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Research paper

A Systematic and Comprehensive Analysis for Recommendation of Proposed IoT-Enabled Smart Indoor Hydroponic System Model in Smart Cities

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Abstract

Rapid population growth and changes in climate have resulted in the depletion of arable lands and require a solution. Hydroponic cultivation is one such solution that uses the approach of soilless smart farming. It requires considerable effort to maintain favorable environmental conditions and provide appropriate nutrition to plants. IoT technology helps in automating all the required processes for better cultivation of crops. IoT helps in enhancing the productivity and cost-effectiveness of growing plants by minimizing the interference of human beings. IoT sensors assist the users in obtaining real-time data to optimize the growth of plants, improve the quality of food, and lessen the cost of production. Smart farming in urban areas has acquired huge popularity as it improves the lifestyle of people by introducing indoor hydroponic farming systems in smart buildings. This type of system needs less space and can be set up inside a room. It makes use of IoT sensors for monitoring the environmental conditions, such as the pH value, temperature, humidity, light control, nutrient control, and soil moisture control, to ensure better and quicker growth of crops and better quality yields. In this paper, a Smart Indoor Hydroponic System for precision farming in smart cities using IOT and AI is proposed that takes less space and provides better quality crops without any human intervention by making use of IoT sensors.

Keywords: *Artificial Intelligence (AI); Hydroponic System; Internet of Things (IoT); Precision farming; Smart city*

1. Introduction

Agriculture is the soul of India, not just a source of living; it depicts the culture, customs, and beauty of traditional festivals celebrated after reaping the crops. However, this beauty and culture are vulnerable to the increasing pesticides, chemical fertilizers, less orientation towards agriculture, fragmented land areas, and shrinking of landholdings due to the increase in population and demand for infrastructure facilities like plants, flyovers, warehouses, or other factories; moreover, the agricultural land is hit by the demand of urbanization and smart cities to be connected and placing globally. Smart City is a concept incorporating information and communication technology, Internet of Things, artificial intelligence, and Machine learning [1] for the city administration and management, and providing smart services to its residents. The concept of smart city emerged due to the various growing issues of cities and urban areas [2,3], like the population increase in the cities, and the shifting of rural families to the urban areas for their children's education. Thus, to handle the populated cities, a degrading environment & services for the residents, work latency, parking, roadside encroachments, mismanaged markets, residential areas, and other environmental issues like fog, etc. The idea of smart cities has emerged as one that is well-managed, controlled, and administered. It requires IoT tools and technologies like sensors, actuators, edge computing, cloud computing, and other smart technologies to support [4]. The perception of smart cities is nowadays known as the Smart 5.0, which incorporates humans as well as Artificial Intelligence with IOT in building smart cities. With the concept of smart cities, smart farming is also required for urban agriculture, as shown in Figure 1. This will reduce the load on rural agriculture and the cost of transportation, and increase the availability of fresh, locally grown food. The core component of the smart cities is the wireless connectivity between the various devices for monitoring and controlling that improves the living standard, efficient operation and services, competitiveness, and concerning the economic, social, and environmental concepts resulting in the sustainable economic growth.

Fig. 1: Smart City comprising villages and multiplexes powered by IOT and AI Tools

Precision farming or urban farming can be done on rooftops, grounds, or vertically on the walls [5]. However, the unavailability of personal ground or parks increases the flats population, working community, and high cost of maintenance of vertical farming on walls or roofs due to safety, security, and other yielding processes. Thus, with the decrease in land and an increase in smart city cultures, flat systems, it is mandatory to find a way that can fulfill both requirements, i.e., healthy food with less cost of production. Therefore, implementing a hydroponic system may reduce the land requirements, be free of pesticides or chemicals, and require less physical work and traveling to the land. The system can be placed anywhere in the house under the roof at a suitable location and requires IoT tools for an automated control system and alarming messages. The various components of monitoring through IOT are data collection through sensors, data transfer to the cloud, an application server for analysis, and monitoring devices [1]. This indoor hydroponic system in a controlled environment can be put anywhere, like in the living room, the center of the house, the balcony, or a covered terrace where the hydroponic system takes less space and is designed in a flooring system with proper lighting, sensors, and other hardware tools [6]. Wireless sensor networks are the core of IOT and the use of AI and ML methods for data normalization, training, classification & prediction is vital for smart farming. Due to the less space taken by the herbs, proper monitoring, and efficient control, the hydroponic yield can give better and healthier results [7]. The hydroponic system is used not only for vegetable and plant growth but also as home décor and a source of happiness. It is the best breeding soilless eco-friendly technology for the plants that aid in cultivating herbivorous plants or crops by combining hydroponics and aquaculture, though not very mature in Haryana, India. The system can be automated to look for nutrients, pH levels between 5.5 and 7, light intensity, water excess or shortage, room temperature, humidity control, crop ripening time, etc. Various companies offer smart hydroponic systems in a compound box that can be assembled and augmented with IoT sensors & actuators at a small cost. The hydroponics system can handle increasing food demand and the availability of specific food items. Apart from the Internet of Things, artificial intelligence is vital in improving crop quality and production [8]. The hydroponic system is an inexpensive and quality food product for the increasing population using the water solvent containing the essential mineral nutrients for the plant's growth and controlled systematically for better yield. The facility helps smart citizens get fresh and rare food items when required. IOT helps minimize the cost of maintaining and upgrading automated products. The hydroponics systems powered by IOT and AI will also sort out the issue of crop irrigation as it is a soilless technology; moreover, in the houses, the issue of water leakages is reduced as this plantation method has a well-controlled watering system. At the user end, various measures are set according to the temperature of lightning and type of plants, client requirements for the automation and control via smartphones, electrical wiring, suitable place, safety measures, and outlook of hydroponics systems designs and graphical user interface for the reports, alerts, status, and user commands, messaging, email. Using the AI methodology, the crop life cycle, the status of crop health & nutrients in the water solvent, and ripping time can also be accurately predicted [9,10].

