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Life Cycle Assessment Framework for AI Controlled Vertical Farming in Sustainable Urban Agriculture

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Abstract – The conventional food production systems are under increased pressure due to the high rate of urbanization, climatic changes and scarcity of resources. In this paper, we review an artificial-intelligence and Internet-of-Things-powered vertical farming system (VFS) in the framework of a smart urban agriculture (SUA) application and provides comparative analysis of its functionality to that of a conventional open-field farming. A five-layered nutrient-film technique (NFT) hydroponic system was incorporated in the system with programmable LED lighting, real-time sensing and machine-learning-based adaptive control. The findings of the experiment indicate an increase in yield by 120-150kg m^{-2} yr^{-1}, a decrease in water consumption of 90% (5-7L kg^{-1}) and a 70% increase in the efficiency of land-use. Vitamin C storage increased by about 35% and AI algorithms had over 93% predictive performance and saved up to 18% of energy. In conclusion, life-cycle analysis affirms significant reduction in carbon-emission in a renewable-energy environment.

Keywords – Smart Urban Agriculture, Vertical Farming Systems, Internet of Things, Artificial Intelligence, Hydroponics, Life-Cycle Assessment, Controlled Environment Agriculture, Sustainability.

I. INTRODUCTION

Traditional open field farming (OFF) is faced with great challenges in maintaining high yields of food production and fair distribution to meet the needs of the rising global population about food production. The current world population relies largely on farming practices, largely accepted as unsustainable to sustain nearly 3.3 billion individuals [1]. It is estimated that by 2050, the world population will exceed 10.2 billion, and that more sustainable methods of food-production will have to be adopted sooner. Traditional agriculture contributes to the decrease of the water resources, water quality degradation, and approximately a quarter of the overall greenhouse gas emissions in the world.

Traditional soil-based agriculture, often known as OFF (open-field agriculture), is confronted by the fact that it requires large amounts of land, high labor intensities, and large amounts of water. Additionally, a significant part of urban lands is not arable, and the land that is available has low fertility due to the poor geomorphology or topography. The latest issue that was emphasized is the lack of labor force to operate in standard open fields. In this regard, soil-less cultivation is an opportunity and an effective option as has been suggested [2].

Traditional OFF is a pillar of the global food systems, especially in the rural and large-scale production set-ups. However, these systems are becoming limited by soil erosion, stochastic climatic variability, and water scarcity. Conversely, Soil-Less Farming (SLF) has received a lot of interest as a viable solution to supplement food production in urban and resource constrained environments and of horticultural crops. SLF technologies are designed to be regularly employed in supervised settings such as vertical farms, rooftop greenhouses and climate-regulated indoor facilities, which, in turn, results in the stability of yields that would be insulated against the external weather conditions.

Smart urban agriculture (SUA) breaks into two main fields of research, including smart farming and urban agriculture. Urban agriculture involves the cultivation, processing, and the commercial distribution of food in an urban setting. The level is between small-scale personal gardens and elaborate, commercially oriented, high-technology indoor gardens that produce mainly vegetables, fish, and meat. Because of the scarcity of traditional farming fields in urban areas, some of the systems focus on growing food on building exteriors, rooftops, or indoors greenhouses. Smart farming, in its turn, refers to the use of digital tools to promote agricultural production in terms of its sustainability, quality, and efficiency [3].

Cloud computing, the Internet of Things (IoT), and robotics are the leading technologies used in SUA. Robotics can control the work of the tractor, mechanical weeding, and perform planting, sorting and harvesting fruits, or autonomously control the feeding of animals. Incorporating the experience of urban agriculture with the context of intelligent farming, SUA is defined as the implementation of modern digitalized innovations to enhance food production in urban ecosystems to increase sustainability, quality, and efficiency. SUA provides the tools of autonomous control of the environmental parameters, including temperature and humidity, in urban environments, as well as contributes to the establishment of novel ideas, such as closed-field vertical farming, in particular [4].

Vertical Farming (VF) is an approach to agriculture that supports the massive food production in high-rise buildings. VF allows a fast increase and controlled production due to accurate control of environmental factors and nutrients solution by the use of hydroponics, utilizing modern greenhouse methods and technologies. According to Cheung et al. [5], VF is a combination of engineering and natural sciences, and it has a variety of possible applications in both societal and environmental settings.

The above challenges require new ideas that would go beyond the ordinary form of agriculture. Controlled Environment Agriculture (CEA) offers the solution to food production that is scalable and sustainable. CEA integrates growing plans in monitored ecosystems such as indoor farms, greenhouses, and other enclosed or semi-enclosed environments where temperature, humidity, nutrient levels among other parameters are carefully controlled to increase the productivity of plants. The technique utilizes a small amount of water, reduced use of pesticides and fertilizers, and allows food production in areas where extreme weather patterns or a small area of arable land exist. The proposed research will design and experimentally test an AI- and IoT-based VFS (vertical farming system) and compare its productivity, resource efficiency, nutritional value, and environmental sustainability to conventional open-field farming using statistical and cradle-to-gate Life-Cycle Assessment model.

The rest of the present manuscript will follow the following structure: Section II presents the review of the literature referring to the concept of vertical farming systems VFS, the use of artificial intelligence in agriculture, and the sustainability of food production strategies. Section III defines the materials and methodology, which includes the system architecture, the experimental design, the data collection procedures, the performance metrics and the analytical framework and procedures used. Section IV will provide the findings and explain the results through the prism of resource productivity and efficiency, the nexus between optimal nutrition and AI, and the environmental and socioeconomic implications of the suggested system. Lastly, Section V ends the manuscript by stating that AI-enhanced VFS outperforms traditional agriculture in increasing efficiency in harvesting processes, consuming less water and land, and improving nutrition quality.

