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Sustainable and Inflatable Aeroponics Smart Farm System for Water Efficiency and High-Value Crop Production

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Abstract: Existing smart farming technology faces sustainability challenges due to high costs and environmental pollution. This study introduces a novel, sealed smart farming system utilizing misting technology to address these limitations. The system is designed to efficiently use water and nutrients, making it particularly suitable for high-value crop cultivation in urban environments with architectural constraints. Over a one-month experimental period, we monitored the system's performance in a controlled environment. The methodology included setting up the system and regularly measuring water usage, nutrient delivery, and plant growth metrics. The experimental results showed a significant reduction in water usage compared to traditional methods, with precise control of micronutrient delivery. Additionally, the system's ability to maintain a consistent sealed environment was demonstrated, which is crucial for optimal plant growth. The system's portability and space utilization efficiency were also highlighted as major advantages. Furthermore, the system demonstrated potential for cultivation in extreme environments, such as water-scarce regions, by maintaining optimal indoor conditions for crop growth. Challenges such as nozzle clogging and uneven mist distribution were identified, indicating the need for further research in cartridge design and misting methods. Overall, this smart farming technology shows significant promise for enhancing global food security and contributing to sustainable agricultural development by minimizing water usage and optimizing nutrient management.

Keywords: inflatable smart farm; aeroponics for high-value crops; sustainable system

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1. Introduction

In the face of escalating climate change and environmental pollution, the agricultural sector is under increasing pressure to find sustainable solutions. Smart farming, which integrates Information and Communication Technology (ICT) into agriculture, has emerged as a promising approach to optimizing crop growth environments remotely or automatically, transcending the limitations of time and space [1,2]. The early 2000s saw rapid advancements in sensor and actuator technologies, making smart farming more accessible and cost-effective, thus driving its commercial expansion.

However, the journey of smart farming, particularly indoor hydroponic systems, has not been without challenges. Many companies have faced bankruptcy due to high costs and the inability to compete with the pricing of traditionally grown crops [3–5]. This economic hurdle, coupled with the environmental issues arising from waste solution disposal, has fueled skepticism about the sustainability of smart farming technologies [6–9]. Yet, the relentless progression of climate change, environmental degradation, and groundwater depletion underscores the urgent need for innovative agricultural practices [10–16].

Our study introduces an inflatable and sustainable aeroponics smart farm system designed to address these critical issues. By focusing on the cultivation of high-value crops, our system aims to maximize economic gains while maintaining a stable and uniform internal environment. The enclosed structure of our smart farm isolates crops from external environmental influences, ensuring consistent and reliable growth data [17]. This data-driven approach not only enhances the quality of the produce but also supports economic viability by reducing dependency on unpredictable external conditions [18,19].

One of the key elements in ensuring the sustainability of smart farm facilities is the cultivation of high-value crops to maximize economic gains [20,21]. For the cultivation of these premium crops, it is crucial to maintain a stable and uniform internal environment, and in this context, accurately collected growth data play a vital role. Specifically, to produce high-quality crops, smart farm installations must maintain an isolated, enclosed structure independent from external environmental influences. Such enclosed smart farms are evaluated as effective structures because they minimize variables that could arise from external changes and support research and development of crops through stable data collection. These systems allow for systematic environmental management based on growth data, contributing to a sustainable model that can operate economically and independently from external risks such as climate change and environmental pollution [22,23].

The most widely known type of enclosed smart farm utilizes intermodal containers [24]. These container-based smart farms inherently have high frame costs and lack basic insulation, necessitating additional insulation work. Their complexity of installation and large size makes them difficult to place in standard indoor spaces. An alternative method involves using pre-insulated expanded polystyrene sandwich panels (EPS sandwich panels), which are relatively inexpensive. However, this approach still faces issues, such as energy loss due to gaps between panels and high installation costs [25]. Once installed, these setups are difficult to relocate, underscoring the need for new enclosed smart farm designs that minimize energy loss and simplify installation and relocation while efficiently using indoor space. Such smart farms need to reduce fabrication and installation costs, maximize energy efficiency with airtight structures, and offer flexibility to adapt to various indoor environments.