2. Literature survey

- It is expected that the urban population will hold 50% of the world population by 2050, and India will face the problem of freshwater re- resources. In smart cities, precision agriculture and urban agriculture are the probable answers for the issue of food, security and safety, and sustainable life in the urban areas. Hydroponics cultivation is a boon to the agricultural sector; it enhances the cultivation of plants in an organic way by enabling Internet of Things (IoT) technology and combines technology and conventional nutritional mechanisms to enable the co-plant's growth without the strain of nutrient deficiency [48]. To ensure optimal resource allocation and maximize yields, we have used machine learning models and trained them to recommend suitable crops from the given parameters and refer to the changes in parameters that are needed for better plant growth [49]. The use of machine learning and IOT can help in farming and various agricultural activities. Agri- cultural activities include irrigation, fertilization, breeding animals, rain and drought conditions, etc. Urban agriculture comprises the green lands, universities, and home plantations, livestock, aquaculture, and needs proper irrigation practices for best water utilization for profitable and sustainable agriculture practices. Thus precision agriculture is the best solution that applies the technology in agriculture for the best results improving the overall production and controlling and monitoring various parameters of agriculture like temperature, pH, humidity. India has only a share of 4% of the world's fresh water resources. IOT combined with ML giving valuable solutions [1]. Automation using IoT sensors have helped the farmers in monitoring different types of variations in the plants and sur- rounding environment [11]. Hydroponics help in growing crops without utilizing soil and in growing crops in urban areas. This type of system can be installed vertically inside the house and saves space also [12]. Hydroponics can be used to solve different problems related to supply of good food, saving from allergic diseases due to heavy metals and so on. In this, IoT can be used to balance the environmental conditions and maintain proper nutritional needs of plants automatically [13]. The users can easily monitor the different parameters including humidity, temperature, nutritional needs using a smartphone through Blynk app. In a hydroponic system, plants are kept in tubs, and their roots float in nutrient-rich liquid, allowing them to develop rapidly and become a mass [46]. With the development of smart Internet of Things (IoT) hydroponic system integrated with an Android mobile application for small scale urban farming [47].

The development and implementation of an AI-based system integrating a controller, IoT environment, fuzzy logic algorithm, and NFT (nutrient film technology) hydroponics; the creation of a user-friendly interface for farmers through the Smart-Hydroponic application, enabling hybrid monitoring and control of hydroponic farms; the establishment of an IoT-based cloud environment for sensor data monitoring; the implementation of a smart hydroponic system for nutrient sensing, monitoring, and control; and a comparative analysis between smart and conventional hydroponics based on morphological results[50]. In an IoT Based Automated Indoor Vertical Hydroponics Farming which does not depend on the outside climate and capable to grow common type of crops that can be used as a food source inside homes without the need for a large space [51]. In a smart hydroponic and aeroponic greenhouse system based on Internet of Things (IoT) technology, where the greenhouse is connected to many various tools for controlling the weather conditions automatically inside the greenhouse, consistent with the plant type and season. The indoor environment is equipped with a set of IoT sensors to measure various parameters such as temperature, Humidity, luminous intensity, and total dissolved solids [52].

2.1 Comparison of previous works

The table below reviews significant works on AI-assisted and IoT-enabled hydroponics systems, concentrating on their connectivity platforms, hardware configurations, crop outcome metrics, and automation logic. Each method is estimated for its remarkable profits, restrictions, and appropriateness for practical deployment. It highlights both low-cost advanced AI-integrated and DIY solution approaches, assisting controlled agriculture environments in decision-making.

Table 1: Comparison table of previous works

Method and Reference	System Hardware & Sensors	IoT / Connectivity Platform	Automation& Control Logic	AI/ML or Decision Support	Crop / Outcome Metrics	Notable Benefits / Trade-offs	Limitations
Methods X, 2023 – ESP32 hydroponics monitoring [46]	ESP32 microcontroller; sensors for pH, TDS, water-level, temperature	Blynk mobile IoT app	Automatic dosing of nutrients, water, and salt; manual control via app	None	System validated- stable parameter control	Simple, low-cost; limited scalability; manual override support	1. Issues like crop irrigation 2. Water leakages 3. graphical user interface for the reports, alerts, status, and user commands, messaging, and email
SMART GROW, HardwareX, 2024 – low-cost urban hydroponics [47]	ESP32; pH, EC, water-level sensors	Android app interface via Wi-Fi	Monitors & auto-mates pump control for water & nutrients	None	Suitable for herbs/vegetables; DIY replicable	Cost-effective; basic sensing; Sensor readings improved; no ML	1. Small-scale urban farming.
MethodsX, 2024 – home-scale smart hydroponics [48]	Compact microcontroller + sensors (pH, EC, temp) in mini-system	Proprietary mobile/ embedded app	Monitors core parameters; manually configurable controls	None	Laboratory/home testing; consumer-oriented	Compact urban design; limited automation; focused on hobbyists	1. Requires electricity to be able to function autonomously. 2. Requires an active internet connection for real-time sensor data updation
ScienceDirect, 2024 – AIoT crop recommendation system [49]	Standard hydroponic sensors (pH, EC, temp, humidity)	IoT + cloud integration platform	Automated monitoring; dashboard alerts	ML algorithms (Random Forest, SVM, KNN, XGBoost) used for crop selection and parameter suggestions	Achieved ~97.5% crop recommendation accuracy	Supports decision support; complex but higher intelligence	1. The effectiveness of the crop recommendation system heavily relies on the quality and accuracy of the input data collected by the IoT 2. Electric power consumption and pricing Maintenance and replacement costs for these components may also contribute to higher operational expenses
INFOTEL, 2024 – fuzzy-logic smart hydroponics [50]	Sensors for EC, pH, temperature; control pumps	IoT cloud + Smart-Hydroponic UI	Fuzzy logic controller regulates nutrient dosing and temperature	AI-based fuzzy logic system	NFT-based growth showed better morphological outcomes vs conventional	Accurate nutrient control; reduced labor; moderate complexity	Effective nutrient management relies on accurate sensor readings, and any discrepancies can lead to suboptimal adjustments, requiring regular calibration and maintenance.
MDPI Sensors, Qatar, 2020 testing bed [51]	Arduino Mega/Nano; calibrated EC, pH, water-flow, level sensors; power monitoring	Local AC control; serial communication between modules	Pumps and AC are automatically controlled based on sensor thresholds	None	Achieved stable EC/pH; quantified energy consumption under AC	Field-tested, measured power usage; scalable to greenhouse testbed	1. Cost is Expensive in terms of Scalability and sensor requisition
Ain Shams Eng. J., Egypt 2024 – IoT hydroponics & aeroponics [52]	Multi-sensors: TDS, humidity, luminosity, temp	IoT platform with remote dashboard access	Automated climate, nutrient, and pest control; low user input	None	Batavia lettuce: water-use ~80% lower, doubled yield, cutoff to 45 days	Attractive smart urban greenhouse deployment; strong savings; higher development complexity	1. High initial construction cost required 2. Needs frequent maintenance to avoid damage or low efficiency and productivity for yield
MDPI review, 2023 – literature on	Survey of existing IoT-enabled CPS	Various platforms discussed	MES and CPS used to monitor/control	ML algorithms (KNN,	Yield enhancement, growth	Review-level insights; identifies gaps in	1. Meticulous monitoring and control of various plant growth parameters

hydroponics control parameters [53]	and digital-twin systems	(dashboards, CPS, cloud storage)	ambient & nutrient parameters	prediction models, digital twins) improved yield by 21%, prediction up to 93%	prediction accuracy	standards, security, and cost; supports smart city applicability	to be economically and socially viable.