II. RELATED WORK

The recent studies on the development of sustainable food in urban settings have been subject to a high level of attention in both scholarly and practice fields. According to Tablada et al. [6], there are still critical technological and practical issues related to the adoption of the vertical farming systems (VFS). Currently, these farms grow mostly various crops in urban areas of China, England, UAE, Singapore, United States, Italy, Canada, Japan, South Korea, and Netherlands.

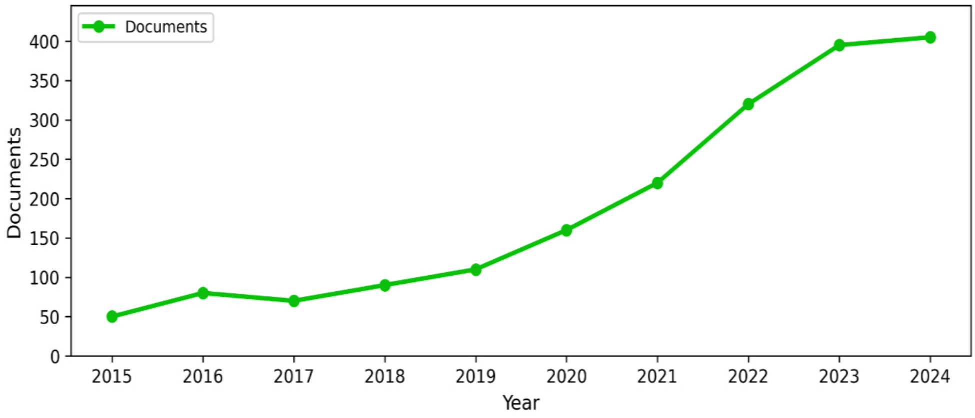

Fig 1. Publications Between 2015-2024.

Chen et al. [7] aimed at finding all articles contained in the Scopus database published between 2015 and 2024 which covered the following topics: CEA, reinforcement learning, neural network, fuzzy logic control, predictive control, machine learning, deep learning, AI (artificial intelligence), vertical far, high tunnel, greenhouse. Before the start of the review, the inclusion and exclusion criteria were determined strictly. The **Fig. 1-4** give details with indications of an extreme upward trend in the number of publications during the given time and hence implying a growth in the research production. The number of documents increased approximately to 50 in the year 2015 and continued to rise to above 400 in the year 2024, which implies that there is increased interest and continuous investment in research in these areas.

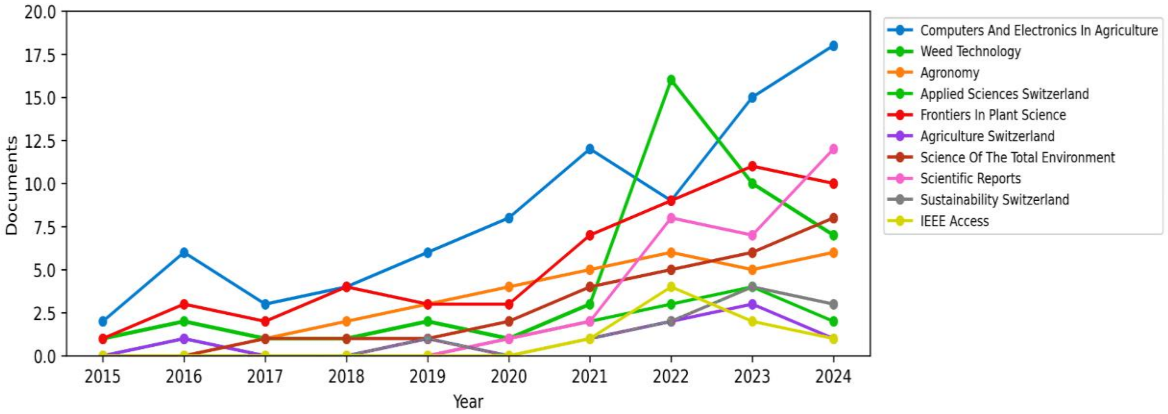

Fig 2. Journal Documentation Between 2015-2024.

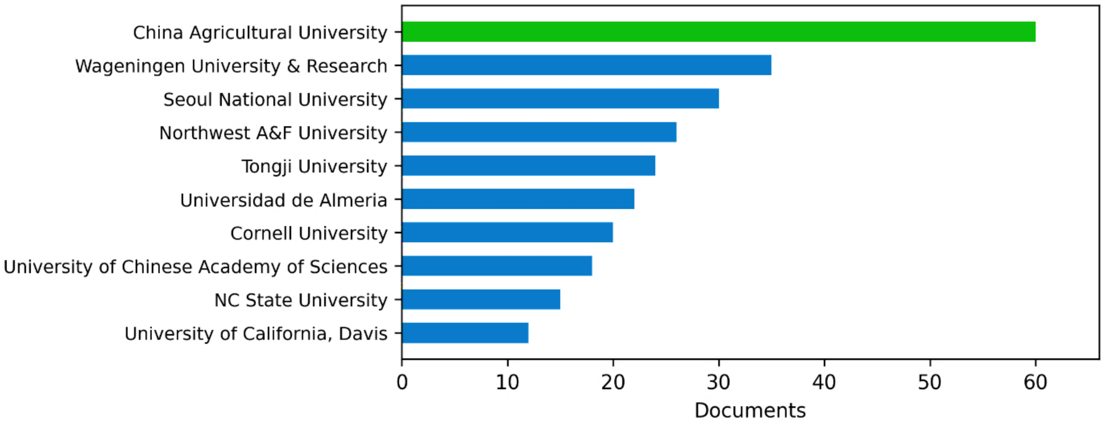

Fig 3. Association of the Corresponding Papers.

