Journal of Agriculture and Biology
ISSN: 3007-1755 (Print), 3007-1763 (Online)

Review Article

The Impact of AI and Robotics on the Sustainability of Vertical Farming

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ABSTRACT

Vertical farming has been a promising solution to global challenges, resource scarcity, environmental degradation, and food security. This review looks at artificial intelligence (AI) and Robotics as transformative elements for improving the environmental and economic sustainability of vertical farming. On the other hand, precision irrigation for smart irrigation, energy-efficient lighting, and climate control systems made possible with AI-driven optimization allow for a huge reduction in resources like water, energy, and land usage for instance. Automating laborious chores for example, planting, harvesting, and maintenance, robotics help to decrease operation costs and raise production efficiency. AI systems also help to reduce environmental impacts thanks to process optimization for the delivery of nutrients and reduced use of pesticides using improved pest detection and management technologies. Renewable energy sources are integrated to increase vertical farming operations' sustainability further, and life cycle assessments show the potential for energy use to be balanced with sustainable practices. High initial costs, technological barriers, and concerns about energy consumption present challenges, but technological advances in AI and robotics, as well as support in public policy, provide a way out. This review highlights the need for further research, investment, and collaboration to make the most of the combined potential of AI and robotics to transform vertical farming into an essential element of sustainable agriculture to create and grow food for an ever-increasing global population without using up precious environmental resources.

Keywords: Vertical farming, Artificial Intelligence (AI), Robotics, Environmental sustainability, Economic sustainability, Precision irrigation.

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Article History
Received: November 29, 2024
Accepted: March 05, 2025
Published: March 27, 2025

INTRODUCTION

Vertical farming is a modern agricultural technology used for cultivating crops vertically in multiple layers or inclined surfaces, usually in an urban setting. This is because this model could cater to global issues such as scarcity of arable land, water shortages, and the adverse ecological effects associated with traditional farming practices. With a projected growth in the global population of an additional 2 billion by 2050, to 9.7 billion people, traditional farming methods are unsustainable because of their requirement of large amounts of land and heavy use of water. The migration to cities is also forcing more and more land out of agriculture, for vertical farming (Wang, 2022).

This is one of the main advantages of vertical farming, that least of the land will be required for the production of food. Vertical farms allow crops to be grown in vertically stacked layers to increase the yield of a given crop per square meter—especially in urban settings where land is scarce and expensive. Moreover, vertical farming requires 90% less water to operate than conventional farming, which is very often the reason for wasting water (Lin, 2024). Vertical farming also has the reduced environmental impact of eliminating pesticides and herbicides and replacing them with pesticides and fertilizers in a controlled environment. The atmosphere of these systems is biologically isolated from one another, largely eliminating chemical alteration of environmental details (Baccarelli, 2023).

But vertical farming comes with its challenges, namely that it requires energy to power it and relies on artificial lighting and climate control systems. However, current roofing and lighting technologies provide advances that help mitigate these concerns and the demands of vertical farming remain critical to its sustainability. Furthermore, the initial capital investment can serve as prohibitive for small, first-time producers to set up a vertical farm (Vatistas, 2022).

Role of Technology

AI and Robotics work as transformative tools in vertical farming. However, to solve these difficulties and to make the most of the vertical farming potential it is possible to count on the advances brought by technologies like artificial intelligence and robotics. Vertical farms are relying more heavily on the power of AI and robotics to improve efficiency, sustainability, and the economics of their operations (Kabir, 2023).

By artificial intelligence, we mean the simulation of human intelligence processes by machines, especially computer systems. These processes include learning (the acquisition of information and rules for using the information), reasoning (using rules to reach approximate or definite conclusions), and self-correction. In vertical farming, AI may be applied to monitor and adjust temperature, humidity, light levels, nutrient delivery, and other factors underlying the farming environment. Through this, it's possible for AI algorithms with access to an enormous amount of data, which is being collected from sensors embedded in the farming system, to make real-time decisions that help facilitate the optimal growth of crops while also minimizing the usage of resources. For example, the lighting and temperature can be adjusted to the optimal conditions for the photosynthesis of crops, while minimizing energy consumption at the same time. Additionally, AI can forecast the growth cycles of the crops, so farmers will know when to harvest and therefore waste less (Rhoads, 2023). On the flip side, robotics means using automation machines to carry out tasks that we in our human flesh would normally complete. The number of tasks that robots are being used for in vertical farming, from planting to harvesting, pruning, and packaging, is growing. They can either function on their own without human control or be controlled remotely to reduce the need for manual labor greatly. Robotics enables more precise and efficient operations like the automatic application of nutrients, water, or pesticides (Botta, 2022). For instance, this can teach robots to deliver the nutrients exactly into the respective plant's root systems to ensure the ideal combination of nutrients for each plant with nothing wasted on the extra nutrients.