3. Market Size of Hydroponics

The hydroponics industry involves growing plants without soil, utilizing nutrient solutions in a water-based system. This method, with ancient origins, offers benefits such as accelerated plant growth, increased yields, and the ability to cultivate plants in diverse locations like rooftops and greenhouses. Hydroponics enables water and nutrient recycling, promotes organic food production, and is even used in space exploration programs. Despite its advantages, hydroponics necessitates initial investment and technical expertise. In essence, the hydroponics sector is expanding, transforming traditional farming practices by providing a soil-less and effective approach to growing various crops. The global hydroponics market was valued at USD 5.34 billion in 2023 and is expected to reach USD 8.19 billion by 2031, with a CAGR of 5.50% from 2024 to 2031 [14] as shown in Figure 2.
The global market of hydroponics is currently witnessing rapid expansion, driven by recent advancements in the latest technologies. Devel, including the use of vertical farming, systems controlled by Artificial Intelligence, and LEDs for lighting, helps enhance crop yields and efficient utilization of resources.

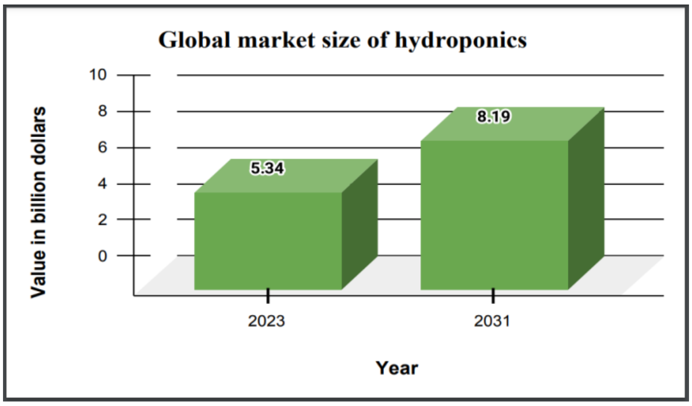

Fig. 2: Global market size of hydroponics

This upsurge indicates a larger shift towards sustainable farming practices, positioning hydroponics to transform food production on a global scale. As the need for organic and fresh food products increases, so does the interest in the use of innovative solutions that are propelling the sector to make more progress in the future.

3.1 Figure Captions: Market Size of Hydroponics by Geography in 2024

The global Hydroponics System market size is projected to reach USD 12.5 billion by 2024, as per Cognitive Market Research Report. In this total market size, the market size of different regions in 2024 [15] is shown below in Table 2:

Table 2: Market size by geography in 2024

Sr. No.	Region	Market Size
1.	North America	USD 5.03 billion
2.	Europe	USD 3.77 billion
3.	Asia Pacific	USD 2.89 billion
4.	Latin America	USD 0.62 billion
5.	Middle East and Africa	USD 0.25 billion
	Total Global market size	**USD 12.5 billion**

The market size can be expressed with the help of a graph, as shown in Figure 3 below:

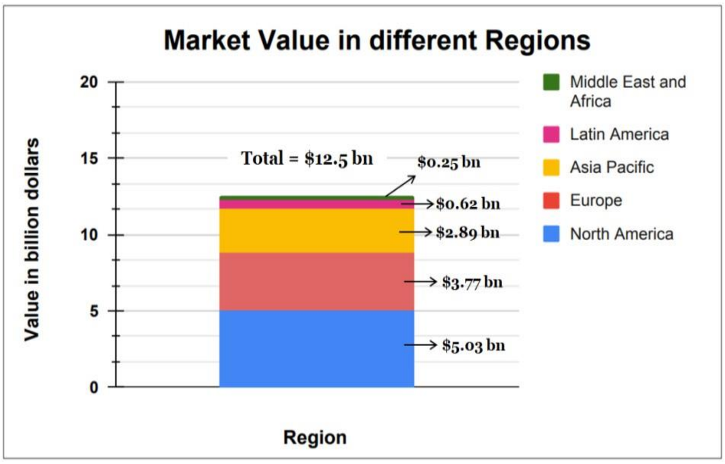

Fig. 3: Market size of different regions in 2024

The Hydroponics market is segmented by region into North America, Europe, Asia-Pacific, the Middle East & Africa, and Latin America. In 2024, North America leads the market with over 40% of global revenue, followed by Europe with a market share of over 30%. Asia. Pacific holds around 23% of the market share, Latin America has more than 5%, and the Middle East & Africa accounts for approximately-ly 2%. It is shown in Figure 4 below:

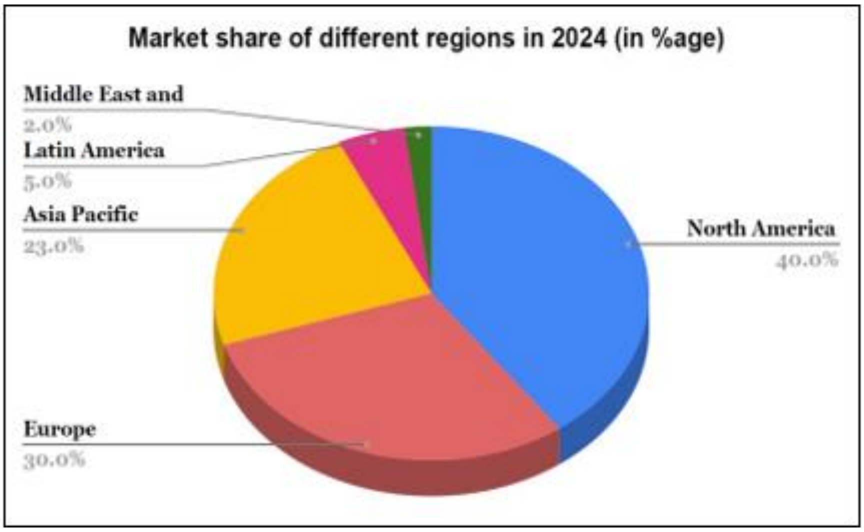

Fig. 4: Market size of regions in %age

It can be seen in the above figure that North America emerged as the dominant market in 2024. The growing trend of cultivating fresh vegetables locally is gaining popularity among North American consumers. The need for year-round production in controlled environments can now be met even in metropolitan areas with space constraints, all thanks to hydroponic systems. Moreover, the region's strong foundation in technology innovation and acceptance has played a crucial role in the advancement of cutting-edge hydroponic systems. This encompasses precision agricultural techniques, automation, and IoT integration for monitoring and control.

