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Digital Based Technology Approaches for Human Free Microgreen Agriculture to Support a Sustainable Future by Improving Nutrition and Monitoring Environmental Conditions

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Abstract
Microgreens or seedlings refer to young plant vegetables harvested as soon as the first actual leaf or cotyledon stage occurs and are recognized as being more nutritious in comparison to other vegetables. Microgreens refer to young edible seedlings. Microgreens promote nutritional value and health benefits if incorporated in the daily diet of consumers. However, the existing production method makes it difficult to achieve high-quality production of the product, which should still be nutrient-dense. Environmental volatility, the risk of contamination, resource overuse or waste, tethering of the cultivation to labor resource, all of these factors are just some of the many challenges that are present and limit the food safety, scale and productivity of the crops grown. These challenges made the need for new and more precise methods of cultivation evident. Digital Microgreens cultivation is the first to bring together cutting-edge techniques which include the use of sensors, automation, Lighting Emitting Diodes (LEDs) and all of which integrated hydroponic systems, to maintain optimal levels of all relevant elements of plant growth including temperature, humidity, light, water and nutrient cycles. Mobile and computer applications facilitate real time system monitoring, which in turn fosters data-driven management which guarantees consistent growth, optimum yields and enhanced nutritional density. Furthermore, digital farming greatly facilitates water conservation, reduction in the wastage of nutrients as well as the reduction in labor, while at the same time ensuring clean growth environments. Digital microgreens farming, in general, is a sustainable and efficient approach to

modern farming. Its application in indoor settings, along with the ability to produce continuously without any concern for climatic conditions, makes it a promising technique for future food security. The use of smart technology together with sustainable farming practices, such as in microgreens farming, is extremely helpful in catering to demands for healthy food and ensuring that sustainable farming practices are used in farming.
Keywords: Microgreens, Digital Farming, Hydroponic Systems, Smart Agriculture, Nutrient-dense.

Introduction

Microgreens are young, tender vegetable and herbal seedlings that are harvested in their cotyledon or first true leaf stages. They have received immense attention within recent past years because of their richness and nutritional value and their health functions and characteristics. They contain relatively higher amounts within their compositions of essential vitamins, minerals, and antioxidants than full-grown leafy vegetables, and their emergence within the globe, therefore, offers it an important position within controlled environment agriculture. (Marios C Kyriacou et al., 2016)

Conventional agricultural methods include a number of challenging activities that could hinder their large-scale production despite a number of benefits associated with microgreens production, including their high labor requirements, which could result in variability in their quality as they could be expensive because they could require a high level of labor. Frequent human contact during planting, irrigation, harvest and handling could lead to the risks from microbial contaminants, hence becoming a food safety issue. Besides, controlling temperatures, moisture, lighting, nutrient levels, among other things, would be hard to implement in agricultural production. (Yanqi Zhang et al., 2021)

In recent years, digital technology has incorporated agricultural processes as a result of their viability in overcoming the mentioned difficulties. Minimal human interaction or completely without agricultural practices, which would mainly focus on agricultural crop handling with minimal interaction with humans. In microgreens, technology helps in effectively controlling environment factors to ensure optimum growth with high standards of cleanliness and food safety. An elevated level of productivity will thus not only be achieved but also help in promoting conserved usage of resources such as water, energy and nutrients. In addition, controlled environment agriculture using technology makes it possible to grow microgreens throughout the year despite climatic factors. (Uyory Choe et al., 2018)

Technologies such as advanced monitoring and automation help in proper decision-making in microgreens to ensure consistency in quality and heightened nutrient retention in the microgreens. In turn, it plays a major role in determining food security in urban zones, which experience high standards of land scarcity and increasing demands for food. Implementation of the microgreen farming systems using digital-based and human-free concepts is a significant innovation in the modern agricultural systems. (Sven Verlinden et al., 2020)

Adoption of smart sensing concepts for monitoring along with automated controlling systems ensures efficient management for optimal requirements related to constant cultivation in a pollution-free environment with increased nutrition values with minimized contamination along with optimized water, energy and nutrient utilization. Implementation of these systems supports the concept of sustainable agriculture with an efficient solution for the production of microgreens in a controlled environment based on advanced technologies providing significant support. (N Malligarjunan et al., 2025)

Objectives

- To study the nutritional importance of microgreens.
- To understand the need for human-free microgreen cultivation.

- To highlight the role of digital technologies in monitoring and controlling growth conditions.
- To emphasize sustainable and safe microgreen production systems.