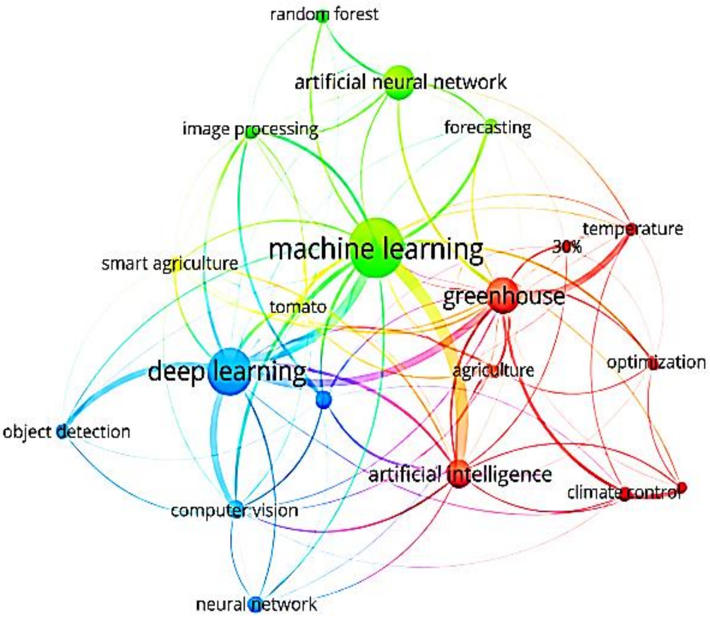

Fig 4. Bibliometric Visualization of the use of the Keywords Selected by the Author.

As described by Mowla et al. [8], IoT denotes the systems of interlinked actuators, sensors, and cloud-oriented applications that allow the actual-time automation and monitoring of major agricultural procedures. These models have been able to provide large high-resolution data concerning the soil properties, climatic features, crop growth and insect events and thus allows making decisions based on the data. These capabilities are enhanced through AI, which is used to analyze sensor information, predict the future, and automatically act on the sensor data, reducing the need to involve human input. IoT combined with AI-powered systems can be used to promote accurate agriculture, permitting agriculturalists to apply fertilizers, pesticides, and water in the most efficient way, therefore, reducing costs and leading to a reduced impact on the environment.

In a study by Pawlak and Kołodziejczak [9], the importance of the technologies can be explained by the fact that they increase the agricultural output with a minimum number of resources, therefore, ensuring food security and sustainability. To improve the agricultural activities, agribusinesses, research institutions, and governments around the world are highly investing in AI-based analytics, IoTs, and robots to increase agricultural workflows. However, with all the promise of transformation, these technologies face major issues of adoption certainly in massive-scale arable farming and extensive grassland control schemes where the environment is more difficult and complex to control.

Jha et al. [10] consider the automation of agriculture in the world. The rate of agricultural automation should match the rising population in the world. At the moment, machines have to some extent replaced human labor and animal power. The authors indicated that America and Europe are leading in the agricultural revolution of automation and Japan comes after that. The automation concept has also been taken seriously by the other parts of the world. The primary concerns of the research devoted to the improvement of the quantity and quality of agricultural products, more efficient use of agrochemicals, energy savings, and environmental preservation are agricultural automation.

The study by Rahman and Hasan [11] focused on the effect of automation in farms on the labor demand in wheat production in Northern Bangladesh. They have shown that wheat yields on the plots that used automation increased to 2.65^{-1} t/ha compared to the 2.57 t/ha with conventional. On mechanized farms, the variable costs (Tk 10,102) are high and at the same time, they bring more gross margins (Tk 14,168). There has been an increase in the cost of power tiller replacement parts, which are perceived to be a major barrier to automation. The results indicated that the agricultural mechanization would greatly reduce the work requirements.

According to Brandão et al. [12], decision-making assistance is commonly obtained with the help of life cycle assessment (LCA), carbon footprint analysis, and other methods of greenhouse gas (GHG) accounting. In LCA, a potential eco-environmental impact interlinked with lifecycle of a service or product is evaluated by way of a Life Cycle Inventory (LCI), comprising of essential output/input data and emissions gathered on the models linked with the service or product of interest. The wide breadth of LCA is an advantage in the area of avoiding the relation of problems set one stage of the cycle to the other, one place to another, or one environmental question to another. Even though the carbon footprint might be less complex than LCA due to its simplicity, it uses a one signal, which is likely to be oversimplified.

Razek et al. [13] argue that it might be counterproductive to optimize the performance of systems through GHG emissions only and cause more loads on the environment with other pollutants, including NO_x and SO_2. This systemic or holistic approach is thus essential in the analysis and the diversity of types of emissions employed by different studies can have a greater effect on the outcomes.

III. MATERIALS AND METHODS

In this section, the experimental design, data gathering procedures, and analysis strategy are outlined to compare VFS and SUA, with the traditional open-field agriculture.

Architecture and Study Design

The experimental environment was a vertical farming system (VFS) that was confined in an insulated growth room of area 120 m^2 with a controlled-environment. The system adopted a five-layered stacked hydroponic architecture that used the Nutrient Film Technique (NFT) to grow leafy vegetables that are lettuce (Lactuca sativa) and spinach (Spinacia oleracea). Such vertical arrangement provided a high productive area in comparison to a normal ground level layout as shown in **Table 1**.