Ensuring the sustainability of smart farms requires addressing environmental pollution issues. To prevent soil contamination, hydroponic methods such as the Deep Flow Technique (DFT), the Nutrient Film Technique (NFT), and Aeroponics are employed. DFT keeps the roots of the crops fully submerged in nutrient solution for continuous nourishment, while NFT delivers nutrient solution in a thin film to the lower roots, offering the advantage of providing ample oxygen to the root zone. These methods involve simple installation and minimize the impact on crops during technical issues. However, they may cause physiological problems in some crops [26], and the water used can become increasingly contaminated over time, necessitating waste solution management. This increase in waste solution accelerates environmental pollution, undermines the economic viability of smart farms, and requires the installation of costly water purification systems to meet stringent agricultural environmental regulations [27,28]. Additionally, these methods often require expensive iron frameworks to store large volumes of water, significantly increasing the overall system costs.

On the other hand, the aeroponic method uses comparatively less water, which significantly reduces the volume of wastewater produced. This technique achieves high productivity through efficient oxygen and nutrient supply [29–31], making it ideal for cultivating root crops such as ginseng sprouts, seed potatoes, and carrots [32,33], as well as high-value medicinal and functional plants like burdock, nettle, yerba mansa, lavender, thyme, and St. John's wort [34,35]. However, the technical complexities of aeroponics, such as the extensive use of spray nozzles, maintaining spray pressure, ensuring uniformity of spray, high initial installation costs, and the potential negative impact of residual pesticides and fertilizers in the nutrient solution on surface and groundwater, must be considered [36–39]. This paper proposes a new recirculating aeroponic system that addresses these issues by minimizing water use and wastewater production, effectively meets environmental regulations, and provides an economically viable model for cultivating high-value crops.

While numerous studies have explored various smart farming technologies, our research uniquely focuses on the development of an inflatable and portable aeroponics system designed for high-value crops. Unlike traditional fixed structures, our system offers unparalleled portability and ease of installation, making it particularly suited for urban environments and areas with limited space. Therefore, this study develops a new smart farm structure that integrates enclosed smart farming with aeroponic hydroponic methods while addressing the major limitations of current systems, such as production and installation costs, indoor space utilization efficiency, energy loss, wastewater generation, and water use efficiency. This work aims to present a new direction for sustainable smart farm technology. The structure of this paper is as follows: Section 2 provides a detailed description of the proposed smart farm structure; Section 3 presents the experimental results using this structure; Section 4 discusses the implications of the research findings and future topics for discussion; and Section 5 summarizes the conclusions.

2. Proposed Smart Farm Structure: Overall System—Inflatable Aeroponic Enclosed Smart Farm

Figure 1 provides a structural overview of the smart farm system developed in this study. Additionally, Figure 2 shows the system in operation. This system takes in water 'A', nutrients 'B', and power 'C' from external sources to facilitate the growth of plants 'H'. The enclosed structure '1' creates a uniform and controllable growth environment, ensuring independence from external climate variations. Water within the system circulates through two paths, enabling efficient use of water and reuse of nutrients for hydroponic cultivation. The supplied water 'A' and nutrients 'B' are mixed in the right proportions by the Nutrient Mixer '2' to form the nutrient solution needed by the plant roots. The Misting System '3' delivers this solution as fine droplets to the roots located in the growing beds 'D'. Excess solution not absorbed by the roots is collected by the Drainage Manager '4', goes through an internal filter, and is recirculated, with the purified water '$\bar{A}$' being reused to make more nutrient solution. The plants use the absorbed water and nutrients in their metabolic processes, and the water vapor released through transpiration in the leaves is captured by the Air-control System 'E' and recycled back into liquid form.

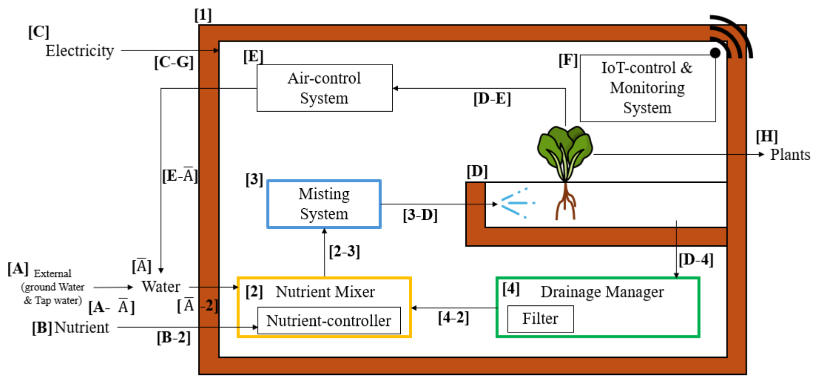


Figure 1. Schematic overview of the closed-system misting smart farming system. This schematic illustrates the key components and resource flow within the closed-system misting smart farming setup.