Microgreens and Their Nutritional Importance

Microgreens basically comprise young vegetable and herb seedlings in the cotyledon stage or first leaf stage after germination at approximately 7–21 days. Though young in nature, microgreens possess a very rich nutritional value and hence exhibit a rich source of vital vitamins like C, E, K and beta-carotene and inorganic matter such as iron, potassium, calcium, magnesium and zinc. Microgreens also possess several bioactive and antioxidant agents like polyphenols and flavonoids, which help in reducing stress, tension and inflammation. (Nicole Enssle et al., 2020)

Microgreens also possess several nutritional and medicinal uses like boosting immunity and improvements in cardiovascular and digestive systems to slow down several diseases. Unlike leafy vegetables, a weight of microgreens has apparently established a concentration of micro-nutrients approximately 4–40-fold higher in concentration in microgreens than in leafy vegetables, thus making them a precious functional food product. The microgreens possess a tremendous future potential in slowing down malnutrition in general and in urban settings in particular; in fact, they possess a revolutionary role as optimal sources in fulfilling increased demands of micronutrients in a more economical and eco-friendly manner. (Shiva Dubey et al., 2024)

Challenges in Conventional Microgreen Cultivation

Conventional microgreens cultivation techniques have several critical limitations that are hindering the scalability and feasibility of microgreens cultivation on the large scale commercially. Human dependency is one such critical problem that occurs since most of the operations like sowing, watering, harvesting and sanitation practices are done manually. Microbial contamination is one critical problem associated with microgreens since most of them are grown in an uncontrolled environment with openness to contamination of E. coli and Salmonella easily being contaminated on the seeds, water and mediums on which the microgreens are grown. Water and resources are mostly being wasted during the conventional practices of irrigation and nutrient application. (Shabir Ahmad Mir et al., 2017)

Climate change is one critical problem that is brought by variability of temperatures that negatively affects the temperature and climate sensitive crops like microgreens pertaining to their minute variations of temperatures, rain and climate conditions. Other issues are pest infestation outside the natural environment, microgreens are products with short shelf life vegetables, microgreens post-harvest loss is high in malpractices, microgreens quality is not standard in traditional malpractices, microgreens are less traceable in malpractices. (Michael G Parkes et al., 2023)

Concept of Human Free Microgreen Agriculture

Human-less or minimal intervention micro-green agriculture could be described as a method of growing crops, where the plant growth process could be controlled with less or no human interaction and could be controlled using automated and digital technology. This definition differs from but is also closely associated with Controlled Environment Agriculture (CEA). (Kuanysh Bakirov et al., 2025)

In CEA, controlled environment agriculture, important plant growth parameters like temperature, humidity, intensity of light, CO_2 concentration, availability of water and nutrient supply are controlled in a way that ensures quality and quantity of crops are maintained constantly. In that manner, human-less microgreen agriculture could help control microbial contamination, an important factor in food safety and shelf life, in a considerably minute way. Automation devices like sensors, Internet of things and robotics help in a significant way with management of irrigation, lighting and nutrient supply in a highly accurate manner. (Figen Tasci Durgut et al., 2025)

Smart Sensing and Real-Time Environmental Monitoring

The smart sensing and monitoring of the surrounding conditions have been recognized as a revolutionary factor in modern microgreen farming technology as it employs IoT sensor technology, cloud technology and smart analytics in creating optimal microgreen farming conditions. Highly advanced sensors are designed to measure temperature, humidity, lighting intensity, CO2 levels and nutrients for their concentrations because of their ability to provide accurate real-time data collection and processing through cloud-based software applications. (Waidyaratne et al., 2025)

Remote monitoring functionality and automated notifications enable instant action and adjustment regarding surrounding changes, thus reducing manual intervention to a large extent and minimizing opportunities for any operational error. Automation and intelligence through advanced control systems further boost productivity because of their ability to automatically control watering, nutrient supply and climatic conditions. AI-enabled decision-making algorithms process all sensor data to maintain optimal or ideal growth conditions because of their ability to precisely analyze growth patterns through machine learning-based yield trend predictions. (Maria Castellino et al., 2018)

Smart lighting and energy-efficient solutions promote sustainable farming practices because of their ability to provide optimized lighting solutions enabled by innovative LED lighting applications for enhanced photosynthesis and nutrient accumulation because of their energy-efficient operational nature. These energy-efficient solutions further minimize carbon emissions because of lower power usage. The convergence of sensing technology, automation, and smart lighting systems enables the creation of a data-intensive cultivation environment and makes digital microgreens farming a sustainable and viable solution in urban and controlled agriculture in terms of efficiency, resource management and scalability. (Vito Michele Paradiso et al., 2018)

Environmental Monitoring and Control Systems

It is along this basis that environmental monitoring and control systems are crucial in modern microgreen cultivation through advanced technological interventions for optimal growth conditions. Temperature is carefully managed by climate control systems and sensors to provide optimal thermal conditions that enhance fast germination and growth of the crops. The relative humidity is maintained by monitoring the conditions and employing humidifiers, dehumidifiers, and ventilation systems to optimally remove and prevent moisture-related diseases and microbial contamination of the crops. (Stagnari et al., 2020)

Control of light intensity and duration is simplified by utilizing energy-saving and optimal LED systems that are able to modulate light spectrum, duration and intensity for enhanced photosynthesis and nutrient uptake by the crops. Fertigation systems and management of the nutrient solutions are ensured by automated fertigation systems that use sensors to promote optimal pH, EC and concentrations of minerals and nutrients for appropriate and accurate release and uptake by crops. Air quality is maintained by employing optimal control of CO2 levels, CO2 flow and air filtration systems that enhance respiration and prevent pathogens from being airborne. (Marina Astapova et al., 2021)