One of the most exciting things in robotics is swarm robots, meaning multiple small robots work together in a coordinated way to perform a task. In vertical farming swarm robots could monitor the health of plants, identify how they can be pest-ridden, and essentially do some routine maintenance work (Figure 1). Technically, swarm robotics can help to accelerate farming processes, and also omit human action.

The integration of AI and robotics positively improves operational efficiency in vertical farming but also contributes significantly to the sustainability of such a system (Van Delden, 2021). AI and robotics help create more sustainable farming practices with help optimizing resource use, reducing waste, and minimizing chemical input. In addition, these technologies are making it economically possible to create vertical farms, by increasing productivity, lowering labor costs, and enhancing production efficiency.

Objective

This review investigates how AI and robotics can be used to enable vertical farming to be environmentally and economically sustainable. It demonstrates how these technologies can conserve energy, water, and nutrients as well as minimize waste and maximize efficiency. AI can also be useful in optimizing pest detection systems, which will eliminate the use of chemical-based fertilizers and pesticides. Vertical farming also reduces environmental impact by way of better waste management and through controlling environments. Instead, from an economic point of view, AI and robotics can decrease labor costs and raise production efficiency by automating labor-demanding assignments for example planting, harvesting, and maintenance. Additionally, AI-based systems can predict crop yields so that planning and optimization of farmer operations can be achieved (Akintuyi, 2024). Combining AI and robotics in vertical farming is thought to be a way to minimize resource consumption, environmental footprint, and economic viability for the future of agriculture.

Figure 1. Vertical farming facility with AI and robotics integration (https://www.montel.com/blog/the-role-of-ai-in-vertical-farming).

REDUCED RESOURCE CONSUMPTION THROUGH AI-DRIVEN OPTIMIZATION

The agricultural systems that feed our growing population are amid the two most important transitions of our time: However, food demand continues to increase, and at the same time extreme environmental problems like climate change, water scarcity, and land degradation are hitting the world. Combining vertical farming with artificial intelligence (AI) and automation offers a promising way to reduce resource consumption while remaining competitive or even increasing the performance of agriculture (Erekath, 2024). The main areas where AI-driven optimization could make a big impact are water, energy, and land use efficiency, indeed. In this section, we will introduce how AI-powered systems can help optimize these resources in vertical farming for water efficiency, energy optimization, and land use.

Water Efficiency

One of the agriculture problems is that water issues happen in agriculture with traditional methods, which consume up to 70% of Earth’s freshwater poorly. When vertical farming is coupled with AI-powered irrigation systems, it is a more sustainable solution. For example, by applying sensors within the farming environment, such as soil moisture, humidity, and crop water requirements AI-driven irrigation systems monitor the environment live. This data allows these algorithms to figure out exactly how much each crop needs, and prevents water waste.

Using forward weather forecasts, crop growth stages, and environmental conditions, AI systems can optimize irrigation schedules to water crops with the correct amount of water at the right time. It saves water because it's precision irrigation, but it also stops over watering causing root rot (Abioye, 2022). The Dutch proved a case study of how AI can be used to optimize water use in vertical farming. An AI irrigation system from Wageningen University & Research (WUR) cut water use by 40% compared to traditional methods, with no loss in crop yield.