3.2 Global Hydroponics Nutrients Market

Hydroponic farming systems do not use soil, so they depend on nutrient solutions to provide the necessary micronutrients for plant growth. Hydroponic fertilizers contain all the essential elements needed for plants to develop, making them well-suited for gardening and indoor farming. Some of the basic micronutrients and macronutrients found in hydroponic nutrient solutions are carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, and sulfur. The increasing adoption of alternative farming methods, like hydroponics, plays a crucial role in the expansion of the hydroponics nutrients market. Additionally, the demand for pesticide and chemical-free food items is propelling market growth throughout the forecast period. Significant obstacles include the high costs associated with setting up and maintaining hydroponic farms, as well as a lack of expertise among farmers. Based on the analysis, North America and the Asia Pacific region are expected to dominate the hydroponic nutrients market due to limited agricultural resources. The increasing prevalence of hydroponic cultivation methods is fueling the expansion of the hydroponic nutrients industry. The Global Hydroponic Nutrients Market Size was about USD 3.3 Billion in 2022 and is projected to reach USD 7.5 Billion by 2032, with a CAGR of 8.6% from 2023 to 2032 [16]. It is shown in Figure 5 below:

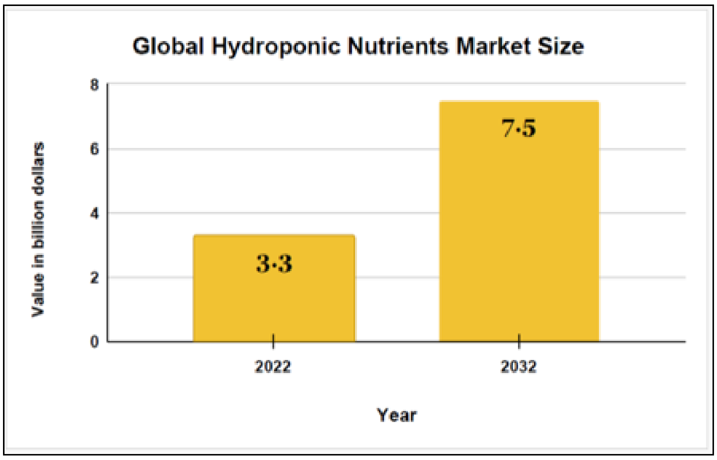

Fig.5: Global Hydroponic Nutrients market size

The global expansion of the hydroponics nutrient market can be attributed primarily to the decreasing availability of arable land worldwide. This growth is due to the increasing need for premium, pesticide-free fruits and vegetables, surging interest in urban agriculture and rooftop gardening, progress in hydroponic technology and equipment, resulting in improved yields and crop quality. North America dominates the global hydroponics nutrients market, representing 32.7% of the total market value [17]. It is shown in fig. 6 below:

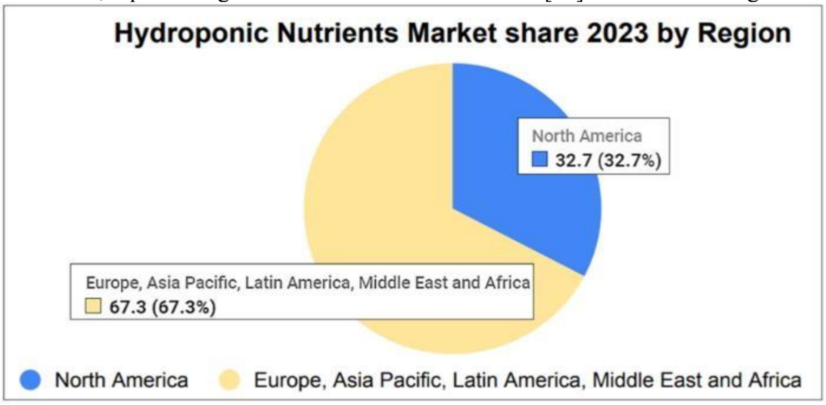

Fig. 6: Hydroponic Nutrients Market Share 2023 by Region

North America, specifically the United States and Canada, represents a substantial market for hydroponic nutrients. The increasing desire for locally sourced crops, along with the necessity to address the limitations of conventional farming techniques, has led to the widespread acceptance of hydroponic farming in the region. Due to the prevalence of extensive hydroponic farming ventures in this area, the utilization of hydroponic nutrients is extensive.

3.3 Indoor and Outdoor Hydroponic Farming

Hydroponic systems are versatile and can be used either indoors or outdoors. Indoor gardens can vary in size, from a small closet to a larger indoor garden, while outdoor gardens can be exposed to the elements. The three main components of hydroponic systems are light, climate, and size, and each of these components can vary depending on the chosen system. The hydroponics sector is forecasted to hold a 49.9% share of the indoor farming market in 2022, as shown in Figure 7. It is expected to grow at a compound annual growth rate (CAGR) of 6.5% over the upcoming decade [18].

It can be seen in Figure 7 that the global indoor farming market share in 2022 was 24.8% for the North American region and 32.1% for the Asia Pacific region.