Role of Digital Microgreen Farming in Sustainable Future

Digital microgreen production is a significant phenomenon that supports the development of a sustainable future by increasing the strength of all major sustainable factors while dealing with issues posed by contemporary food systems. Environmentally speaking digitally controlled production systems lead to a significant reduction in water usage, nutrient efficiency and pesticide utilization through central monitoring and automation. This immediately reduces ecological footprints. Financial sustainability is ensured by increasing the efficiency levels of production through higher production rate capacity, labor efficiency through automation and reduced manual labor costs, as well as increased production within controlled environment settings. This improves income stability for farmers. Social factors are also strengthened through safer production systems, enhanced availability of fresh and nutritious produce, as well as employment generation within urban agricultural setups. (Rindang Dwiyani et al., 2025)

Digital microgreen production also supports food security within urban settings by allowing production within close proximity to the consumer. This eliminates the need for a longer production chain. The climate-resilience technology is such that it makes it easy to grow the crops regardless of the season and the land. By integrating the use of smart technology and sustainable technology, the digital microgreen farm is the scaling solution for the efficient management of resources, climate-resilience and sustainable agricultural growth and, therefore, is very important for the sustainable agriculture needed for the future. (Shiva Dubey et al., 2024)

Impact on Nutrition and Food Security

Adoption of controlled and technology-based microgreen production systems has a major positive effect on nutrition and food security. Environmental control during microgreen production helps retain better nutrients by reducing exposure to stress conditions like high and low temperatures, insect damage to vegetables, and reduced nutrient composition during vegetable storage. Use of organic methods eliminates pesticide residues in microgreens and reduces human handling, producing safer and cleaner greens with better hygiene levels. (Avinash Sharma et al., 2024)

Microgreen production in controlled environment agriculture ensures release of veggies throughout the year in all seasons to cater to continuous demand for nutrient-rich food. Microgreens are most needed in developing countries like Africa where environmental constraints regarding land availability for cultivation, adverse conditions like variable climate and temperatures during different seasons, malnutrition in humans, and lack of access to fresh veggies are major concerns. Microgreens can play an effective part in fulfilling this demand by producing sufficient microgreens for consumption in urban and peri-urban environments. (Sylvia Y Lee et al., 2024)

Future Perspectives and Emerging Trends

The future of microgreen farming is also becoming increasingly influenced by the incorporation of advanced digital technology that offers greater efficiency and transparency of processes. Fully autonomous farms using AI technology are a rapidly developing area as entire farming processes can be controlled by artificial intelligence systems right from environmental control to harvesting and monitoring of quality with least human labor. Such technology makes extensive use of constant analysis of data to enhance precision and consistency in results. (Kyra Marie Smith et al., 2018)

Another fast-developing area in microgreen farming technology is the increased use of Blockchain technology for ensuring food safety by documenting every stage of food production right from seeds to storage and transportation in a secure manner and in a way that boosts consumer confidence. The use of smart city technology offers even greater possibilities in digital microgreen farming by making use of rooftops, unused lands in urban areas for food production in such a manner that transportation emissions can be completely eliminated. (Gayathree et al., 2019)

Automation advances, modular system design and energy-efficient technologies also contribute to the reduction of costs and enhance scalability, making digital microgreen farming viable for small entrepreneurs and large commercial operations alike. Altogether, these emerging trends position digital microgreen farming as a resilient, future-ready solution that can support sustainable urban food systems and meet the growing global demand for fresh, nutritious produce. (Shabir Ahmad Mir et al., 2017)

Conclusion

This study heavily emphasizes the significance of microgreens, a type of functional food heavy with nutrients, for addressing rapidly increasing nutritional demands and food security challenges, particularly within urban settings.

On one side, microgreens have shown to have values of vital vitamins, minerals, antioxidants and biologically active components far greater than conspectus leafy greens, whereas traditional farming of these crops has its limitations regarding heavy reliance on manual labor, lack of controlled environments, risk of microbial growth, climatic conditions and improper usage of water, energy and nutrients. On the other side, digital-based and human-independent solutions for microgreen farming can provide a plausible fix to these limitations by integration of digital sensing solutions, simultaneous measurement of environments, automation, AI and CEA for accurate measurement and control of vital factors including temperature, humidity, intensity of light, supply of nutrients and purity of air.

These systems greatly improve the level of food safety, hygiene and quality while retaining nutrients and reducing losses in the post-harvest sector by greatly reducing human interaction with the systems. In addition, microgreen farming with the use of digital technology is ideal for sustainable resource management by using optimal inputs and is ideal for production regardless of climatic changes by being suitable for smart city-based agricultural systems.

Indeed, with increasing innovation in autonomous farming using AI technology, traceability using blockchain technology, increased efficiency using low-cost energy solutions, human-free digital microgreen agriculture stands out as a future-proof system for improving the sustainability of the food system for better nutrition for a fast-growing population in cities across the globe.

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