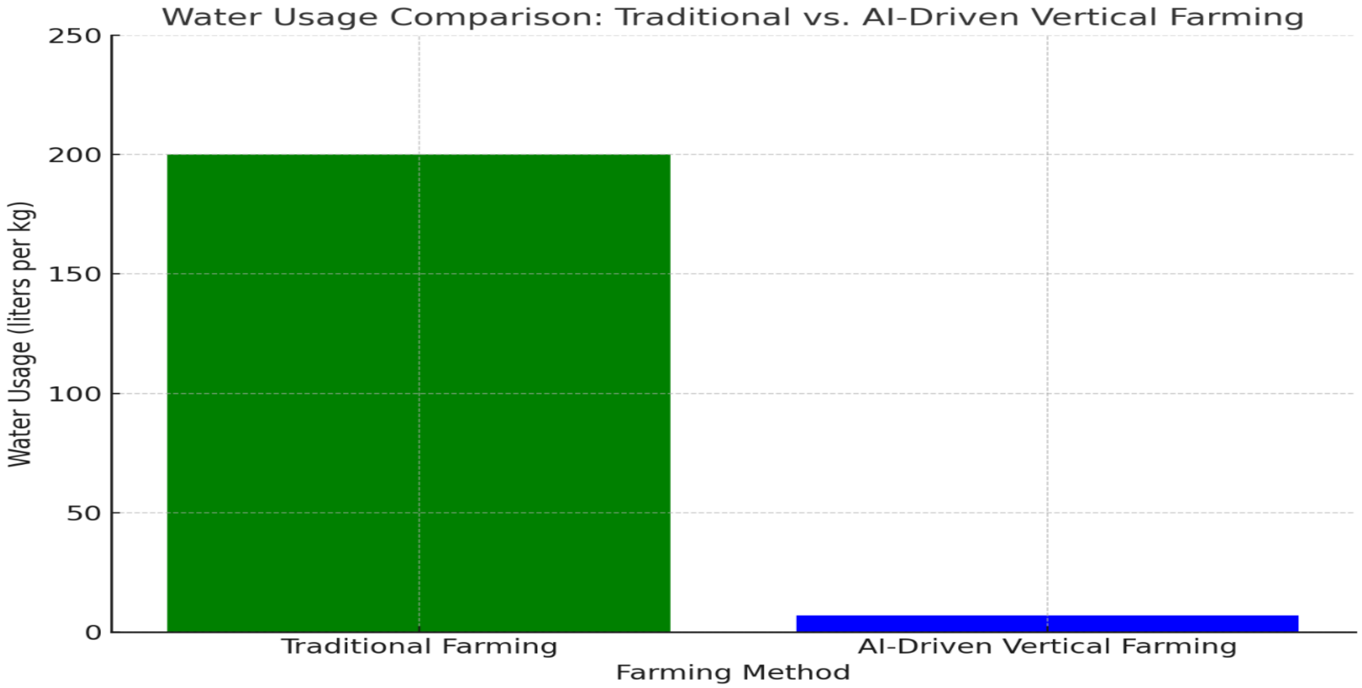

Figure 2. The bar chart comparing water usage in traditional farming and AI-driven vertical farming.

An example here is a vertical farm in Singapore which is implemented with an AI-based hydroponic system to grow veggies without soil. The water level and nutrient concentration are monitored and the farm can supply the crops with water and nutrients in exactly the amount then they need for growing. Yet this system can use up to 90% less water than traditional farming methods (Figure 2).

Energy Optimization

A significant challenge for vertical farming in terms of lowered overheads (energy requirement) lies in the processing of systems that rely on artificial lighting and climate control systems. Vertical farms optimize energy usage thanks to AI tweaking the intensity and spectrum of the light at different stages of growth, per plant. For example, AeroFarms, in the United States, has revealed that an exhaust-sterilized air hydroponic system that circulates water and nutrient solutions to a nutrient-sealed LED light gardening platform can greatly reduce energy consumption, by as much as 50%, compared to traditional lighting systems and increase crop yield (Figure 3).

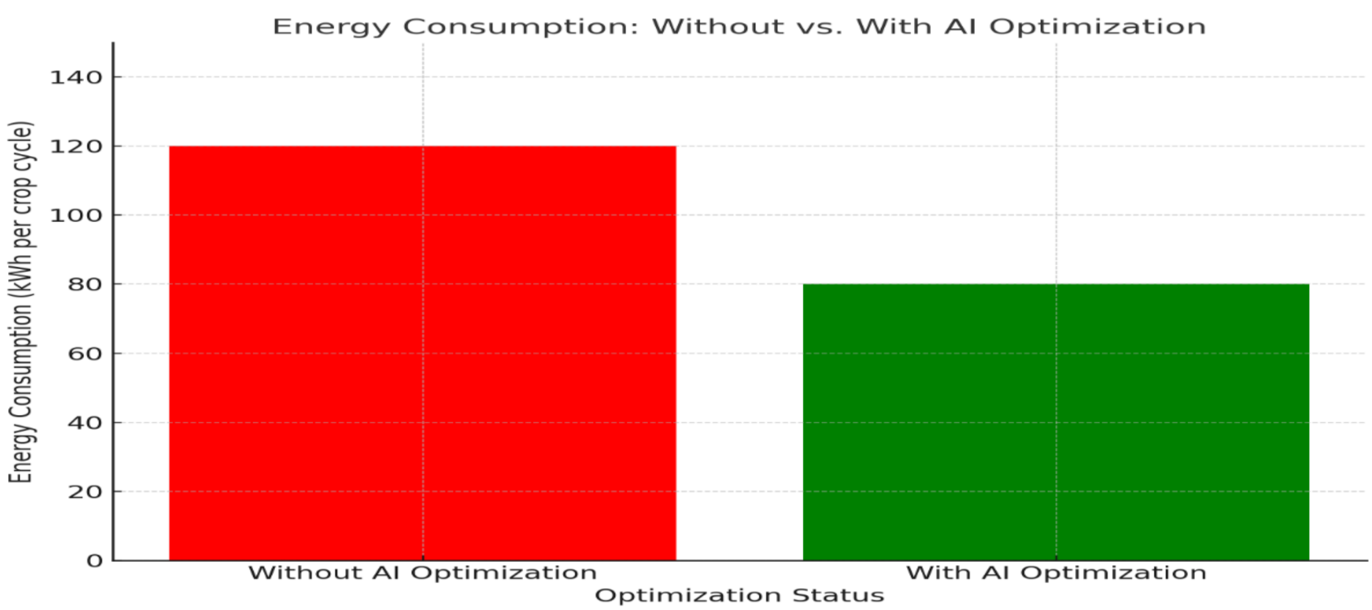

Figure 3. The graph comparing energy consumption with and without AI optimization.