Table 1. VFS Technical Specifications

Component	Specification
Growing Method	NFT Hydroponics
Layers	5
Lighting	Programmable LED (Red/Blue)
Sensors	Temp, RH, CO_2, pH, EC, PAR
Control System	IoT + AI-based optimization

Artificial lighting was provided by programmable full-spectrum LED panels which had short 16-hour photoperiod and then 8-hour dark periods where spectral ratio of red and blue wavelengths could be altered. The field parameters including temperature (20-24 ℃), relative humidity (55-70%), CO_2 concentration (800-1000 ppm), nutrient solution pH (5.8-6.5), and electric conductivity (1.622 cm^{-1}) were automatically controlled to provide the optimality of the conditions in the field.

A sensor network, which is based on the IoT, was used to measure temperature, dissolved oxygen, electrical conductivity, pH, CO^2, humidity, light intensity, and water flow. The information was relayed to a cloud database after every 5 minutes.

Rand Forest and Artificial Neural Network (ANN) models are AI systems that have been created to forecast yield and optimize irrigation, lighting and application of fertilizers via adaptive feedback management. In the comparative study, the same varieties of crops were grown in a traditional OFF plot which was observed during the same season.

Fig. 5 illustrates the system architecture which includes feedback connections that include sensors, cloud-based analytics, and AI controllers, and actuators.

Collection of Data and Performance Measurement

The measurements were made in three cultivation periods which were all 90 days. The fresh biomass yield was measured in kilograms per square meter in the cycle and extrapolated to an annual productivity use (kilograms per m^2 per year). Online flow meters were used to trace the rate of usage of water, and productivity of water utilization was based on liters per kilogram of product (L per kg) (see **Table 2**). The efficiency of land-use was calculated by dividing the effective stacked growth area with the ground footprint.

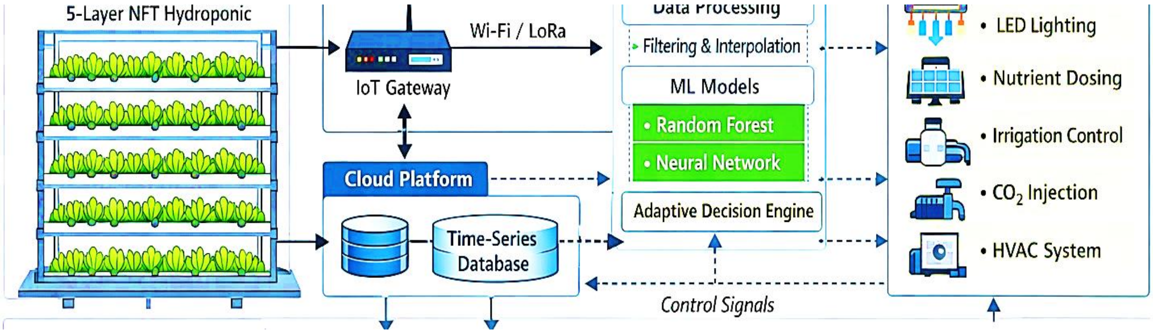

Fig 5. Architecture of Vertical Agricultural Systems with The Help of IoT and AI.

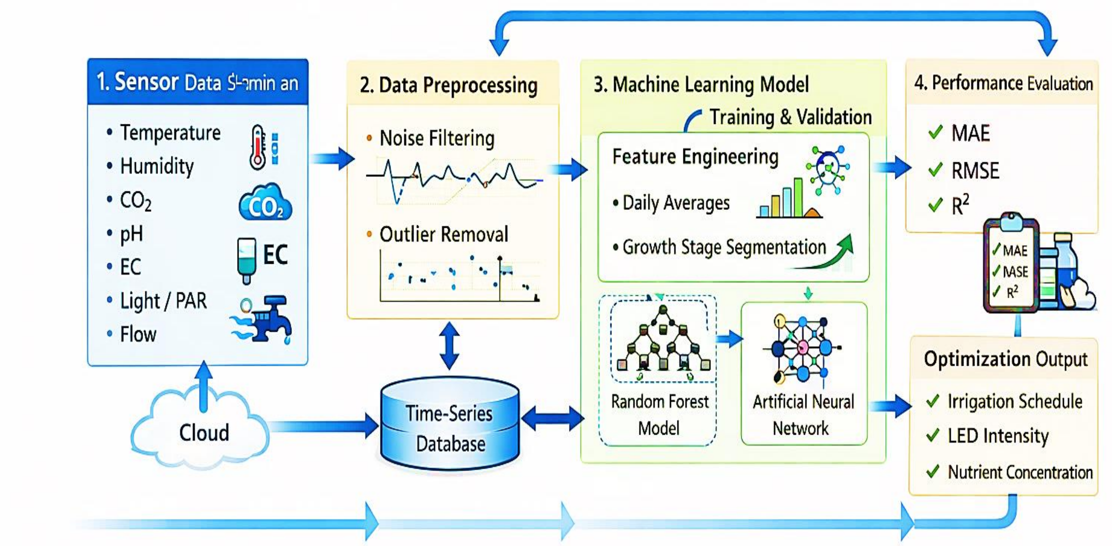

Fig 6. Data Collection and Processing Workflow in the Smart Urban Agricultural System.

The nutritional profile; that is, vitamin C and folate levels were measured by the High-performance liquid chromatography (HPLC). Smart meters were used to measure energy consumption and give it in kilowatt-hours per kilogram of product. All sensor data were stored as time-series in database and preprocessing operations such as outlier removal and mild interpolation of missing values were then performed. **Fig. 6** cycle also explains why the data-processing sequence and data-collection sequence take the described course.