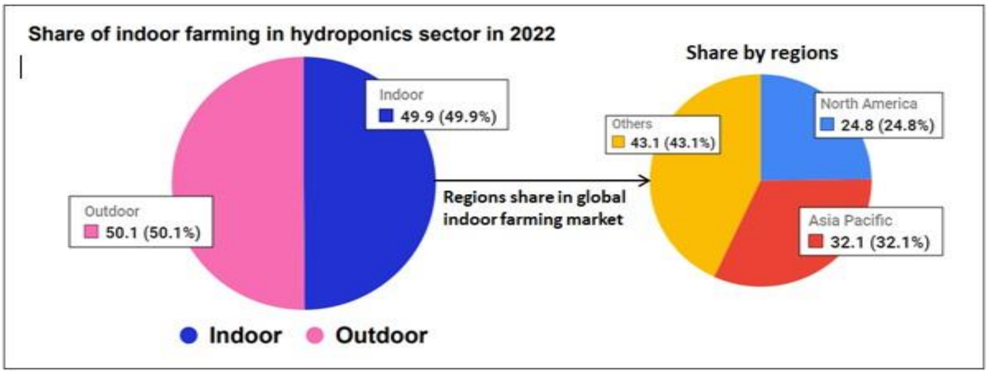

Fig. 7: Indoor farming market share in hydroponics sector in 2022

The indoor farming market is projected to grow at a remarkable CAGR of 11.3%, reaching a value of US$118.17 billion by 2033, according to Fact.MR is a leading market research and competitive intelligence provider. In 2023, the market size was estimated to be US$40.51 billion [18]. It is shown in Figure 8.

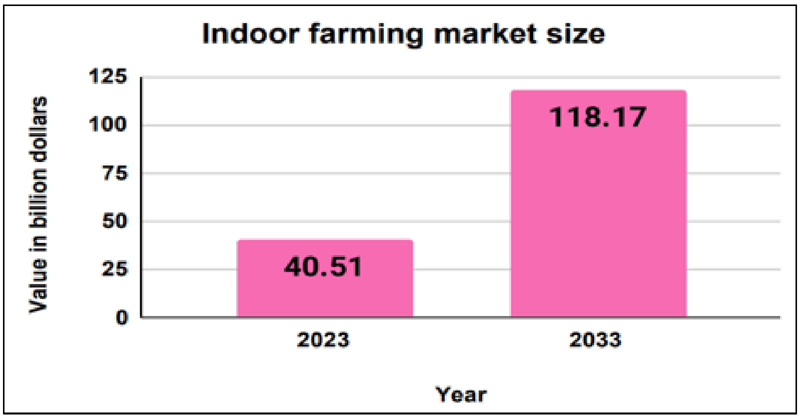

Fig. 8: Global Indoor Farming Market Size

The market is anticipated to experience growth due to the growing consumer knowledge about the benefits of consuming fresh, high-quality food. The expanding global population, particularly in developing countries like China and India, has resulted in higher food demand, which is projected to further propel the indoor farming market in the coming years.

The agriculture industry is being transformed by indoor farming practices. In recent years, the indoor farming sector has garnered significant attention and investment, offering innovative solutions to the challenges faced by traditional agriculture [19]. This cutting-edge field stands out for its ability to cultivate crops in controlled indoor environments, enabling year-round production, improved resource utilization, and sustainability. Automation and data analytics play a crucial role in revolutionizing indoor farming. IoT sensors constantly monitor and regulate environmental conditions to ensure optimal growth settings. Artificial intelligence is utilized for crop monitoring, pest management, and predictive yield analysis, enhancing efficiency and productivity. Advanced LED lighting systems replicate natural sunlight and can be tailored to suit the specific requirements of each crop, boosting photosynthesis and reducing energy consumption. These technologies not only enhance the economic viability of automated indoor farming but also set new benchmarks in sustainability and resource management. The hydroponics sector captured the largest market share in 2023 and is projected to maintain its dominance between 2024 and 2030. Hydroponics is a favored agricultural technique due to its cost-effective installation and user-friendly operation. This method involves replacing soil with a mineral solution surrounding the plant roots for cultivation. Hydroponics is advocated as a means to combat climate change, reduce environmental damage, and prevent species extinction resulting from excessive exploitation and intensive farming. In comparison to traditional soil-based farming, hydroponics offers advantages such as efficient water usage, creation of a controlled micro-climate, reduced labor requirements, soil-free cultivation, and production of higher-quality crops. Moreover, the hydroponics approach eliminates the risk of soil-borne diseases. Increasing consumer awareness about the negative impacts of pesticides is anticipated to drive the demand for hydroponics [20].

4. Comparative Analysis of Hydroponic Farming

For centuries, farmers have been dependent upon age-old conventional techniques to achieve bountiful harvests. Nevertheless, there is a growing number of farmers who are turning to hydroponics as their preferred method of cultivation [21]. Hydroponic farming has become increasingly popular in today's world due to its unique technique that eliminates the use of soil and relies solely on water. This method is considered advantageous compared to traditional agriculture, which has many issues and concerns [22]. As a result, an increasing number of farmers across the world are turning to hydroponic systems. The core components of a hydroponic system include fresh water, oxygen, nutrients, root support, and light.

4.1 SWOT Analysis

The SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis of hydroponic farming techniques [23] is shown in Table 2 below:

Table 3: SWOT Analysis of Hydroponic Farming

Parameter	Aspect	Description
Strengths [24,25]	Requirement of water	Low as the nutrient solution can be re-circulated. Plants cultivated hydroponically are able to make use of only 10% of the water needed by those grown in the field.
	Control over nutrients	Precise control
	Rate of growth of plants	Faster
	Utilization of space	Space is more efficiently utilized
	Output production (Yield)	Potentially higher due to optimal conditions and year-round production
	Labor requirement	Less labor-intensive due to the presence of monitoring equipment and sensors
	Impact of Environment	Less impact
	Seasonality	Year-round production possible
Weaknesses	Equipment and infrastructure requirements	High
	Initial Setup Cost	The implementation of automation and technology in establishing a hydroponic system may necessitate a substantial initial investment for setting up components such as a water treatment plant, nutrient tank, lighting, air pump, reservoir, temperature controller, EC, and plumbing systems.

