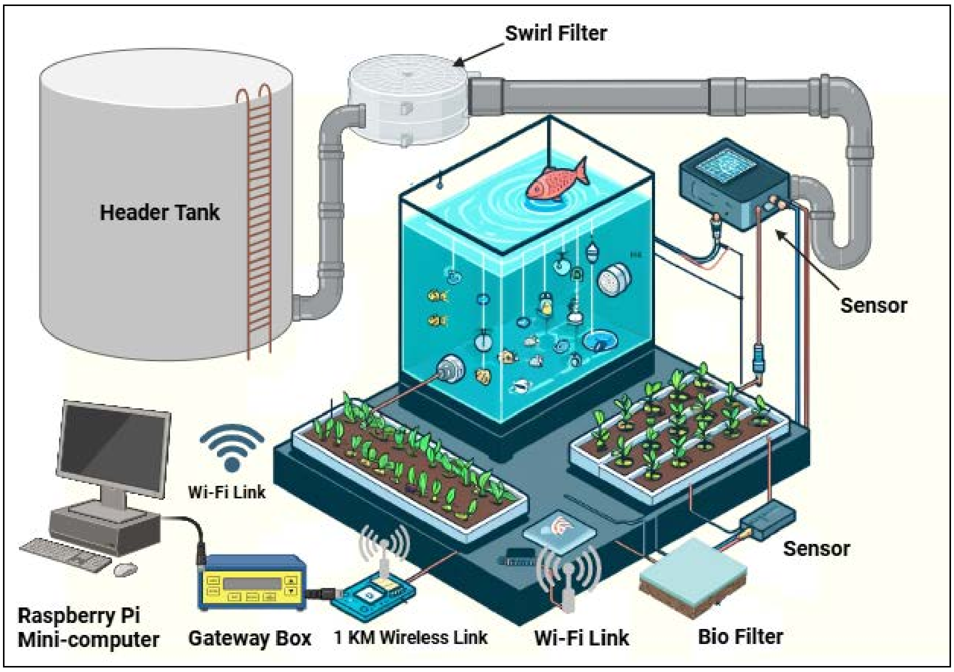

Fig 7: Aquaponics system integrated with IOT sensors

c. The aeroponic system used IoT sensors to gather information on the moisture level of the plants. Predictive models that dictated the water requirement were used so that the water were supplied on time to the crop and that resulted in better yield (Fig.8).