It's also using AI to optimize climate control systems for vertical farms, ensuring the right temperature, humidity, and airflow to grow plants best. AI algorithms using real-time analysis of environmental sensor data will be able to adjust these systems in real time to use energy efficiently (Mazhar, 2023). For example, if the temperature in a vertical farm gets out of the optimal range, AI can change the cooling system to get it back to the range it is expected to be in and save farmers energy dollars in the process.

A vertical farm company called Spread in Japan uses AI algorithms to control temperature and humidity in an indoor farm to reduce energy use and increase crop growth in a case study. Additionally, the company states that AI has helped shrink energy usage by 30 percent below the norm; and that vertical agriculture is more economical and practicable. Also, AI can assist with adding renewable energy sources into vertical farming operations leading to a better integration of renewable energy and reduction of carbon footprint (Rathor, 2024).

Land Use Efficiency

As a result, vertical farming has an advantage in minimizing the amount of land area needed for food production, particularly important in land or space-constrained or expensive urban environments. Now vertical farming relies heavily on AI to achieve maximum land-use efficiency whereby you use algorithms to watch the crops and fine-tune the crop development to get the highest yields per square meter of space available. Through the alteration of natural conditions such as light, temperature, and moisture, AI can forecast the development designs of different crops to ensure the best crop growth (Delfani, 2024).

In the United Kingdom, a case study illustrates how AI can maximize land use efficiency by boosting crop yields up to 50 percent higher than with conventional farming methods. An AI system developed using sensors to monitor and assess plant health and growth, as well as to improve environmental conditions such as providing light, water, and nutrients for plants to thrive at optimum levels has been created by vertical farm company, Infarm. This meant that, with this system, yields up to 50% greater than conventional farming practices can be produced.

Furthermore, vertical farms can leverage AI to scale with minimal effort and to improve space utilization. Because

Furthermore, vertical farms can leverage AI to scale with minimal effort and to improve space utilization. Because traditional farming land cannot be changed, vertical farms can utilize vertical space to grow as much as they can to save time and money. Using AI, growing system layouts can be planned and maintained, space used is optimized, and crops arranged in the most efficient configurations. Reduction of resource consumption, like, water, energy, and land use in vertical farming requires optimization through AI-driven optimization. In case studies around the world, the use of AI to improve resource efficiency and turn vertical farming into a scalable, economically viable method of future food production is shown to be promising. As AI technologies continue to improve, the impact on resource usage in vertical farming will only continue to grow, making it eco-friendlier (Van Delden, 2021).

MINIMIZING ENVIRONMENTAL IMPACT

Traditional farming is depleting natural resources, polluting and destroying ecosystems and there is growing concern for the need for sustainable agriculture. Severe environmental degradation frowned upon by excessive application of chemical pesticides, chemical fertilizers, and inefficient resource management resulted in erosion of soil, contamination of water bodies, and loss of biodiversity. Vertical farming can be the sustainable alternative, and when combined with symbiotic features such as AI and robotics, reduces the use of dirty chemicals, optimizes resource allocation, and minimizes waste. Next, we can see how AI and robotics can selectively reduce the environmental impact of vertical farming while reducing pesticide use and allocating resources (Balaska, 2023).

Pesticide Reduction

Chemical pesticides are heavily relied upon by conventional farming to rid the environment of pests, diseases, and weeds; however, the use of chemical pesticides to achieve this purpose has been proven to contribute to environmental damage. Chemical pesticides can contaminate soil and water and hurt the wrong organisms, which leads to the development of pests that won't die when sprayed. AI-based pest detection and management systems are being utilized for pest detection and management in vertical farming to reduce the use of synthetic pesticides as well as limit their ecological impact.

Pest detection systems powered by AI detect pests, diseases, and stress that may affect crops in real time by using data from sensors, cameras, and imaging systems. The type, place, and extent of pest information provided by these systems are used as input to AI algorithms for prediction and effective pest control. This method helps farmers to be able to control pests more efficiently and cuts back on the general use of pesticides.

With AI-powered drones and imaging technology, Taris can detect pests in crops, identify individual pest species, and assess crop health. With this early detection, pesticide use can be reduced by 90 percent compared to traditional methods. According to Paul Jackson, the founder and CEO of Robotics Plus, an agricultural robotics company, it created an autonomous robot that identifies and uses AI and machine learning to apply organic pesticides to growing crops. Computer vision is used by the robot to recognize pests and diseases, reducing the use of chemicals to only what is needed, with minimal environmental impact through a precise amount of penetration of radiation.
Robotics enables broader use of other pest management strategies such as beneficial insects and biological control agents (Botta, 2022). Combined with AI and robotics, vertical farms could dispense with some of the need for chemical pesticides, reduce the risk of environmental contamination, and help encourage natural pest control mechanisms within greater biodiversity.