Figure 2. Operation of crop cultivation after installation of the closed-system smart farm with air injection. The **left** image shows the interior view of the smart farm, highlighting the organized layout and efficient use of space for optimal plant growth. The **right** image shows the exterior view of the smart farm, demonstrating its compact and enclosed design, suitable for various indoor environments.

2.1. Air Structure Shape '1'

As depicted in Figure S1, the inflatable structural frame using a dual-space fabric structure is a key component of the enclosed smart farm, enabling high energy efficiency and cost-effective installation by reducing energy loss. This structure expands upon air injection and occupies the installation space, encasing the entire area in an air layer with a low thermal conductivity of 0.025 W/mK, a unique design feature. The design's integral configuration without gaps at the joints minimizes energy loss and provides excellent insulation performance. The ability to deflate and compress facilitates transportation and installation through restrictive architectural entries, enhancing adaptability on site. Thus, it represents an ideal solution for constructing indoor enclosed smart farms that are easily installable and removable while minimizing spatial constraints and rapidly adapting to indoor environments.

This inflatable structural frame is suitable for various environments, including inside existing buildings and unused shipping containers. Unlike traditional container-based smart farms that require separate insulation work after setting up the external structure, the air-enclosed frame developed in this research comes already surrounded by a high-insulation air layer, eliminating the need for additional insulation efforts. This significantly reduces the cost and complexity of installation, allowing for the immediate commencement of crop cultivation within the smart farm. The application of this structure not only enhances the scalability of smart farm technologies and contributes to increased agricultural productivity but also holds significant value in resource recycling and environmental protection for sustainable farming practices.

In traditional enclosed smart farm systems, there is the inconvenience of having to add separate growing beds and support frames for crop cultivation after the structural frame is installed. In contrast, the air structure introduced in this research is designed as an integrated unit with the outer walls '1' and the internal growing beds 'D' as shown in Figure 1, eliminating the need for additional installation work. This integrated design allows for the simultaneous setup of the cultivation space and growing beds through air inflation, significantly reducing installation time. This also greatly enhances the mobility of the farming facilities, enabling the construction of flexible smart farms that are not limited by location.

The air structure used in this study is based on a drop-stitch fabric that uses tens of thousands of polyester fibers to maintain a fixed distance between the upper and lower fabrics. This unique construction is designed to stably maintain the shape specified by the user upon air injection. The dual-space fabric employed is manufactured by Airbox and features both primary and secondary TPU coatings, providing exceptional durability and resistance to abrasion. Moreover, it exhibits superior resistance to various environmental factors, including ultraviolet light, ozone, oil, chemicals, solvents, and heat [40]. Additionally, the dual-space fabric structure is designed for long-term use, with an expected lifespan of around 10 years under typical usage conditions.

The air structure designed in this study is a multi-panel air structure system, with each panel incorporating at least one air inlet. These panels are manufactured to fit the standard dimensions of a 20-foot shipping container (length 6 m, width 2.3 m, height 2.4 m), allowing for performance comparisons with existing enclosed systems. The size of the structure was determined with consideration of the typical ceiling height of buildings (2.5~2.7 m), and when folded, the dimensions are 2.3 m × 1 m × 0.8 m, making it suitable for movement and placement through doors and elevators. As seen in Figure S2, the structure comprises five main sections, including the ceiling, side walls, front wall, and back wall. To manage minor air leakage, these five sections are designed to be continuously charged through a single air charging device.

The internal cultivation structure in this study consists of a three-tier layout with six growing beds, each 75 cm wide, positioned on either side of a central corridor ranging from 60 cm to 70 cm in width. These growing beds are constructed using the same dual-space fabric material and are directly attached to the walls of the inflatable structure. A 10 cm gradient is set at both ends of each growing bed to induce a unidirectional flow of water. Unlike traditional rigid-material beds, the flexible woven film material used here poses a risk of sagging in the middle of the 6 m long growing beds, potentially impeding water flow and bed functionality. To prevent this, as shown in Figure S3, ropes are attached to the ceiling and the walls of the growing beds to prevent sagging in the center. This structural reinforcement allows the beds to maintain a slight incline of about 1 degree (0.96 degrees), ensuring smooth water flow despite not being made of plastic or metal.