Table 2. Performance Metrics

Metric	Unit	Method
Yield	kg/m²/year	Digital weighing
Water Use	L/kg	Flow meter
Land Efficiency	Ratio	Area calculation
Vitamin C	mg/100 g	HPLC
Energy Use	kWh/kg	Smart meter

Data Analysis Framework and Analysis Procedures

All variables were conducted at the level of independent-sample t-tests, and descriptive statistics tests were used to determine the statistically significant differences at a level of 95% confidence. The 10-fold cross-validation of machine-learning models was followed by measuring the efficiency of ML models through these metrics: RMSE (root mean square error), MAE (mean absolute error), and R^2 (coefficient of determination).

The environmental performance was evaluated using LCA (see **Table 3**) that was carried out as per ISO 14040/44 standard. The cradle-to-gate system boundary was set and the functional unit was defined as 1 kg of fresh product. Three cases have been looked into and these are: traditional open-field farming, vertical farming using grid power and vertical farming using renewable energy. Global Warming Potential (GWP) was given as kilograms of CO_2-equivalent/kilograms of product and sensitivity analysis was performed to understand the change that can be due to varying sources of energy. The system boundary diagram (in comparison) of the life-cycle assessment (LCA) is illustrated in **Fig. 7**.

Table 3. LCA Situations

Scenario	Energy Source	Emission Level
Open-Field	Grid/Fossil	High
Vertical (Grid)	Grid	Moderate
Vertical (Renewable)	Solar + Recovery	Low

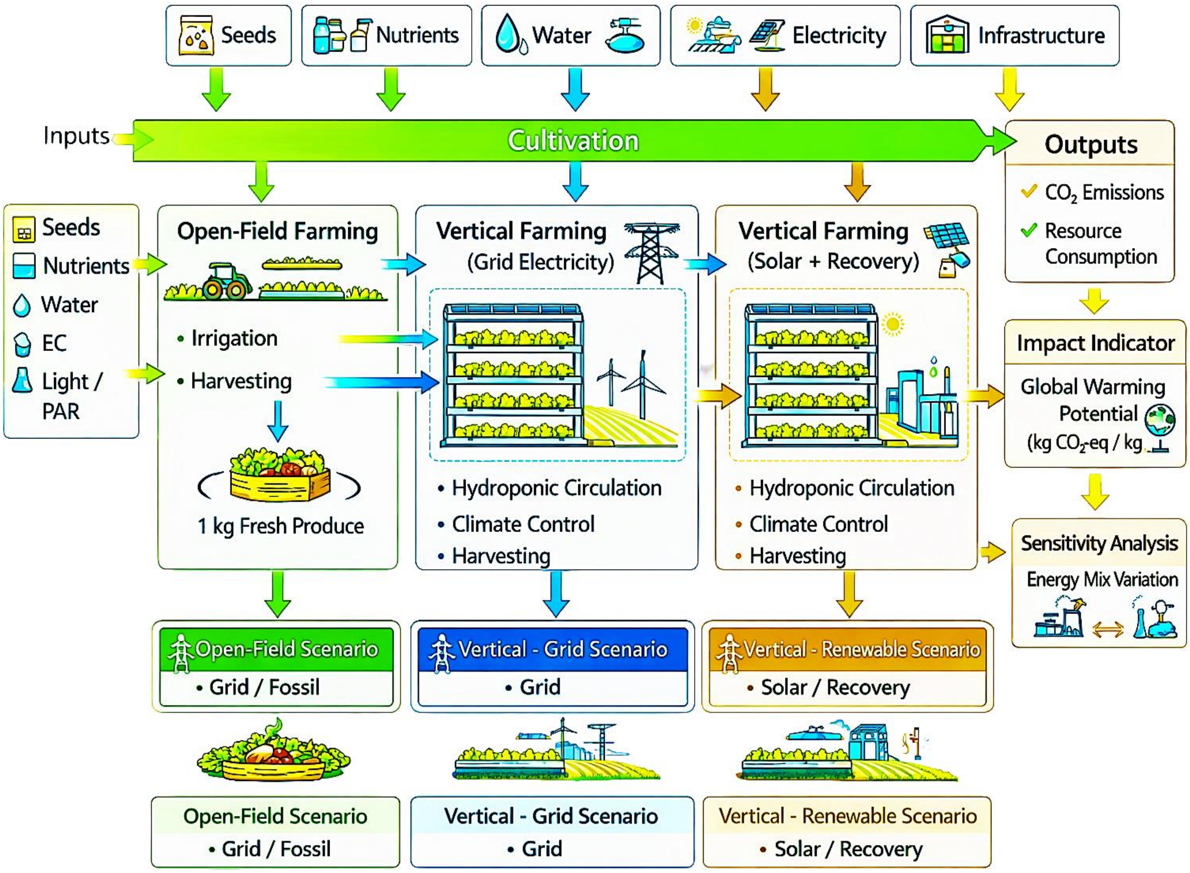

Fig 7. Boundaries of the Cradle-to-Gate LCA System of Farming, Grid-Powered Vertical Farming, and Vertical Systems.

IV. RESULTS

Comparative study of selective urban agriculture (SUA) and vertical farming (VFS) and traditional outdoor farming (OFF) demonstrates a high level of productivity improvement, resource use efficiency, and quality of the nutrients. Moreover, vertical synthetic farming (VSF) implementation and the use of Internet-of-Things (IoT) technologies to monitor food systems and artificial intelligence (AI) technologies to optimize the systems provide significant contributions to the robustness and sustainability of urban food production systems.