Resource Allocation

Vertical farming represents an alternative that better utilizes resources like water, energy, and food nutrients. AI-driven monitor systems are used to optimize the delivery of nutrients to crops, cutting down the waste and use of fertilizer and reducing nutrient pollution. Excessive use of fertilizer in traditional farming methods often results in nutrient runoff to the close by water bodies as well as harmful algal blooms (Table 1). However vertical farming offers controlled environments and resource savings—less fertilizer and less nutrient pollution (Figure 4).

Table 1. Comparison of traditional farming and vertical farming.

Aspect	Traditional Farming	Vertical Farming
Land Use (per kg of produce)	High (extensive fields)	Low (stacked layers)
Water Consumption (liters per kg)	150-300 liters	5-10 liters
Pesticide Use	High (broad application)	Low (targeted application)
Yield (kg/m)	1-2 kg	10-20 kg

Figure 4. Comparison of traditional farming and vertical farming across various aspects.

US vertical farming company, Plenty, employs AI-backed systems for real-time monitoring and optimization of nutrient delivery based on data coming from sensors placed in the growing medium. This system delivers nutrients only when plants need them, optimizes when they receive them, eliminates waste in the process, and therefore avoids overfertilization. In addition to improving crop health and increasing yield, it cuts down on the environmentally damaging use of fertilizer as well (Mondal, 2021).

As an important agricultural resource, water is optimized for use within the vertical farm; hydroponic or aeroponic systems are utilized in vertical farms using up to 90% less water than traditional farming methods. AI-managed irrigation systems measure variables like soil moisture, humidity, etc. to figure out just how much water is necessary for each crop. Additionally, AI helps to adjust water delivery in real time to apply just the right amount of water to crops, without the typical associated waste, thus reducing the impact of agriculture on the environment.

Towards Waste Reduction in AI Managed Vertical Farms: Case Studies

Vertical farming creates the opportunity to do AI-based resource optimizations to reduce waste and improve sustainability. This way not only make operations much more efficient, but it will also cut down costs as well as pollution of the environment. Vertical Harvest Farm in Jackson Hole, Wyoming, is using case studies to demonstrate how AI is used to optimize plant growth and minimize packaging waste. In farm is a global vertical farming company with AI-driven farming operations and reusing packaging waste. To reduce packaging waste, they use AI to monitor crop growth and schedule harvests the instant those crops are ready, so that they are ready to be packaged and shipped only when necessary. In farm also applies AI to detect usage patterns and other demand changes to intelligently predict when supply is needed, and more accurately time harvest (Akintuyi, 2024).

A New York City vertical farm for crops uses AI to watch the crop, manage growth, and minimize the use of its resources. Also, it makes use of AI to predict food waste, by forecasting the production quantities and shelf life, thereby helping to forecast the customer demand and avoid overproduction. It also tracks a harvested crop's shelf life so the product won't be distributed before it spoils.

Vertical farms are able to minimize waste and maximize resource consumption, boost yield, and correct for overproduction, thanks to AI-driven systems (Figure 5). Vertical farms can become more profitable as they lower the environmental cost of growing food. AI and robotics have historically played a key part in minimising vertical farming's environmental impact, which has historically been low, compared to other farming methods. Through the use of AI-based pest detection and management systems, farmers can manage the pest control process effectively helping them to use sustainable pest management systems. Furthermore, AI-based monitoring systems would optimize the delivery of nutrients and also sprinkle of water, wasting less, and less pollution to the environment.


Figure 5. AI-powered irrigation system (https://mottech.com/news/how-ai-powered-irrigation-systems-are-disrupting-the-agricultural-industry/).

A further advantage of vertical farming as an agricultural solution is its considerable potential for mitigation of environmental footprint and this potential will continue to improve due to ongoing advancements in AI and robotics. These technologies can be integrated to enable vertical farming to practice a more sustainable form of agriculture that will mitigate the environmental cost of food production and help us meet the rising demand for fresh local food.

ENHANCING ECONOMIC VIABILITY

What makes wide-acre vertical farming adoption possible is its economics. There are many environmental benefits of vertical farming, but it must be shown to be economically competitive with high-production farming practices to survive. Artificial intelligence and robotics help to increase both the economic value and the advantage of vertical farming in terms of agricultural production efficiency, lower labor costs, and therefore better competitiveness of vertical farming in the market of agriculture. The production efficiency, labor cost reduction, and market competitiveness that arise from the economies of the technology related to economic sustainability in this section will be discussed (Hernita, 2021).

Production Efficiency

The use of AI and robotics could increase production efficiency in vertical farming. The use of these technologies is automating key tasks such as planting, harvesting, and maintenance, which typically can be very labor-intensive and time consuming when done manually. The automation of these processes through vertical farms' use of robotics means crops can be planted, tended and harvested at the right time with no human involvement.

Well, AI makes sure that crops grow in the best they can possibly grow by constantly analyzing environmental factors, like temperature, humidity, light levels, and the nutrient concentration of the water they're grown in. With AI-powered systems, they are able to correct real-time optimal growing conditions so they are always optimal. It may lower energy costs and increase yield.