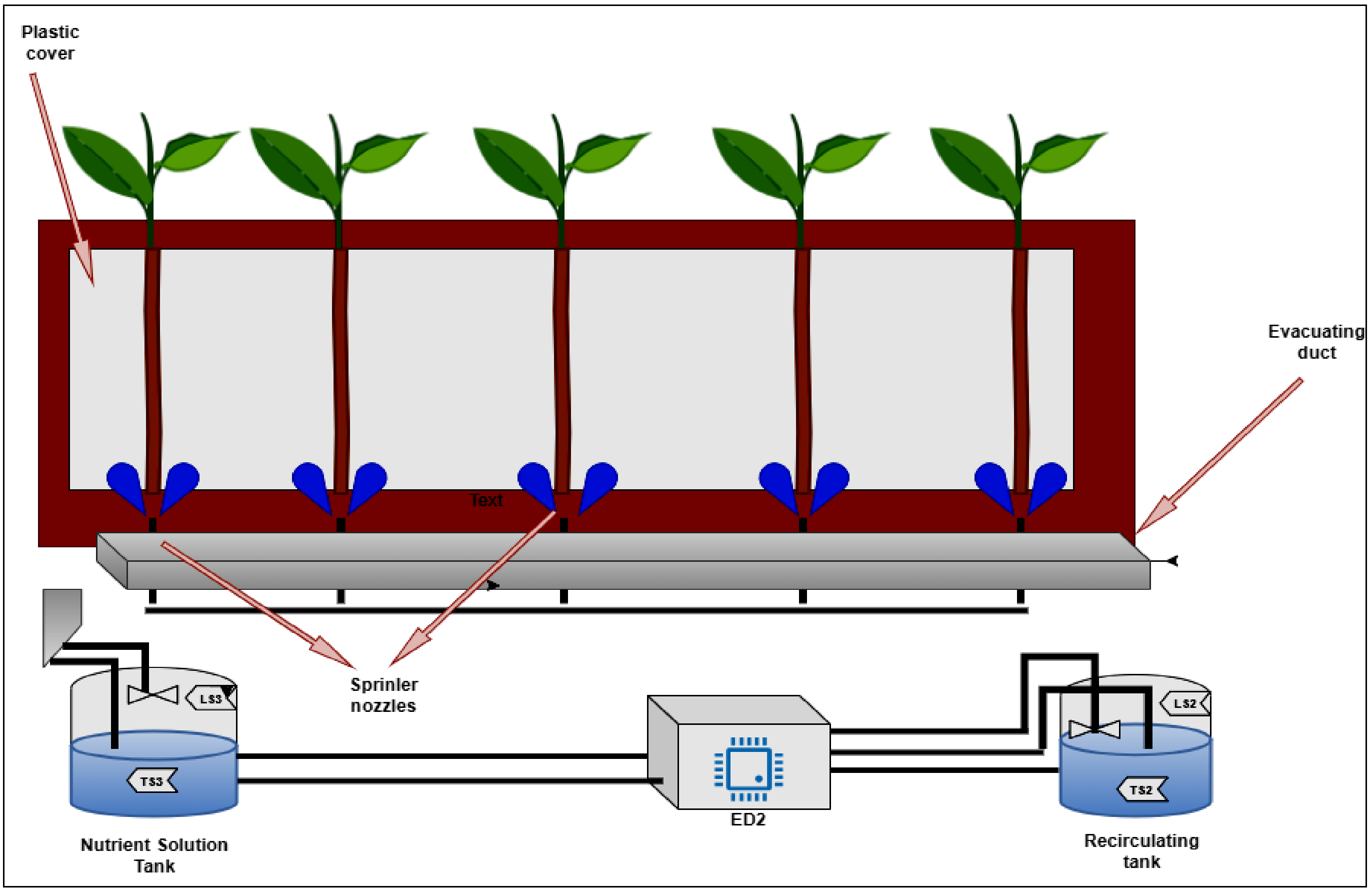

Fig 8: IOT integrated aeroponic growing chamber

Overall, integrating IoT and ML technologies in vertical farming systems can significantly improve efficiency, productivity, and sustainability. By optimizing various aspects of vertical farming, such as environmental control, resource management, automation, crop monitoring, and disease detection, these technologies can help address the challenges of urban agriculture and promote sustainable practices (Rajendiran *et al.*, 2023) [27].

Big data analytics

"Big data" is a term used to describe large, complex sets of information that pose extra challenges for storage, analysis, and applying additional procedures as well as for extracting results due to their volume and intricacy. By "big data analytics," we mean studying huge amounts of intricate data to reveal hidden patterns or find hidden connections (Jain *et al.*, 2016) [11]. Vertical hydroponics are vastly improved through the continuous monitoring and management of critical parameters such as nutrient content, water levels, and plant growth, which is made possible by big data analysis. By leveraging seasonal variations, this technology assists small-scale producers in making prudent choices regarding crop cultivation, thereby maximizing resource utilisation and productivity. The system, connected to a centralized server and accessible via an Android app, alerts farmers to critical changes, ensuring efficient farm management. Integrating IoT and big data analytics also facilitates water recycling, reducing consumption and promoting sustainability. This approach is cost-effective, technically empowering, and particularly beneficial for small-scale farmers, marking a significant advancement in smart farming practices (Shrivastava *et al.*, 2023) [27].