The growing bed design includes specialized cultivation surfaces essential for plant growth. As shown in Figure S4, circular ports with a diameter of 20 mm are arranged at intervals of 12.5 cm horizontally and 15 cm vertically, allowing each growing bed to accommodate up to 185 plants. The cultivation process involves sowing seeds into 30 × 30 mm square sponges, followed by a growth period of approximately 2–3 weeks, after which the plants are transplanted into these circular ports. This structure provides the necessary support during the initial stages of plant growth and ensures adequate space for the root systems during the transplantation process, promoting healthy development.

The integrated doorway in the air structure is positioned in the central panel, creating an opening measuring 60 cm in width and 180 cm in height. This opening is designed like camping doors made from acrylic and plastic materials and can include locking mechanisms such as locks or deadbolts to enhance security as needed. This design maintains the airtightness of the air structure while ensuring accessibility for users and providing security for equipment and plants.

2.2. Water Circulation System '2, 3, 4'

The proposed inflatable enclosed smart farm system in this study adopts a frame maintenance technique reliant on air pressure to minimize structural load. This approach is evaluated to have excellent interoperability with aeroponic methods, which are less sensitive to load compared to other techniques, such as the Deep Flow Technique (DFT) or Nutrient Film Technique (NFT). As depicted in Figure 3, the system employs two types of circulation methods to optimize water use and minimize wastewater production. The first method involves recirculating the nutrient solution not absorbed by the roots in the form of mist. The second method recycles the water vapor transpired by the leaves and absorbed by the roots within the enclosed environment, using an air circulation system that captures and reuses atmospheric moisture. Nutrient circulation is critical for managing the nutrient mix, spraying, and drainage, while air circulation depends on an HVAC system to reuse the moisture in the air. This study focuses particularly on nutrient circulation, offering specific enhancements, and both circulation methods are utilized in experiments to collect and analyze data on water use efficiency. The nutrient circulation system is configured as shown in Figure 1, linking the Nutrient Mixer '2', Misting System '3', and Drainage Manager '4'.