In a case study from California-based vertical farming company Iron Ox, we see how robotics and AI help with increasing production efficiency (Kabir, 2023). The plants are planted, watered, and harvested by autonomous robots powered by AI sensors and cameras that have been vertically stacked by the company's growing systems. Given that these robots can look at plant health, and decide in real time what a plant needs, we can have increased yield, lower energy usage, and efficient resource usage, making the farm economically viable. In general, the use of AI and robotics in vertical farming is improving things get done in vertical farming, making it more productive and minimizing losses.

Labor Cost Reduction

The use of AI and robotics in farm work has caused a reduction in labor costs for vertical farming, a traditional type of farm. Vertical farming is more cost-effective and economically sustainable when these technologies are used to automate planting, harvesting, and maintenance tasks. Crops ready for harvest can be spotted by robots with an AI-enabled vision system, which can then pick them with accuracy reducing the need for human labour. Moreover, such tasks as pruning, cleaning, and monitoring plant health can be automated to decrease the need for human participation. This reduction has big economic implications. Vertical farming provides a position of lower financial position in small farmholds in urban areas with high land and labor prices. It also enables more efficient scaling which means a greater focus on capacity growth, technology upgrades, and market awareness. Bowery Farming, a greenhouse vertical farming company is a prime example of the degree to which labor cost reduction through automation can affect a company's bottom line. Eliminating manual labor with the automation of key tasks, including planting and harvesting, plus monitoring plant health has drastically reduced Bowery's dependence on new workers (Nidweski, 2021). The idea has made the operations more profitable and the output has become more competitive to the market). The idea has made the operations more profitable and the output has become more competitive to the market.

Scalability and Associated Operational Costs are the Economic Implications

Using AI and robotics also significantly improves vertical farming, a more scalable way than horticulture. They are the technologies that can automate the core processes and let more and more manual labor disappear more efficient operations and more sustainable manufacturers. That makes them also able to optimize environmental conditions allowing the crop to grow over a greater area and with the same yield.

Besides enhancing scalability, AI and robots bring down operational expenses; labor, energy, and resources. Environmental conditions are monitored and optimized by automated systems which enable the desire to reduce the need for energy-intensive climate control systems and lighting systems. Vertical farming optimizes not only water and nutrient use, which makes it more economically viable but also allows the farms to stay competitive as they scale (Van Delde, 2021). As a result, vertical farming is more economically viable and sustainable, which means it is a viable option for businesses that want to expand business operations.

Market Competitiveness

Technology-driven efficiency makes the agriculture market competitive. The main advantage of vertical farming is that it's a method of growing food that allows growers to produce year-round, fresh produce in urban environments. On the other hand, vertical farming will need to be able to grow high-quality crops at a competitive cost or undercut traditional farming methods. This process is heavily based on AI and robotics. With such technologies, vertical farms can produce high-quality crops using fewer resources that meet the needs of sustainability and food security consumers. Moreover, vertical farms can grow automatically, and scale without adding any costs that scale along with that to meet the rising need for fresh and local food in the urban areas.

Vertical farming company Lettuce Grow hydroponically grows lettuce, but uses AI and automation to optimize as well as cut costs. Lettuce Grow gives high-quality crops to market at a competitive price point and automates key tasks, while optimizing resource usage (Petropoulou, 2023). However, with the need for AI and robotics to help improve production efficiency, bring labor costs down, and ensure that production is economically feasible for the agricultural market, vertical farming production is not yet viable.

DISCUSSION

Life-Cycle Environmental Impact of AI and Robotics

Potential negative effects of AI and robotics on the environment within vertical farm structures are now being assessed right from the cradle to the grave stages. It is self-evident that such systems offer environmental advantages including saving resources and pesticide use and minimizing wastes but they pose an environmental impact. The topics covered include; the effect of energy use on the environment, material and manufacturing consequences, and the long-term solvency of AI and robotic vertical farming (Chowdhury, 2023).

Usage of Energy in AI and Robotics Systems

There is a great ecological challenge in using AI and robotics in vertical farming because data processing, real-time decisions, and technologies related to machine learning consume a lot of energy. This has to be done by balancing the use of AI and robotics in reducing energy consumption and the use of renewable energy sources. Some of the sources of power being used in vertical farms include solar panels, wind power, or geothermal power. Nevertheless, the environmental risk can be availed by incorporating renewable energy in vertical farming. Smart utilisation of energy with the help of Artificial Intelligence has already been done to reduce the usage of energy, and more AI module work to do variation in energy utilisation in-line with real-life feedback. It means that the robotic systems can control the energy needed for both carrying out required tasks and the environmental elements such as low-power motors used and battery JFrame technology (Kabir, 2023).

The Effect on Material and Manufacturing

AI and robotic systems also pose a significant life cycle influence on the material and manufacturing by coming up with materials that result in habitat destruction, and water pollution among others. With the increasing use of vertical farm facilities and the deployment of Artificial Intelligence and Robotics, the manufacturing process needs to be environmentally friendly. To extend the usability of these systems, environmentally friendly and reusable materials, bio-degradable as well as reusable materials, and even the improved design of sustainable systems can be applied. Such an approach also helps to reduce the amount of electronic waste created by having systems that are difficult to upgrade and require complete replacement (Mim, 2025).