Case studies and applications

Siropyan *et al.* (2022) [33] recently explored the use of Artificial Intelligence (AI) for vertical farming (Fig. 9), specifically for the recognition of plant diseases in lettuce plants. This is an area of great interest to improve the productivity of vertical farming. Vertical farming refers to the technique of growing crops in vertically stacked layers. This technique has the advantage of using up to 70% less water than conventional farming. The main focus of the study is an AI model based on ResNet50 architecture and ImageNet, deployed on TensorFlow framework. The main objective of the model is the recognition of plant diseases in lettuce, which is a green leafy vegetable among the most consumed crops in the world.

Fig 9: An AI-Integrated Vertical Farming Model - This schematic represents a high-tech vertical farming system with LED lighting, CO2, air circulation, and temperature/humidity control, all optimized by artificial intelligence for early detection and prevention of diseases in lettuce crops

The training dataset is a set of four classes of lettuce, containing 134 images: bacterial (21 images), viral (17 images), fungal (76 images), healthy (20 images). Model learning and distinguishing the ailments influencing lettuce through this classification is significant. To compensate the small size of the training dataset and avoid overfitting, random flip, rotation, contrast adjustment and crop were experienced. In this way, they all helped to make the model more general and ability to learn from new data. Although the dataset was not good, the result of try larger number of frames and a large model was trained with 86% accuracy. Unfortunately, this training took 125 epochs over the ResNet50 model and 25 epochs over the fine-tune added layer. These findings from the study, demonstrate the massive potential of AI to help reinvent agriculture espacially in the area of indoor and vertical farming. This can be deemed as a validation that utilization of modern-day innovations in the pursuit of sustainable agricultural methods is indeed not only feasible but also proven-efficient as established by the AI model achieving disease diagnosis from imprecise data. This is important, especially in worldwide challenges like the limited land resources or the requirement of effective food production methods.

Hwang *et al*. (2022) [10] developed a novel plant growth surveillance system for vertical farms incorporating deep learning, as well as region-of-interest (RoI) prediction. They introduced this pseudo-crop mixing (SC-Mix) technique, and it indeed demonstrates its effectiveness, by which a much higher prediction accuracy of 76.9% MAP (mean Average Precision) was achieved in places with very dense planting populations, where the productivity was expected to be increased (Fig. 2). This is a 12.5% improvement over classical processing. The efficiency of this system is shown with specific examples, especially for crops with long growth periods, in terms of savings on dataset updates and benefits to the vertical farming operation. This research highlights the promise of emerging technologies to transform agriculture, to make fresh, local food more prevalent in our diets, and to make farmland more efficient and environmentally sustainable, especially in the vertical farms that could be coming to a nearby city block.