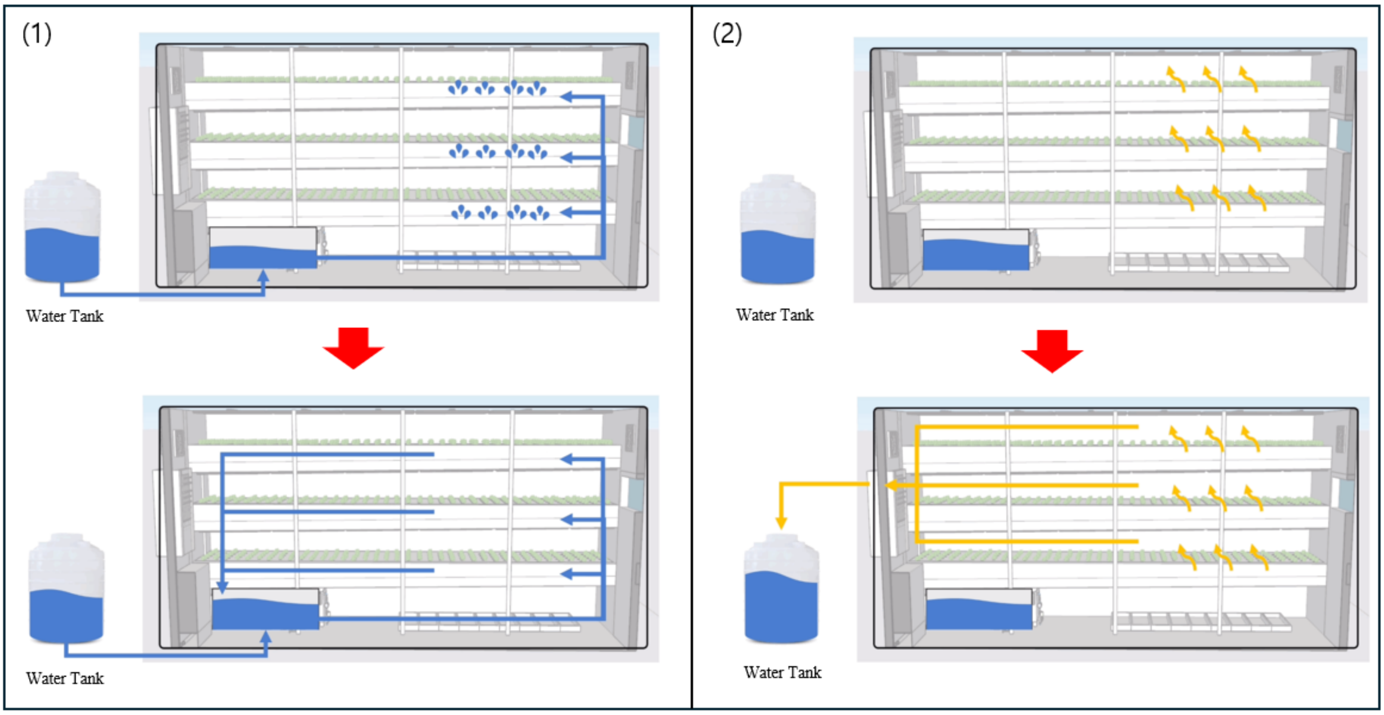


Figure 3. Two water circulation methods in the air-injected smart farm. The first method (**1**) shows nutrient solution circulation, where the nutrient solution is distributed to the plants and then recirculated back to the water tank. The second method (**2**) illustrates water vapor recirculation, where air is injected to facilitate nutrient absorption, and the evaporated water vapor is collected and returned to the water tank.

2.2.1. Nutrient Mixer '2'

The Nutrient Mixer is an apparatus that precisely measures and mixes essential nutrients (such as nitrogen, phosphorus, and potassium) with water to create the nutrient solution needed by plants [41]. In traditional hydroponic systems, the nutrient mixer monitors electrical conductivity (EC) and pH levels, adjusting the solution based on feedback regarding these parameters. To maintain optimal EC and pH, the concentration of the solution is adjusted by diluting or concentrating the water and nutrient ratio as needed. However, as the demand for the solution decreases, especially for micronutrients compared to macronutrients, which require significantly smaller amounts, the precision in mixing becomes increasingly challenging. The dosing pumps currently used in nutrient mixers have a resolution of about 0.1 L and can introduce slight errors, posing a limit to high-precision control. Therefore, there is a need to develop a nutrient mixer system with higher resolution and lower error rates, emphasizing the necessity for a system design capable of more precise control over small quantities of nutrients.

In this study, to address the need for high precision in controlling small amounts of nutrient solution, a nutrient cartridge method using inkjet printer cartridge technology is introduced. Inkjet printers distribute ink with high resolution in pico-liter units, a crucial feature for precise printing tasks. Typically, in agriculture, 1 L of nutrient solution is diluted with 1000 L of water. However, if the dilution ratio needs to be achieved with only 500 milliliters of water, the total required amount of fertilizer would be 500 microliters.

When the concentration difference between macronutrients and micronutrients exceeds 1000 times (often even greater), the necessary control amount can reach 500 nanoliters. By applying the inkjet cartridge method, it is possible to precisely prepare extremely diluted solutions, not just at 1000 times dilution, but up to 10,000 times. This approach provides the high resolution and precision required in nutrient manufacturing and offers innovative possibilities for creating more complex and finely tailored nutrient solutions.

The physical properties of ink suitable for inkjet technology are defined as having a viscosity of 5–6 centipoise (cP), surface tension of 28–30 dyn/cm (dynes per centimeter), and particle size of no more than 500 nanometers. For water-based inks, viscosity can be adjusted using glycerin. The print head nozzles on the cartridges enable ink ejection ranging from 1.5 to 80 pico-liters. When using nutrient solutions as a substitute for ink, it is crucial to carefully adjust and align properties like viscosity, surface tension, and particle size to meet these standards. However, the current research prioritizes initially assessing the basic feasibility of using nutrient solutions instead of ink in the print heads. This involves ensuring that the physical conditions of the nutrient solutions meet the requirements of inkjet printers and that the properties of the nutrient solutions are compatible with the operation of the print heads. This foundational research is vital not only for adapting the nutrient solutions to the inkjet printer's specifications but also for verifying the reliability and efficiency of the overall system when using these modified solutions.