	Dependence on Continuous Power Supply	The hydroponic farming system is heavily dependent on electricity to operate its different components consistently. In the event of a power outage, there is a significant risk of system failure, potentially harming the plants.
	Susceptible to Waterborne diseases	Hydroponically cultivated plants, being grown in water rather than soil, exhibit a significant increased risk of waterborne diseases.
Opportunities [20]	Growth in Urbanization	Hydroponics has the potential to improve urban farming in regions where land access is restricted for citizens or where climate conditions are unsuitable for outdoor farming. It offers a viable alternative for cultivating certain crops and comes with numerous benefits.
	Advancements in Technology	Automation and machine learning are beginning to have a substantial impact on hydroponic cultivation. The technology that aids hydroponic growers is advancing quickly. Grower solutions are becoming more reliant on data, but they also offer much more valuable insights to the grower.
	Climate Resilience	Hydroponics is proposed as a remedy for addressing climate change, mitigating environmental harm, and preventing species extinction resulting from excessive exploitation and intensive agriculture.
Threats	Market fluctuations	Commercial hydroponic farms are impacted by market volatility, including changes in demand, prices, and competition, like other agricultural businesses. Adapting to these fluctuations is crucial for farmers to sustain profitability.
	Compliance with regulations	Adhering to regulatory standards concerning food safety, water usage, waste management, and other aspects of hydroponic farming is imperative. Non-compliance may lead to penalties or even the closure of operations.
	Economic Feasibility	The varying expenses of energy, nutrients, and maintenance of infrastructure may hurt the profitability. Furthermore, the operation of these systems may necessitate further investment in technology and expertise to ensure effective functioning.

4.2 Cost Analysis

Establishing a hydroponic system might necessitate specific enhancements to the infrastructure in order to establish an ideal environment for growth. These enhancements could contribute to the total expenses of initiating a hydroponic farm. Typical infrastructure enhancements encompass electrical updates, ventilation, and water purification systems. These enhancements guarantee that plants obtain sufficient light, air, and water, all of which are crucial for their development. The expenses associated with these enhancements will vary based on the scale of the system and the particular needs of the plants. The expenses associated with establishing a hydroponic farm may fluctuate based on a number of elements. These elements encompass the kind of hydroponic system, the scale of the system, the desired level of food output, essential infrastructure enhancements, and consumable costs like seeds, grow medium, nutrients, and pH testing kits. It can be seen in Figure 9 that initiating a hydroponic farm requires careful consideration of multiple expenses. The total costs may fluctuate based on variables like the kind and scale of the hydroponic setup, the desired level of food output, essential upgrades to infrastructure, and consumable costs.

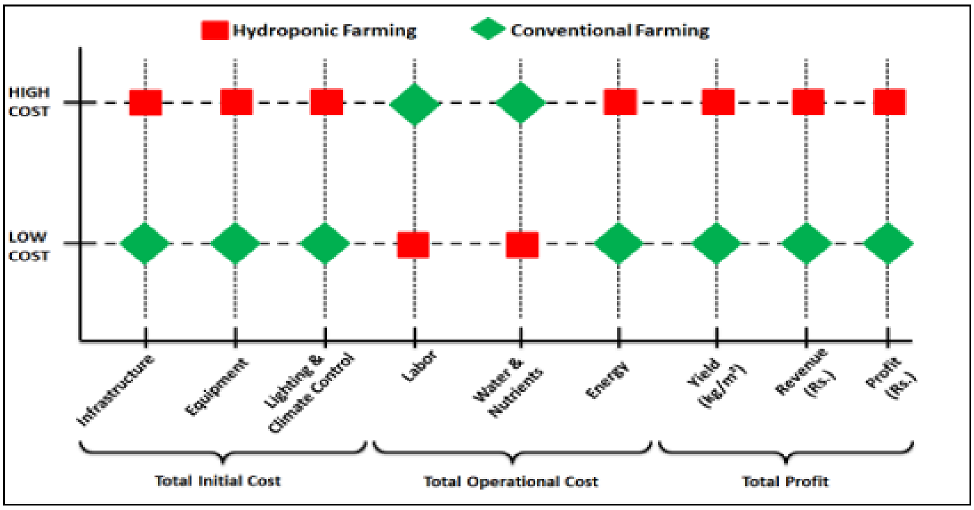

Fig. 9: Cost analysis of Hydroponic Farming

4.2.1 Initial Setup Cost

Building the required infrastructure and acquiring vital equipment make up a substantial part of the initial capital outlay. This encompasses costs for constructing greenhouses, purchasing hydroponic racks or vertical towers, installing irrigation systems, pumps, tanks, and obtaining growing medium. Artificial lighting is crucial in hydroponic systems, particularly in areas with restricted sunlight availability.

4.2.2 Operational Cost

Apart from the initial setup expenses, there are continuous consumable costs that need to be taken into account. These costs involve buying seeds, growing medium, nutrients, pH testing kits, and other operational expenses. The amount spent on these items may differ based on the scale of your setup and the variety of plants being cultivated. Hydroponic agriculture typically demands skilled workers [26] to oversee and regulate the water chemistry, maintain the system, and care for the plants. The cost of labor can be a substantial ongoing expenditure for hydroponic farms. Hydroponic plants rely on specific nutrient solutions for optimal growth [27]. While the price of these solutions may fluctuate, they generally tend to be pricier compared to conventional fertilizers utilized in traditional soil farming practices.

4.2.3 Profitability

Hydroponic farming can yield significant profits due to its ability to produce crops year-round and achieve higher yields. Additionally, the products typically fetch higher prices compared to those from conventional farming, as they are perceived as high-quality and free from chemicals.

5. Proposed Model

The current paper proposed a smart compound hydroponic system model for smart cities for in-house cultivation in a controlled environment using IoT [28] and communication technology for automated controlling and monitoring [29] systems through smart apps that can be placed in the living room as a room decor. Like the RO system for water purification in houses, the controlling system sets the pH level, light intensity, humidity, water flow, and other water nutrients ratios and other measures to be automatically organized [30]. Like CCTV cameras, the system can also be seen on smart mobile devices with internet or Wi-Fi facilities. This paper proposed a model to be placed in the smart city inside the house, anywhere, or in the center of a multistory building (multiplex) for each floor that can also be used as home decor with fresh food or leafy vegetables, as shown in Figure 10.

Fig. 10: Smart Home Décor Growing System

The system can benefit elderly people having hobbies on the plantation, for the smart city manufacturers to mount the smart hydroponic system on each floor of the building near the stairs or lift or at the center of the halls, entry area, etc., and to meet the requirements of the working family who have no time to look after plants or to go to “sabzi mandi” or greengrocers for green leafy vegetables, the rare or non-seasonal medicinal herbs can also be planted within this smart hydroponic system.