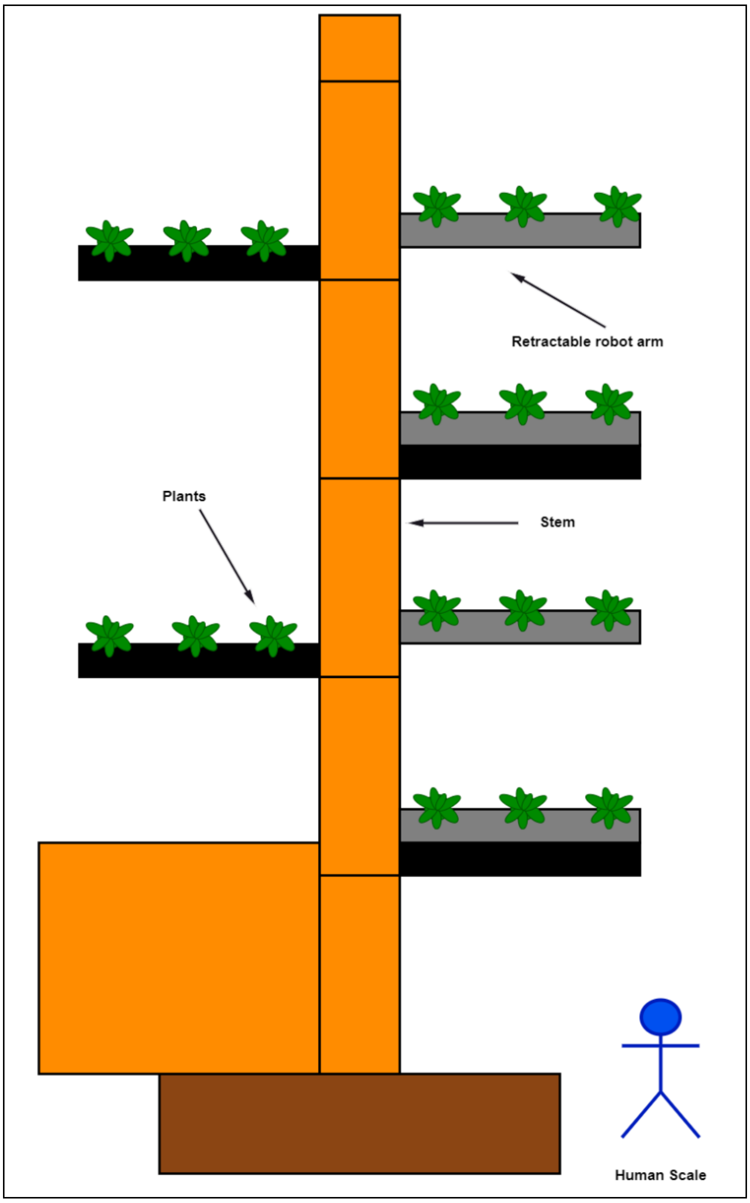

Fig 10: Autonomous Vertical Farm with Self-Assembly Feature

The cutting-edge research led by Watawana & Isaksson (2023) [37] shows a historic moment for Urban Agriculture. Fabrication and Virtual Testing of a Self-Assembly Smart Vertical Farming System for Urban Environments (Fig. 10) which introduced an advanced concept of vertical farm methods that promotes automation to resolve the beer problem of less arable land. The study is a carefully managed expedition into the processes of design and virtual testing of a revolutionary self-structuring vertical farming system that automates the creation and the deconstruction of the systems- the dependency integrity of a pour-and-play scenario with automation that can lessen human works and uplift operations as performance. And this autonomous system is not just a theoretical speculation as it is verified by detailed virtual simulations, which make it evident that it could significantly change and improve urban farming, while making it more scalable, and more efficient. Their innovation lies in the combination of the most advanced robotics and automation technologies, turning the vertical farm into self-configuring and self-adapting to environmental and operational conditions.

Watawana and Isaksson (2023) [37] go into great depth on the technological details and procedures behind the self-assembling process, including the utilization of robot arms for exact positioning and component assembly of the farm. This strategy helps the farm to have less of a physical impact. It highlights the system's ability to greatly reduce carbon emissions and water use compared to conventional agricultural techniques, therefore guaranteeing an ecologically friendly and environmentally sustainable answer to urban food production.

Moreover, the study highlights the system's versatility and resilience, which may run across different metropolitan settings and meteorological circumstances, therefore providing a flexible answer to problems of world food security. Such developments in vertical farming, according to the writers, could be absolutely essential in meeting the food needs of metropolitan populations by offering a dependable, sustainable source of fresh vegetables.

Watawana and Isaksson (2023) [37] provide a robust argument in favour of incorporating automation in vertical farming systems and are thereby not only a source of considerable knowledge on the environmental and socio-economic advantages of these systems but also a benchmark in the development of vertical farming systems for years to come. The significance of this study is that it provides evidence for the necessity of technological advancements to support these resources and maintain the competitiveness of urban agriculture as natural resources are depleted and urbanization increases.