The nutrient mixer hardware system, designed for precision nutrient formulation, utilizes a modified common printer setup as depicted in Figure 4. The system incorporates an Epson XP600 print head (Seiko Epson Corporation, Suwa, Japan) and a motherboard equipped with a Xilinx ZYNQ XC7Z010 processor (AMD, Santa Clara, CA, USA), capable of managing six different types of nutrient fertilizers. Each type of fertilizer, as specified in Table 1, is mixed with distilled water and filled into cartridges measuring 18 cm × 5 cm × 8 cm, each holding up to 720 milliliters.

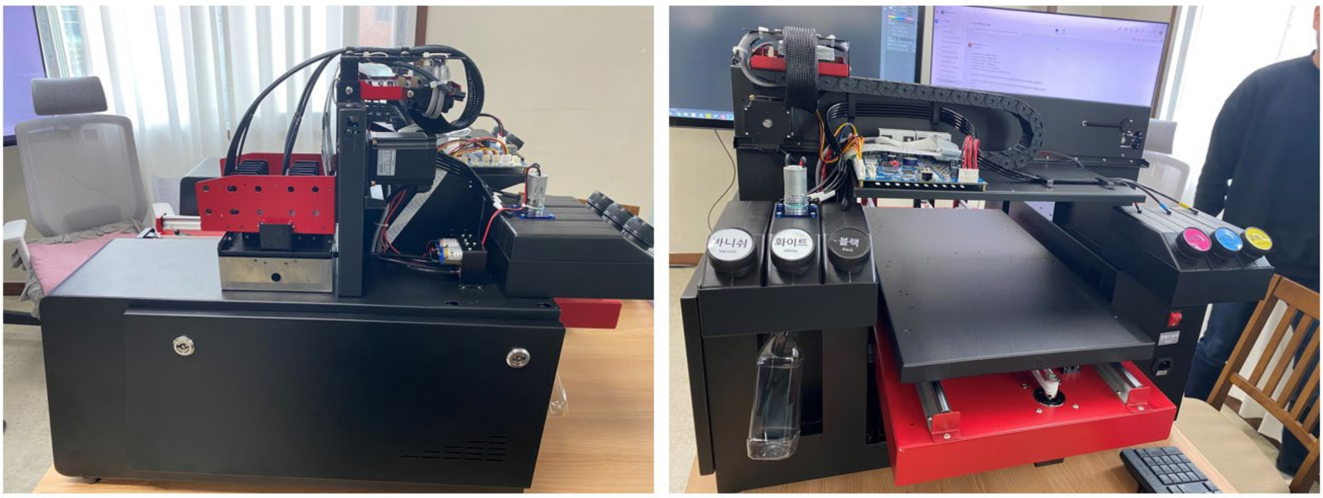


Figure 4. Modified inkjet printer for precise nanoliter volume control in nutrient solution cartridge.

Table 1. The six salts used, with their concentrations and dilutions. Each salt was diluted to 100 mL with the following amounts: 100 g, 20 g, 20 g, 6 g, 50 g, and 20 g.

Nutrient Solution Ingredients	Solubility (Based on 25 °C)
$Ca(NO_3)_2$ (Calcium nitrate)	121.2 g/100 mL
KNO_3 (Potassium nitrate)	35.7 g/100 mL
$MgSO_4$ (Magnesium sulfate)	30 g/100 mL
K_2SO_4 (Potassium sulfate)	12 g/100 mL
$MgNO_3$ (Magnesium nitrate)	71 g/100 mL
$NH_4H_2PO_4$ (Ammonium dihydrogen phosphate)	36 g/100 mL

The operation process involves creating a file for nutrient solution preparation using graphics software like Adobe Photoshop (v.25.9) and then executing multi-color printing in CMYKWV format, as illustrated in Figure S5. This innovative system allows for precise monitoring of the quantity and distribution of the sprayed nutrient solutions, providing the real-time data essential for accurate nutrient compounding and distribution.

2.2.2. Misting System '3'

The Misting System is a pivotal component of aeroponic hydroponics, designed to supply plant roots with fine water droplets. This system integrates pipes fitted with nozzles that directly spray nutrient solutions produced by the Nutrient Mixer onto the roots. This method uses relatively less water compared to traditional hydroponics, significantly reducing water load. Despite its low water usage, the overall water consumption of the system remains high, and it faces technical challenges such as nozzle clogging, nozzle stability, and the ability to evenly distribute mist across the roots. Consequently, further research and development are crucial to enhance the efficiency and performance of the Misting System.