5.1 Proposed Architecture Model

Working Algorithm:
Step 1: Start with the Supply of Water through the INFLOW System
Step 2: Water gets supplied to the Plant through the Grow Tray Container, and the different Sensors are kept inside the Container.
Step 3: pH Sensor- Senses Nutrient Solubility, Microbial Activity, and Toxicity Risks.
Water Level Sensor- Check the status of Water Storage
Oxygen Level Sensor- To adapt to a varying availability of oxygen, plants sense O2 via the conditional proteolysis of transcriptional regulators.
Nutrient Control Sensor- Monitor and manage nutrient levels in soil, crops, and irrigation water.
Soil Moisture Sensor- Measure the volumetric water content in soil
Temperature & Humidity Control Sensor- Sensing pathways in plants to respond to abiotic stresses at the molecular level are Reviewed.
Electrical Conductivity Sensor- Assess the soil's electrical conductivity, indicating its capacity to conduct electrical currents.
LED Grow Light- Designed to mimic the natural light that plants need for photosynthesis.
Step 4: Once the Sensors sense all the data, the entire data gets recorded on the Mobile phone, capturing the Entire data
Step 5: Based on step 5, the necessary elements are supplied for the cultivation of several plant species

6. Materials and Methodology

The agglutination of smart city technologies with smart farming initiatives depicts a transformative synergy that handles the intricate challenges of modern civilization while improving agrarian sustainability [31]. In this interspersed archetype, smart city architecture, comprising IoT sensors, big data analytics, and internet connectivity, comes together with state-of-the-art technologies used for farming, creating a seamless and productive ecosystem. Urban areas are being ameliorated for vertical farming, hydroponic farming, and rooftop lawns, intensifying land usage in the context of space shortage in smart cities [32,33]. IoT sensors assist in monitoring environmental situations, assuring accurate control over components and set parameters, thus enhancing optimum growth of crops [34]. Big Data analytics applied to the crop data obtained from the amalgamated system enables farmers to make better-informed decisions, forecast challenges, and improve overall efficiency [35]. The fusion of smart farming and smart city not only revolutionizes regional crop production, minimizing dependency on outside sources, but also adds to environmental sustainability by reducing the emission of greenhouse gases due to transportation, and emphasizes both the welfare of its inhabitants and the renewable plantation of necessary resources. The methodology for implementing smart farming on every floor of a smart building presumes the planned deployment of different sensors based on IoT and other pioneering technologies, such as ML (Machine Learning), as an interconnected system for analyzing the real-time data obtained from sensors [36] that makes it easier to make informed decisions. An ideal microclimate for the growth of plants is built using automated climate control systems along with actuators and controllers that help in acclimatizing environmental circumstances on the basis of the insights obtained from sensors [37]. Précised irrigation systems, directed by soil moisture sensors and climate data, ensure proficient water utilization. In addition, nutrient concentrations can be precisely monitored and controlled by integrating hydroponic systems that are powered by IoT sensors [38]. Energy-proficient LED lighting, receptive to normal light circumstances, improves energy savings and custom-fitted illumination for crops. Monitoring of crops, detection of diseases, and growth forecasting are made possible by incorporating image sensors with machine learning models. A water storage tank is installed to store the extra amount of water, and the different sensors are deployed in this tank to control the temperature, water level, pH, and EC [39]. A water pump is provided in the storage tank for pumping the water from the tank to the grow tray.

6.1 IoT Sensors

In a smart hydroponic system within a smart building in a smart city, the deployment of IoT sensors [40] is essential, and the different types of IoT sensors used in the proposed smart hydroponic system on each floor of a smart building are as follows [13]:

1. pH Sensors

The acidity or alkalinity of the nutrient solution in hydroponic systems is measured by pH sensors. Maintaining the right pH level is necessary for better nutrient absorption by plants, and these sensors make sure that changes can be made in real-time [41].

2. Electrical Conductivity (EC) Sensors

In hydroponic systems, EC measurements are essential for maintaining optimum nutrient levels needed for the growth of plants. By routinely observing and changing the supplement concentration on the basis of EC readings, cultivators can guarantee that plants get the balanced nutrients. This prevents issues like deficiency of nutrients, enhances yield, and encourages the development of healthy plants [42].

3. Dissolved Oxygen Sensors

In smart farming, hydroponic systems require dissolved oxygen sensors, which assist with keeping a high-impact climate for plant roots and amphibious living beings, forestalling issues like root decay. Aeration and oxygenation mechanisms can be precisely adjusted due to the ability of automated systems to respond to changes in dissolved oxygen levels.

4. Temperature Sensors

Temperature sensors are essential in hydroponic systems as they provide the necessary data needed to ensure ideal growing conditions for plants. In order to keep an eye on both the temperature of the nutrient solution and the surrounding air in the hydroponic environment, these sensors are strategically placed. The temperature of the nutrient solution influences the solubility of nutrients and microbial action, impacting the proficiency of nutrient uptake by plant roots. Also, observing air temperature is essential for controlling plant wellbeing and metabolic cycles, like transpiration and photosynthesis. Temperature sensors, which are incorporated into the control mechanisms of the hydroponic system, enable automated adjustments like activating cooling or heating systems, enhancing lighting conditions, or altering the concentrations of nutrients. By forestalling outrageous fluctuations in temperature and stress conditions, these sensors add to the avoidance of possible issues, guaranteeing that plants flourish and accomplish their full development potential. The data gathered by temperature sensors permits informed decision-making, analysis of patterns, and the execution of proactive measures for improving the overall productivity and sustainability of hydroponic cultivation.

5. Humidity Sensors

Humidity sensors continuously observe and regulate the relative humidity within the farming environment. These sensors measure the quantity of moisture in the air, providing necessary data for maintaining ideal growing conditions. Controlling humidity prevents issues like mold, mildew, and excessive transpiration. High humidity levels can create a favorable environment for fungal growth, while excessively low humidity can result in enhanced water loss through plant transpiration. Humidity sensors enable automated adjustments, such as activating humidifiers or ventilation systems, to guarantee a stable and favorable humidity range. This precision in humidity management fosters an environment that is conducive to robust and healthy crop growth, improves nutrient absorption, and lowers the risk of diseases [43].

6. Water Level Sensors

Water level sensors help in observing and maintaining the appropriate water levels in the hydroponic system, which ensures that plants receive the required amount of hydration without any risk of flooding.

7. Nutrient Solution Flow Sensors

These sensors monitor the flow of the nutrient solution through the hydroponic system, which helps in making sure that nutrients are supplied to the plants in a consistent and controlled manner.