Challenges and opportunities

Higher capital costs and automation complexity is restricted for seeding, planting, irrigating and harvesting task and are among the key technical barriers for automation of vertical farming. At the end of the day these systems still need human input for quality checks and maintenance. Energy efficiency in turn is a big issue, and the returns and energy use needs to be optimized for. One of the complicating factors with vertical farming systems, especially in the examples described above of stacked horizontal layer systems, is the complex electrics and plumbing and HVAC systems that are involved. Data management is particularly taxing as it demands an exhaustive range of environmental and plant growth data to be captured and processed. In the refined setting of vertical farms, managing pests and upholding rigorous food safety standards pose distinct challenges. The industry grapples with obstacles stemming from a dearth of cooperation and information exchange, resulting in redundant efforts and inefficiencies. While artificial intelligence holds promise for enhancing decision-making processes, it faces constraints imposed by proprietary limitations. Implementing AI in sustainable vertical farming is further complicated by challenges such as data accessibility and quality, intricate integration needs, energy consumption considerations, scalability issues, and cost concerns. Nonetheless, avenues for future exploration and innovation exist, including tailoring AI models to suit the unique demands of vertical farming, integrating edge computing technologies, and devising AI-driven decision support systems (Chowdhury, 2023) [7].

Artificial Intelligence (AI) is a single most crucial link that fuses all this massive data to be turned into actionable data and that forms the third layer and core foundation of Internet of Things. This merger is an intricate system that also includes a myriad of sensor networks and continuous surveillance. Many IoT based vertical farming systems are still theoretical or are in the trial phases for agricultural management, health monitoring, irrigation regulation, and intercropping. Intelligent agriculture is required but have many difficult in the development and execution, for example smart irrigation, lightning, disease identification should have use machine learning and deep learning. This complexity and depth is compounded by innovative farming methods such as aeroponics, aquaponics and hydroponics, all of which are critical for us to be good stewards of our environment in urban areas.

It remains a massive technological challenge to make agricultural practices more environmentally friendly and climate resilient, while also reducing crop loss and nitrogen fertiliser use. Their difficulties underline the basic necessity of next-generation complete answers for the automation in vertical farming (Siregar *et al*. 2022) [32]. The integration of automation with vertical farming has brought new dynamism to the agricultural sector, unbundling a mix of economic efficiency and productivity aside from delivering positive environmental aspects. Some of the key economic factors that drive this turnaround include investment cost, ROI and changes in market trends.

One of the most crucial aspects of automation in vertical farming is the dramatic improvement in efficiency (reducing manual labour and speeding up the farming process), leading to the overall growth of the agricultural sector (Kanjilal *et al.*, 2014) [14]. Cost-efficiency is visible in the design of automatic vertical farms, using the waste of resources and the coverage of robotic arms for plant servicing and can reduce the high cost of operation as a whole (Watawana & Isaksson, 2023) [37]. This is boosted even more through the implementation for artificial intelligence robots and drones. These technologies will help to reduce water, pesticides, and keep soil fertility which is ultimately enhance the productivity and quality of produce (Talaviya *et al.*, 2020) [35]. The relevant benefits of Urban Smart Vertical Farming (USVF) to provide labour cost benefits which can make the difference in food production security protection separate from the financial challenge, especially in depression periods have been highlighted (Saad *et al.*, 2021) [29]. Additionally, the integration of the Internet of Things (IoT) in farms leads to improved productivity, harvest rates and farm production ensuring the growing need of consistent food supply (Hassan *et al.*, 2022) [9].

In the beginning, technological progress was at the forefront of the first generations of vertical agriculture, through the implementation of mechanisation in hydroponic agriculture and the use of state of the art LED lighting technology, which laid the groundwork for the advanced farming systems of today (Van Gerrewey *et al.*, 2022) [36]. Furthermore, vertical farming using IoT based Tracking systems, which is a function of controlled environment agriculture (CEA) with timely production of more harvests promoting no land problem with increased crop yield, quality and accuracy (Chand *et al.*, 2022) [4]. Vertical farming provides a large growth potential due to land use efficiency, year-round crop production, and lower production cost, especially in terms of energy (Oh & Lu, 2022). Nevertheless, vertical farms automation cannot be analyzed as a mere technological or economic process, but as technological objects that imply moral, labor and societal values (Catts *et al.*, 2021) [3]. Thus, the utilization of automated practices in vertical gardening are inspired by the possibilities brought in above for enhanced productivity, low-cost viability, and for pace. Artificial intelligence (AI) and internet of things (IoT)-power devices and the rapid progress of controlled-environment agriculture (CEA) technologies make vertical farming a complementary and sustinable way to provide for future agricultural demands, however, also considering economic viability and societal impacts.