Long-Term Sustainability

AI and robotics for vertical farming also have a longer sustainability than conventional farming methods since they require more resources and are not sustainable for soil exhaustion, water, and air pollution, and greenhouse gas emissions. The following are the factors that show the long-term sustainability of technologies used in vertical farming: To reduce the effects of AI and Robotics in vertical farming the following key enablers should be practiced; Use of renewable resources in energy, use of environment-friendly resources such as sustainable materials, efficiency in the energy used in the system (Hati, 2021).

CHALLENGES AND LIMITATIONS

There is huge promise to AI and robotics to increase the sustainability and efficiency of vertical farming but challenges and limitations remain before they could potentially reach their full potential. The production of ethanol beings with high initial cost production is also quite technology intensive, and people are also afraid of using and consuming energy for its production and use. If you're hoping AI and robotics have a future in leading the growth of vertical farming, especially in small-scale operations or for scaling up, understanding these limitations is important (Erekath, 2024).

High Initial Costs

A major blocker for the popularization of AI and robotics in vertical farming is the high initial cost of implementation. However, some advanced systems, robotics, and automated farming infrastructure can be too expensive and unimaginable for small-scale or start-up farms. However, the initial costs of these technologies are weighty financial burdens for small-scale vertical farms. But if the success of these technologies depends on them, there will be many small-scale farmers who will have no means of joining the league due to capital constraints and will lag behind larger established farms. Moreover, small farms do not possess the know-how to operate and maintenance of these sophisticated apparatuses, thereby making the economic and operational story more complicated (Liao, 2022). While the long-term economic benefits of AI and robotics are obvious, the initial investment remains difficult. Supporting small-scale farmers in the switch to technologies and more sustainable farming practices needs financial support in the form of government subsidies, grants, or private equity financing.

Technological Barriers

However, a number of challenges remain ahead for the integration of AI and robotics into vertical farming, due to technological barriers, the requirement for access to large quantities of data from existing sensors and monitoring systems, and investment in research and maintenance. However, these challenges are prohibitive for farms that do not have the resources for investing in these technologies. Installing and maintaining these data are costly and difficult to obtain. Also, AI algorithms must be retrained and updated constantly to adjust to environmental changes, and that means never stopping investment in research and continuous maintenance.

Technical challenges of precision, reliability, and scalability facing Robotics systems are also discussed. These, however, have to be able to perform tasks such as planting, maintenance, and harvesting tasks with great accuracy and efficiency, necessitating sophisticated sensors, AI algorithms, and mechanical systems to combine work. Second, when robots are integrated into vertical farming systems there needs to be careful consideration of the crop type, growing conditions, and physical space requirements.

The problem with vertical farms is that they also live in a world with an accelerated pace of evolution of technology, which means they need to constantly evolve the AI and robotics that they work with. For smaller farms that lack the resources and technical know-how to deal with these advancements, can be particularly challenging (Reddy, 2022).

Energy Consumption Concerns

Vertical farming with AI and robotics increases efficiency and sustainability but at the expense of a lot of energy consumption. When AI systems, robotic devices, and automated farming infrastructure are powered by centralized data centers or on the cloud, the additional energy consumption is just one of the side effects. Electricity is also consumed by robotics systems for example electric motors and sensors. A judicious blend of automation and energy utilization is critical for balancing the pros of automation with the energy demand for actions to maintain such systems, herein vertical farming systems.

Nevertheless, AI and robotics have yet to find ways among low-cost or expensive renewable energy infrastructure. The energy from AI and robotics may exceed the benefit of vertical farming on the environment if non sustainable energy is used. Further enhancement of energy efficiency and the development of new energy generation and storage techniques and technologies are required to solve this problem (Abdalla, 2021).

With more action to be taken to solve environmental problems, AI and robotics are beginning to show great potential in increasing the sustainability and efficiency of vertical farming but have yet to address highly constrained scientific ground that arises from the high initial costs of implementing new technologies, technological barriers, as well as high amount of energy consumption, among the others. Further investment in research and development, and financial support will reduce their costs and there will be fewer people who cannot afford such hardware.

FUTURE DIRECTIONS

The system of growing crops and raising livestock states vertically, which has become popular among producers over the recent past, is expected to become more sustainable and efficient in the future. This should be through the complementarity of the use of artificial intelligence, robotics, renewable energy, and policies. The change in technology such as AI and robotics is expected to impact and enhance farming procedures. Swarm robotics that mimics the ants and bees is one promising technology that can transform practices like planting and harvesting, and crop examination too. These robots are used to convey information about the position of the farm and the most suitable manner in which the robots may need to maneuver to accomplish the given exercises competently (Gopireddy, 2024).