8. Light Sensors

Light sensors help in assessing both natural and artificial light levels, which is essential for adjusting artificial lighting systems to augment natural light and enhance optimal photosynthesis.

9. Camera and Image sensors

Cameras and image sensors can be used for monitoring of crops, identification of diseases, and analysis of the growth of plants within the hydroponic system. Image analysis utilizes computer vision techniques that enable early identification of issues in plant growth.

10. IoT-Enabled Actuators

Actuators controlled by IoT systems assist in the automation of adjustments based on sensor data, including nutrient dosing systems and pH adjustment mechanisms, which can be automated for accurate control.

6.2 Smart Hydroponic Model for Precision Farming in Smart Cities

The entire system is incorporated into the building's administrative infrastructure, permitting synchronized operations and boosting a seamless synergy between human solace and agricultural requisites. The productivity and efficiency of the system are aided by its ability to perform predictive maintenance, data analytics, and remote monitoring. This comprehensive technique improves the utilization of resources as well as captivates the community through awareness drives, laying out a feasible and innovatively progressed model for urban farming. The model is shown in Figure 11 below:

The data gathered by these sensors is conveyed to a centralized IoT platform, where data analysis can be done in real-time [44]. Automated IoT sensors can adjust in the hydroponic system based on the analyzed data, assuring optimum conditions for the growth of plants. This data-driven and automated strategy results in the enhancement of efficiency, conservation of resources, and enhanced yields in a smart hydroponic system constructed on the different floors of a smart building within a smart city [45].

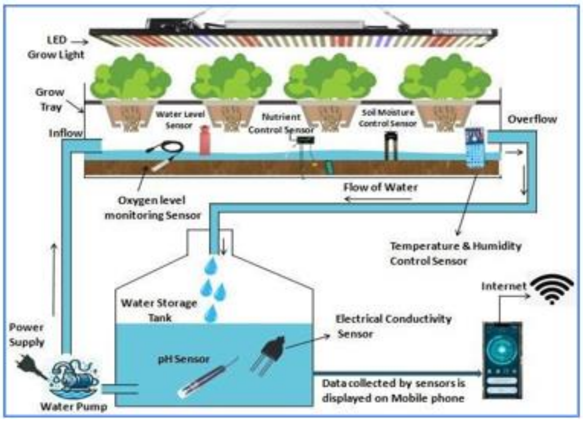

Fig. 11: Smart Hydroponic Model for precision farming in smart cities

For the better administration and management of infrastructure, facilities, and services to the increased urbanized population and increased land, smart cities are the solution to the changing lifestyle, quality of living, globalization, education level, nuclear families, and decreased land ownership. Apart from the residential houses, the smart city also incorporates the multistorey, markets and other services with advanced facilities like smart home appliances, home decor, parking areas, traffic lights, solar charging, etc. Due to the overpopulated urban areas, a hydroponic system can help mitigate the various ongoing issues like degrading health, environmental issues, and diminishing agricultural lands, and provide fresh and healthy food in a small land area that is automatically managed. The system is automated and powered by AI, ML, IoT, and communication technology, and automated surveillance is possible. The working family can easily leave the house, whether for business purposes, education, or a tour, without the fear of the lack of watering plants and their required nutrients. Therefore, the hydroponic system is a must for a sustainable smart city plan and the long-term solutions for the overpopulated urbanization in India.

The proposed model of a smart hydroponic system for smart cities can monitor and control all the given parameters like pH, water level, power supply, temperature & humidity, oxygen level, nutrients, soil moisture, and can report on any kind of abnormalities and events via alerts, notifications, and email. The system will be helpful not only for home décor, but it also benefits in growing the required medicinal plants, non-seasonal leafy vegetables, and rare herbs in-house and automatically managed. The system can also be mounted for experimental purposes for research in plants, and to teach students in an augmented reality environment about the growth and phases of different plants.

7. Results and Discussion

For the better administration and management of infrastructure, facilities, and services to the increased urbanized population and increased land, smart cities are the solution to the changing lifestyle, quality of living, globalization, education level, nuclear families, and decreased land ownership. Apart from the residential houses, the smart city also incorporates the multi-storey markets and other services with advanced facilities like smart home appliances, home decor, parking areas, traffic lights, solar charging, etc. Due to the overpopulated urban areas, a hydroponic system can help mitigate the various ongoing issues like degrading health, environmental issues, and diminishing agricultural lands, and provide fresh and healthy food in a small land area that is automatically managed. The system is automated and powered by AI, ML, IoT, and communication technology, and automated surveillance is possible. The working family can easily leave the house, whether for business purposes, education, or a tour, without the fear of the lack of watering plants and their required nutrients. Therefore, the hydroponic system is a must for a sustainable smart city plan and the long-term solutions for the overpopulated urbanization in India. The proposed model of a smart hydroponic system for smart cities can monitor and control all the given parameters like pH, water level, power supply, temperature & humidity, oxygen level, nutrients, soil moisture, and can report on any kind of abnormalities and events via alerts, notifications, and email. The system will be helpful not only for home décor, but it also benefits in growing the required medicinal plants, non-seasonal leafy vegetables, and rare herbs in-house and automatically managed. The system can also be mounted for experimental purposes for research in plants and to teach students in an augmented reality environment about the growth and phases of different plants.

8. Conclusion

The adoption of a smart farming hydroponic system incorporated with IoT in a smart city yields several benefits that transform urban farming. The precise tracking and controlling enabled by IoT sensors assist in providing optimal conditions for better growth of plants and guarantee efficient utilization of resources. Water efficiency is remarkably enhanced due to the usage of hydroponic systems, directed by real-time data comprising pH value, nutrient levels, and soil moisture, which minimizes water wastage. Farmers are able to easily manage the system from a distance due to the increased operational efficiency brought about by the automation of essential tasks like nutrient dosing and environmental adjustments. Additionally, hydroponics is a suitable solution for urban environments with limited space because it does not require soil and does not necessitate arable land. The data-driven insights of the system add to dynamic decision-making, early identification of issues in the plant, and enhanced crop yields. In addition, by advancing neighborhood and economic food production, the smart hydroponic system boosts food security in the smart city, alleviating the natural effects associated with conventional agribusiness and lessening the emission of carbon due to transportation. Predominantly, the amalgamation of smart farming techniques with hydroponics and IoT technologies depicts a progressivist approach that aligns with the objectives of resource proficiency, sustainability, and resilience in present-day urban farming.

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