Sustainability and environmental impact

Vertical farming contributes significantly to climate change mitigation by providing sustainable food production methods. Vertical layer cultivation, carried out in regulated indoor environments, can reduce the resource consumption linked to urban food production as well as consumption. As a result, this method may contribute to the mitigation of climate change (Petrovics & Giezen, 2021) [25]. Moreover, vertical farming can create a unique environmentally friendly, social, and commercial centre in contemporary urban areas by promoting ecosystem services and nature-based solutions (Zaręba *et al.*, 2021) [41]. In addition, progression is being made in the cultivation of staple crops within vertical farms, with endeavors underway to enhance photosynthesis efficiency, augment crop yields, and curtail energy expenditures - all of which have the potential to aid in the mitigation of climate change (Zhu & Marcelis, 2023) [42]. Although vertical farming may necessitate costly technology, it is suggested that incorporating gamification and the Internet of Things into urban farming could increase user engagement and generate more dynamic results by increasing awareness of the carbon footprint and encouraging behavioral changes; thus, vertical farming has the potential to establish a distinctive and sustainable hub in modern metropolitan regions. It achieves this by advocating for ecosystem services and nature-based solutions, which are beneficial for the environment, society, and commerce (Philimon *et al.*, 2022) [26].

Automation of vertical farming increases food production and reduces the need for chemical fertilizers and crop protection agents. This trend toward automation leads to more sustainable farming practices (Van Gerrewey *et al*. In most urbanised territories globally, high-tech ventilated greenhouses are able to compete with vertical farms in terms of energy use. Knowledge on this is fundamental for the energy assessment of various automated farming systems (Weidner *et al.,* 2021) [38]. The shoot growth of plants in hydroponics controlled by an IoT layout is found to increase significantly compared to soil cultivation. Additionally, year-round quantitative and qualitative product production generates high biomass and dry yield, which evinces the success of autonomous systems in vertical farming. In several aspects, automated vertical farming correlates with global sustainability goals. On the other hand, urban agriculture is a space for growing fresh, healthy, and locally produced fruits, vegetables, and herbs within cities to reduce the environmental burden associated with transporting and preserving food. In addition, vertical farming use hydroponic systems, which recycle water and thereby reduce water usage by 70% compared to traditional farming methods. It is helpful to conserve the water resources (Gowrishankar *et al.,* 2021) [5]. In addition, vertical farming could lead to a reduced need for the use of pesticides and herbicides, which likely manifests in fewer negative environmental and health impacts. Fourth, it is contributed to reduced Land use/deforestation in the sense that Vertical farming equal food production is possible on a smaller land base than conventional agriculture. The new trend of Automated vertical farming integrates more energy efficiency by driving the system by clean energy like solar panels, reducing our dependency on fossil fuel and minimizing the emission of greenhouse gases (Gowrishankar *et al.,* 2021) [5]. Automated vertical farming therefore has an important role to play in helping meet worldwide sustainability goals by providing an environmentally friendly and efficient way of growing food and significantly reducing the negative environmental impact of traditional farming techniques.

Future trends and predictions

In automation, upcoming technologies in vertical farming are changing the agricultural scene. Especially in the metropolitan regions, these developments mostly aim to improve efficiency, lower environmental effects, and guarantee sustainable food production. Planting and transplanting techniques are much simplified by automation. Modern tools with computer vision and robotic arms can precisely seed or relocate young plants to new sites. This insures that crops are evenly spaced and planted at the right depth therefore accelerating the agricultural process. To less their environmental impact, vertical farms are progressively adopting sustainable practices.