Productiveness and Effectiveness of Resources

The findings demonstrate that the yields of VFS are 10-15 times higher than those of the conventional soil-based agriculture. This massive growth can mainly be explained by the use of the multifactorial spatial utilization and the accurate control of the environmental factors including the illumination, temperature, and nutrient contents.

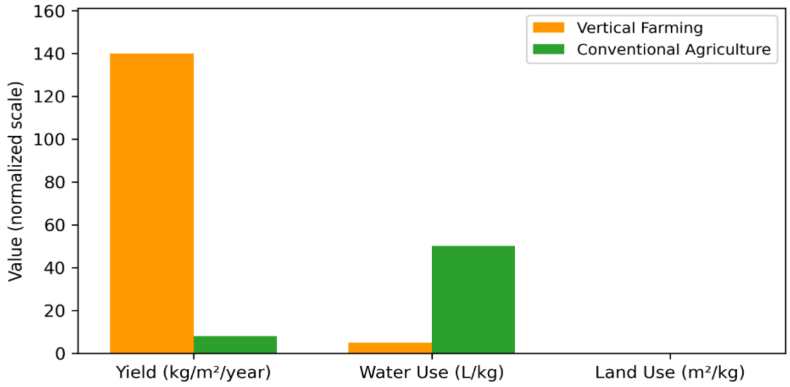

Fig 8. Vertical and Conventional Farming Resource and Yield Efficiency.

Fig. 8 shows the yield productivity of leafy vegetables under hydroponic conditions in a controlled environment was about 120-150/1-2 yr^{-1}, compared to 10-12 kg/m^2/yr in an open field. **Fig. 9** shows a statistical comparison of quantitative measures of performance in SUA/VFS and traditional agricultural activity. These findings indicate that vertical farms have a great improvement in the production, and the average yield is 120-150 kg/m^2/yr/$^{-1}$ compared to 10-12 kg/m^2/yr/$^{-1}$ in the open field.

The water consumed was also significantly less, about 5-7 L/kg^{-1} as opposed to 50-70 L/kg^{-1} in traditional systems, which was estimated to be 90% more efficient in terms of water-use. It was also found that land-use intensity was significantly reduced (0.07 m^2/kg^{-1} vs. 0.25 m^2/kg^{-1}) and shows the improved spatial efficiency that multilayer cropping provides. Moreover, the crops that were grown vertically showed a better nutritional value and the vitamin C content was found to be about 35% more than that of the conventional varieties. These results are in line with the high productivity, resource-efficiency and nutritional benefits of controlled-environment VSF. The information indicates that the yield, water consumption efficiency, land use, and nutrient retention have improved significantly due to the incorporation of the IoT-enabled environmental management and AI-supported control.

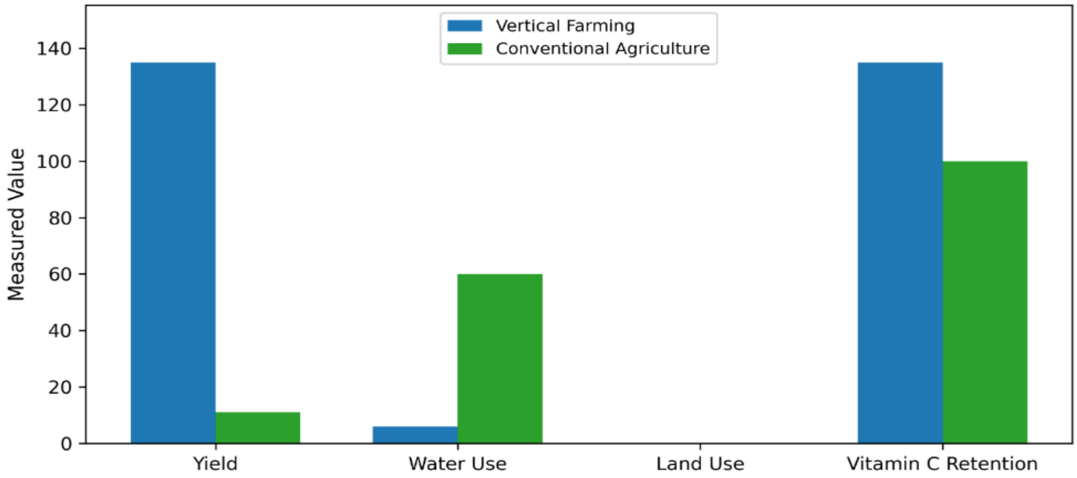

Fig 9. The Summary of The Key Performance Indicators of SUA Systems.

Vertical farms have demonstrated a 90% decrease in water usage and a 70% decrease in land usage, which is due to closed loop fertilizer/irrigation mechanisms which enable real time recycling. These results are consistent with those of Lozano-Castellanos et al. [14], who concluded that hydroponic systems with LED-based controlled-environment agriculture (CEA) could produce the same amount of water savings in relation to the traditional processes, and even in other instances produce greater production. Comparison of yield, water use and land use in vertical farming and traditional open-field agriculture is made using the graph, and it appears that the vertical system has a high productivity rate and at the same time saves water and land needs by a very substantial percentage.

Optimal Nutrition and AI

He [15] investigated the nutritional quality of vertically integrated systems of crop production. A vertical farm is made up of 6 structural components that are critical in offering the best environment where multilayered crop growth will occur (see Fig. 10). Hydroponic systems use a number of methods to provide mineral nutrients to crops, such as deep-water culture, nutrient-film technique, ebb and flow, aeroponics, nutrient-spraying, drip irrigation and stagnant aerated nutrient solution.