This study introduces a misting system integrated with 'dry fog' technology within an inflatable enclosed smart farm. 'Dry fog' refers to an ultra-fine mist with particle sizes of less than 10 μm, capable of remaining airborne for an extended period. This characteristic allows for achieving uniform distribution using fewer nozzles than traditional aeroponic systems, thus resolving issues related to the overuse of nozzles and simplifying the overall system. Two technological approaches to generating 'dry fog' were considered: the first uses an air- and water-driven two-phase (fluid dynamics) nozzle spray method, and the second employs ultrasonic transducers to create and dispense mist.

Two-Fluid Nozzle Spray

The study employs a two-phase nozzle spray system, commonly used in industrial settings for dust removal and in agriculture for pest and disease control [42]. As illustrated in Figure 5, these nozzles operate by generating a mist through the supply of water at low pressure under a constant air pressure setting [43]. Installed within the inflatable enclosed smart farm's cultivation area, this system explores the efficacy and potential improvements of using 'dry fog' mist for cultivation. By maintaining uniform and continuous humidity conditions within the growing environment, the system optimally hydrates plant roots, significantly enhancing the efficiency of hydroponic farming.

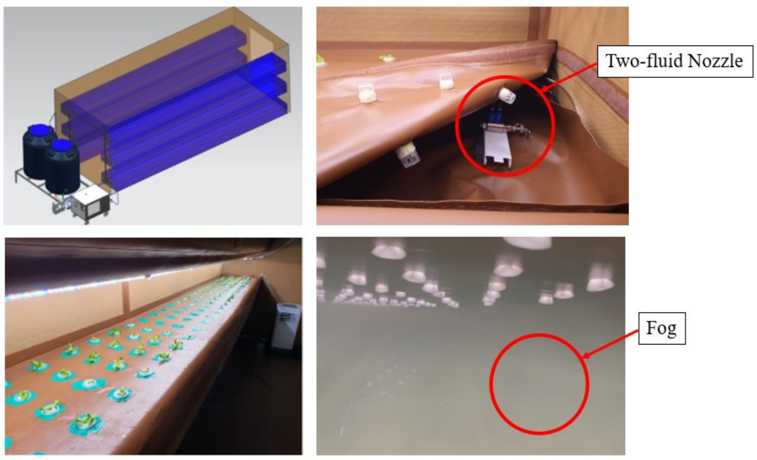


Figure 5. Installation of atomizing nozzles in the cultivation tier of the air-structure smart farm frame. The **top-left** image shows the overall system design with water tanks and misting infrastructure. The **top-right** image captures the installed atomizing nozzles. The **bottom-left** image displays the cultivation area with plants. The **bottom-right** image illustrates the dry fog environment created by the atomizing nozzles.

Ultrasonic Transducer Misting Technique

The study incorporates an ultrasonic transducer misting technique that uses high-frequency vibrations to finely atomize water, creating a ‘dry fog’. This ‘dry fog’ inherently lacks fluidity, and as depicted in Figure S6, a flow fan was installed in the chamber where the ‘dry fog’ forms to use the fan’s aerodynamics to convey the fine mist into the cultivation beds. To ensure uniform distribution of the mist within the cultivation area, gas guide tubes were utilized, and their effectiveness was experimentally assessed. The used 8 mm polycarbonate pipes span 5.6 m, equipped with 65 outlets, with each outlet’s angle adjusted to achieve the optimal spray pattern. Fluid dynamics analysis was simplified using ANSYS software (2024 R1). The cultivation experiments conducted with the ultrasonic transducer misting system installed in the air-structure frame beds demonstrated differences in bed performance depending on the presence or absence of the guide tubes.

2.2.3. Drainage Manager ‘4’

The Drainage Manager system is a critical component for handling water that has passed through plant roots, incorporating a filtration mechanism to remove root debris and other contaminants [44]. The reclaimed solution might contain undigested organic materials from the initial misting process, which can promote the growth of anaerobic bacteria, leading to solution contamination and unpleasant odors. To address this issue, this study utilizes a combination of a biofilter, capable of decomposing organic material, and a mechanical filter. This integrated filtration system effectively enhances the removal of organic compounds, thereby significantly reducing water contamination levels and providing an efficient solution for maintaining the purity of the irrigation solution.