For example, an exemplary scenario would be the utilization of sustainable energy resources like, photovoltaic panels and closed loop water systems for lowering water usage as well as nutrient release into the environment. This helps for optimal crop growth and bring sustainability in agriculture. Machine learning algorithms and artificial intelligence (AI) is an important part of any technological development related to agricultural growth monitoring. This usually means the task of building prediction models for specific regions of interest to overcome challenges such as densely populated areas with many types of crops while ensuring the best performance given a small number of labeled data (Hwang *et al.,* 2022) [10]. A smart example would be the adoption of sophisticated IT-run automation systems by an increasing number of vertical farming companies. These range from weather conditions, plant growth and yield monitoring to data analysis, machine learning (ML), etc. By improving farm operations, yields can be increased while resources used are reduced and the ability of farms to tackle environmental challenges is boosted (Robotics & Automation News, 2023). Vertical farming did this by being the core ideology that has started changing the way we grow crops all over the world, with technologies that are part of the largest and most significant shift in agriculture we have in thousands of years towards more automated, efficient, and eco-friendly practices.

Conclusion

This extensive review of vertical farming (VF) stresses its development and the vital part automation plays in transforming agriculture, particularly in metropolitan environments. Now vertical farming translates a technology solution, allowing cities to grow the food crops they need, and to find new vitality in the wake of decline. Crucial to this, automation has improved efficiency, providing significant labor savings. Transforming over thousands of years, VF evolves from the lighting technologies of ancient civilizations to modern LED lighting and then to the current hydroponics developments - some of which have never been available before for your operation. The execution capacity of vertical farming has been further improved through contemporary technologies such as AI, IoT, COBOTS and the MACARONS system. These technologies can optimize various farming processes like disease detection, resource management, environmental control etc. leading to increased crop yields / resource efficiency. The adoption of smarter farming methods, as seen with the integration of both machine learning and IoT further rattifies the approach to growing of crops, and better performing systems. Vertical farming is also more environmentally sustainable by reducing the demand for chemical products, decreasing water use and incorporating renewable energy sources. Nevertheless, there are challenges such as a high initial investment, energy efficiency, labour requirement of skilled workers etc.

The path of automation in vertical farming is on course to drastically transform the agriculture landscape. As technology improves, agricultural practices also increasingly become efficient, eco-friendly, and high-yielding. The use of AI, IoT, ML, and big data analytics in VF is not only a farming revolution, but a completely new way of thinking towards more resilient, environmentally friendly, and sustainable systems of food production. The social and moral consequences of this transition, notably on employment practices and food stability, are huge. Not only can automation in VF provide for the food needs of an increasing population, but do so in a way that falls in line with global environmental targets. There is a logical solution to many problems facing today's agriculture whether it be the lack of land, consumption of water or ecological destabilization and it comes in the form of this great transition. The integration of all versions of these technologies will continue to refine over time as we move forward, driving potentially even more innovative, efficient and effective means of growing crops. Automation-driven vertical farming is very much leading the charge towards the new age of agriculture - a world where food production is abundant, sustainable and works to benefit both the environment and mankind.

Conflict of Interest: Authors have declared that no competing interests exist.

Author Contributions

a) **Ambethgar Anbu Sezhian:** Conceived the layout and structure of the manuscript and was primarily responsible for writing the entire manuscript.

- **b) Vellaisamy Ambethgar:** Contributed to the conception and design of the review; provided critical revisions and final approval of the version to be published.
- **c) Iyadurai Arumukapravin:** Assisted with literature search and analysis; Contributed to manuscript revisions.
- **d) V.P. Shanthi:** Assisted with literature search and analysis; provided feedback on the manuscript.
- **e) Sundaresan Srivignesh:** Supervised the entire work; provided critical revisions and overall guidance.

Acknowledgement
The authors declare that there are no acknowledgements for this manuscript.

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