Organic substrates; peat, coir pith and wood fiber are provided and inorganic substrates; mineral wool, perlite and sand provide support to roots and provide balance of water and air in the root zone, pH and nutritional buffering. This favorable rooting condition is critical especially when there is germination of seedlings and the further growth of the seedlings.

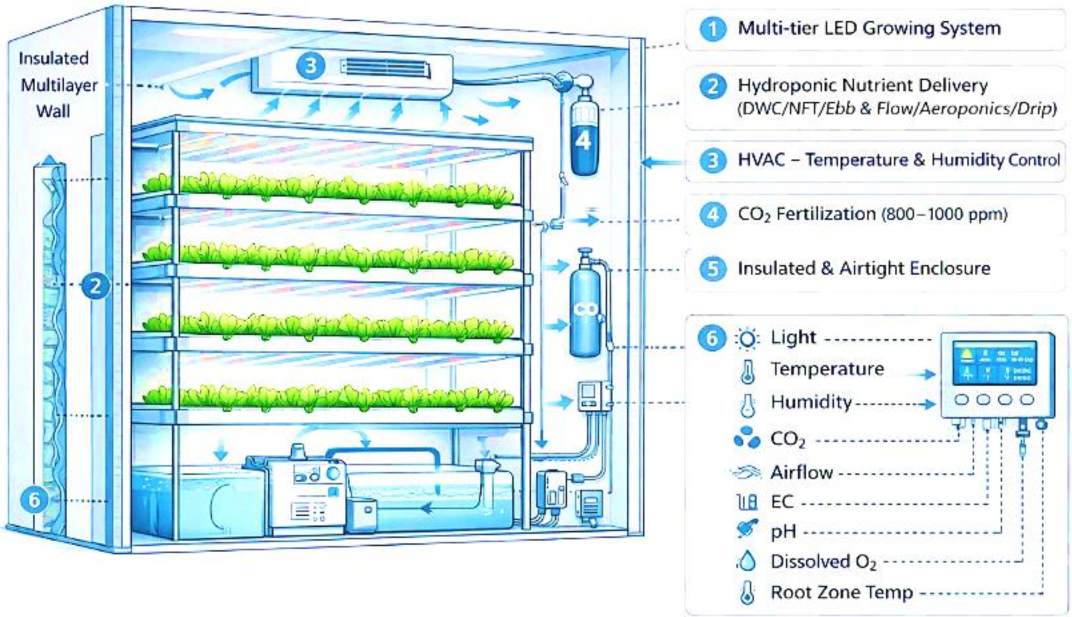

Fig 10. Vertical Agricultural Facility.

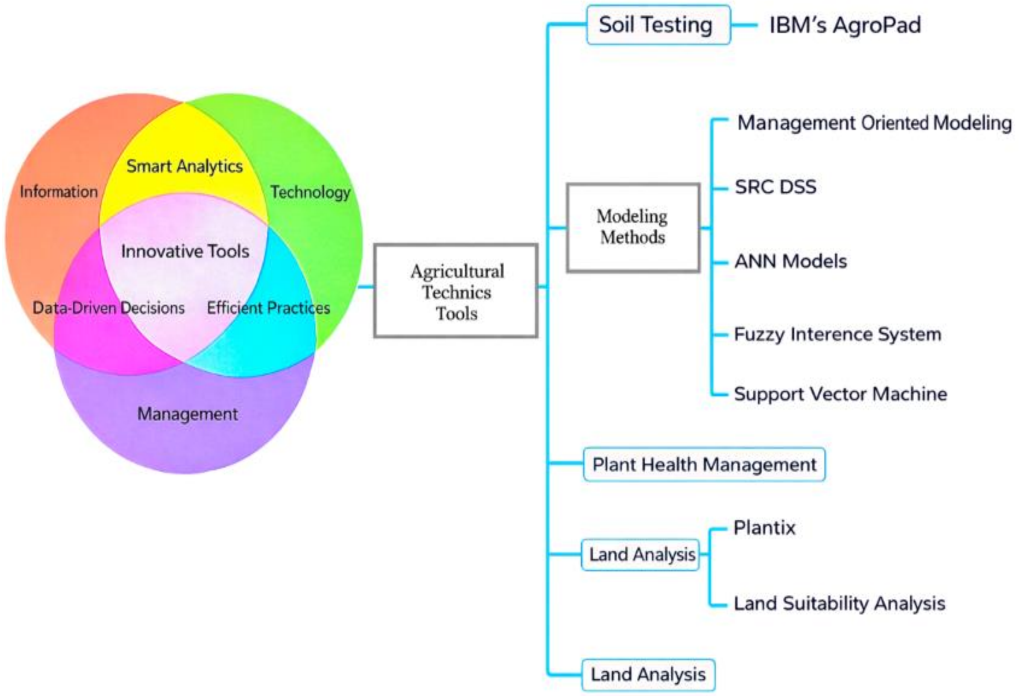

Fig 11. Concept of Precision Farming and the Technologies and Tools that are used in Precision Agriculture.