Some other technologies that also enhance the AI system are also enhancing machine learning techniques. As more and more data from sensors, cameras, and environment monitors is produced, these systems can identify the right climate for plant growth, prognosis of crop yields, and identification of pests and diseases before they become a problem. Given this, AI systems will become better in their decision-making hence making farming more intelligent than what it is in existence today.

Another important aspect of vertical farming includes the integration of renewable energy as a means of generating power supply for the system. Thus, with little input energy from solar sources, AI and robot-based systems can be a good solution for vertical farming. It is recommended that farms, especially those within the areas of urbanization or those established in vertical farming structures, should be provided with roofing systems for their facilities or elsewhere to generate the electricity they use to support their functions, hence diminishing the carbon footprint. Some of the features of the vertical farm include sensors, lighting systems, and robotic devices, which may be used to harness solar energy. These include the use of batteries or hydrogen storage systems that may enable the transfer of energy from one time of the day to the other; at low light or high demand times.

Specifically, the analysis explores how wind energy can power vertical farms, or the lack there of, depending on the extent of wind resources within that region. Thus, when used in conjunction with wind and solar energy, the concept of vertical farming will be closer to zero-emission, thus making the impact on the environment minimal. Through the conversion of wastes produced in farm productions, bioenergy can be used for powering the vertical farms' mechanized equipment reducing dependency on external sources which in turn makes them a closed system.

The book's ideas and perspectives are timely and valuable for the future development of such an activity as vertical farming with the help of state, private, and other stakeholders' contributions. Therefore, for the development of AI, robotics, and renewable energy technology, the policies can encourage growth by providing monetary benefits such as research grants or subsidies. This is good to note since the governments should offer the platform for creating optimum vertical farming in the urban setting while the commercial investors can come in to impact the innovation front and besides that scale up the operations. Another problem which is financing constructions and equipment for small VE can be addressed by combining efforts both private and public sectors, offering subsidies or low-interest loans.

Another factor is that international cooperation is also considered essential to promote sustainable vertical farming across the globe. The Food and Agriculture Organization of the United Nations is among the international organizations that have encouraged the adoption of sustainable agriculture practices. Although promoting advanced vertical farming methods consisting of Artificial Intelligence, Robotics, and Renewable energy there is a need to incorporate strategic policies and subsidies to ensure the widespread of these aspects in an economical and environmentally friendly manner, especially in the agricultural and food industries and bioprocessing. However, as the Food and Agricultural Organization and the Vertical farm industry continuously innovate and collaborate, the vertical farm can become one of the solutions to the food issue in the world with low impacts on the environment (Maraveas, 2022).

CONCLUSIONS

But vertical farming has the potential to make these very real, and AI and robotics could make it so. AI optimization can be used on vertical farms to minimize resource consumption— how much water, energy, and land is used. Providing advanced algorithms, they also provide performance optimization in irrigation systems, energy-efficient lighting, and climate regulation which lead to enormous savings in water and energy. Furthermore, labor-intensive tasks such as planting, harvesting, and maintenance are automated by robotics thus increasing production efficiency and decreasing dependence on labor, a fact that also leads to a decrease in operating costs.

In addition, in mitigating negative environmental impact, AI is central to optimizing the delivery of nutrients and reducing reliance on harmful pesticides. Pest detection and management systems powered by AI can provide early alerts, and targeted interventions, and thus lower overall pesticide usage. Additionally, vertical farming can integrate with renewable energy sources like solar and wind power, reducing its carbon footprint even more, so that it can remain environmentally sustainable.

From an economic point of view, vertical farming has become increasingly competitive in the agricultural market thanks to the greater efficiency derived from AI and robotics. Farms can increase the per capita labor without a similar increase in labor costs, improving profitability and market viability by automating processes.

While the upsides are plentiful, there are still roadblocks, including high upfront costs, technological roadblocks, and concerns over energy usage. Although the development of AI, robotics, and the integration of renewable energy may have a couple of limitations, these, however, present some promising solutions. To overcome these hurdles, research will continue, and investment and collaboration between governments, the private sector, and, the latter in particular, academia will be needed. Promoting wider use of these technologies, particularly in small-scale and urban farms, can help enable more sustainable and resilient food production systems. With advancements in innovation, AI and robotics-powered vertical farming can become a major pillar of a sustainable agricultural future.

ACKNOWLEDGEMENTS

This research was funded by the Postgraduate Research &Practice Innovation Program of Huaiyin Institute of Technology (HGYK202405) and National College Students' Innovation and Entrepreneurship Training Program Funding Project(202411049034Z)

AUTHOR CONTRIBUTIONS

Ruqia Syed Writing the original draft of the manuscript and conceptualization. Dr .Baolei Pei writing-review & editing, conceptualization, supervision, validation, and Funding acquisition. Yunpeng zhang writing-review & editing, validation and software. Jian Cao writing-review & editing, conceptualization, Resources, and visualization. Rania: writing, review, formating. Alexander joe: writing-review & editing, conceptualization, and validation

COMPETING OF INTEREST

No conflicts of interest have been disclosed by the authors.

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