It has also been shown that hydroponically grown lettuce and spinach hold 30 40 percent more vitamin C as well as folate than their soil-grown counterparts. The increase in retention has been explained by the fact that spectral composition, namely blue and red LED light has been optimized, and links photosynthetic activity and other secondary metabolic processes, which are relevant to nutrient production. Such results hold in the works of Zhang et al. [16], who found that high spectral selectivity and strict nutritional regulation may increase the antioxidant content of microgreens by over 35%. The modern part of the fourth industrial revolution is working hard to change the agricultural industry, creating Agriculture 4.0. This age is marked by information-based management, manufacturing tool-driven, sustainability, professionalization and a significant decrease of environmental footprint. Agriculture 4.0 will be supported by the modern smart technologies, such as the IoT, blockchain, computer vision, AI, big data analytics, cloud computing, and the use of robotics, as represented by unmanned aerial vehicles. **Fig. 11** illustrates the principles of precision farming, as well as the agricultural equipment and methods that can be used nowadays in precision farming.

AI in agricultural systems has recorded significant advancement in accuracy of operations. The machine-learning models used to predict yield achieved more than 93% accuracy hence making it possible to make dynamic adjustments of the soil pH, nutrient content and temperature with little human involvement. In addition, adaptive feedback control algorithms devoted to energy use optimization result in Reduction in the amount of energy waste per growth cycle 1218% higher. These performance metrics prove the practicality of the autonomous environmental regulation to reduce the redundancy in inputs and maintain the similar quality of output. The findings support the results of Sobuj and Sohan [17] suggesting that AI-based decision support systems have the potential to increase the resource-utilization efficiency of vertical farming operations by 20%.

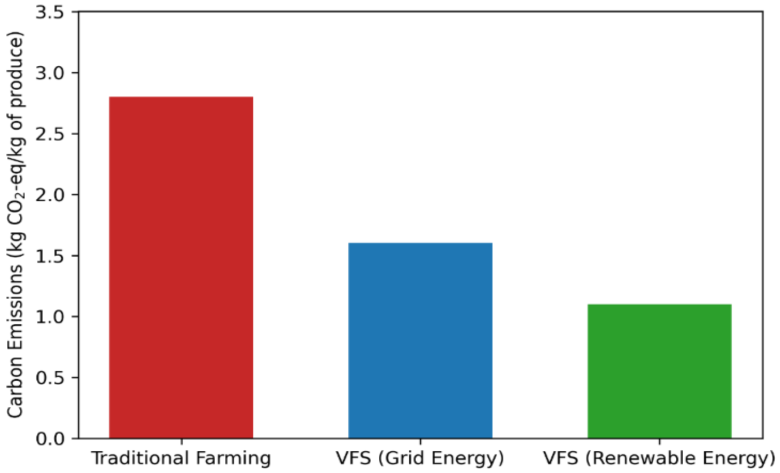

Fig 12. Comparison of Life-Cycle Carbon Emission in Vertical and Conventional Farming System.

Sustainability and Socioeconomic Impact

The findings of the LCA highlight the positive environmental qualities related to digitally controlled vertical farming. The introduction of renewable sources of energy, such as solar photovoltaic and waste-heat recovery unit efficiency is estimated to cut down the total carbon emission up to about 5,560% compared to the conventional open-field supply chains. Besides, local production in urban areas will lower food miles, thus contributing to the reduction of transportation-related emissions and post-harvest losses.

As shown in **Fig. 12**, a comparative evaluation of the Global Warming Potential (GWP) of SUA and VFS to the traditional agricultural practices is established thus demonstrating the benefits of the reduction of carbon emission offered by a smart farming system. The results are in line with the empirical studies by Lin, Zhou, and Gao [18] who had shown similar results of emission cuts attained by local manufacturing and decentralization of supply chains. According to the current research, the combination of the AI-based energy management and renewable energy sources could contribute to the near carbon-neutral operations and provide an alternative to large and sustainable food networks in the cities.

Fig. 12 compares the carbon emissions of conventional farming, vertical farming with grid electricity, and vertical farming with renewable energy and thus shows that vertically integrated systems that are run on renewable energy have the most favorable result. Precisely, such a set up mitigates the emission of greenhouse gases per kilogram of produce by as much as 60%. Besides environmental performance, socioeconomic evaluation indicates that SUA and VFS may lead to the achievement of nutritional equity and urban food security. Vertical farms provide fresh food directly to urban areas with food insecurity and dense populations and, therefore, reduce the length of the supply-chain.

Additional industries that strengthen local economies are creation of jobs in Agritech, AI-led automation and logistics. Use of blockchain traceability systems increases confidence in consumers because it makes it easy to verify product provenance, safety and quality in a transparent way. These operations have been correlated with the goals of sustainable city management and the concept of circular economy models. These findings support the hypotheses that SUA and VFS can have beneficial effects on the environment and still guarantee equal opportunities to enhance nutrition, which is a key factor in the implementation of the United Nations Sustainable Development Goals (SDGs 2, 11, and 12).

V. CONCLUSION

The results prove that VFS, which combine AI and are more effective at harvesting food, consuming less water, and using less land, and preserving nutrients on a better scale than traditional farming. Adaptive machine learning control in multi-layer hydroponic cultivation allows the optimization of the environment, which leads to an increase in yield up to fifteen times and a water efficiency of about 90%. LCA shows that grid-based vertical farms already have less emissions than traditional supply chains, and approaches to renewable energy integration are almost carbon-neutral. SUA is not only environmentally friendly, but it improves the resilience of the urban environment, increases food security, and decreases the supply chain length. IoT sensing and AI streamlining combined with controlled-environment agriculture is one of the scalable future directions of sustainable and data-driven food production systems in the city that are in line with global sustainable development goals.

CRediT Author Statement

The author reviewed the results and approved the final version of the manuscript.

Data Availability

The datasets generated during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interests

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Funding

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Competing Interests

The authors declare no competing interests.

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