To maximize the effectiveness of the biofilter, it is crucial to design the system in such a way that it maximizes contact time between the water and the microbes. As depicted in Figure 6, the biofilter is designed to make the drainage flow through the longest possible path inside the filter box, thereby maximizing the contact period between the organic material and the microbes. This is achieved by filling a vertical circulating filter box with a porous filtration medium, integrating it with bacterial filter media and a six-layer filtering system to enhance fluid dynamics and facilitate the efficient removal of organic matter. The actual installation is shown in Figure S7. A small submersible pump installed at the bottom of the filter box continuously circulates the drainage, reducing the concentration of organic material in the water while promoting microbial life and reproduction. This design of the biofilter effectively utilizes the biological activity of microbes during the water purification process, contributing to the removal of organic substances within the nutrient solution and improving water quality.

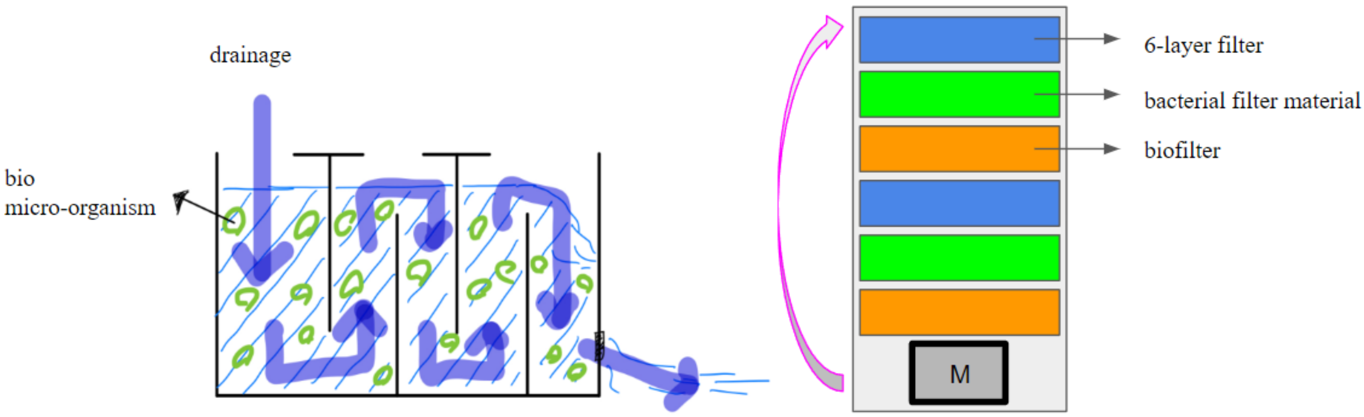


Figure 6. Design structure of the biofilter and conceptual diagram of biofilter implementation. The **left** image depicts the internal layout of the biofilter, showing the flow of drainage and the action of bio microorganisms within the system. The **right** image provides a detailed view of the multi-layered filtration system, including a 6-layer filter, bacterial filter material, and the biofilter itself.

The nutrient solution circulation system necessitates continuous and rapid water cycling; however, the biofilter's processing is inherently time-consuming. Within this system, the mixed solution can become contaminated during the circulation process, often necessitating complete disposal of the contaminated solution. To address this, the study proposes a new Drainage Manager that omits path '4-2' from Figure 1, allowing for the immediate re-spraying of the collected water and thus reducing the volume of water in circulation. This innovative Drainage Manager employs a centrifugal spraying method that does not collect the residual water directly after spraying but re-sprays it immediately, thereby reducing the volume of waste solution. The centrifuge uses a spinning propeller to draw water and project it onto a separation screen, creating particles ranging from 20 to 100 µm in size.

To validate the functional performance of this system, a vertical cultivation platform measuring 2 m in height, 6 m in width, and 35 cm in depth was constructed as shown in Figure 7, with a central centrifugal sprayer installed for the cultivation experiments. The experiment involved growing 250 leafy vegetables for three weeks, approximately 20 days post-seeding. The data obtained from this experiment demonstrated that this drainage management method could reduce the amount of water recaptured while ensuring normal plant growth, thus confirming its potential efficacy.

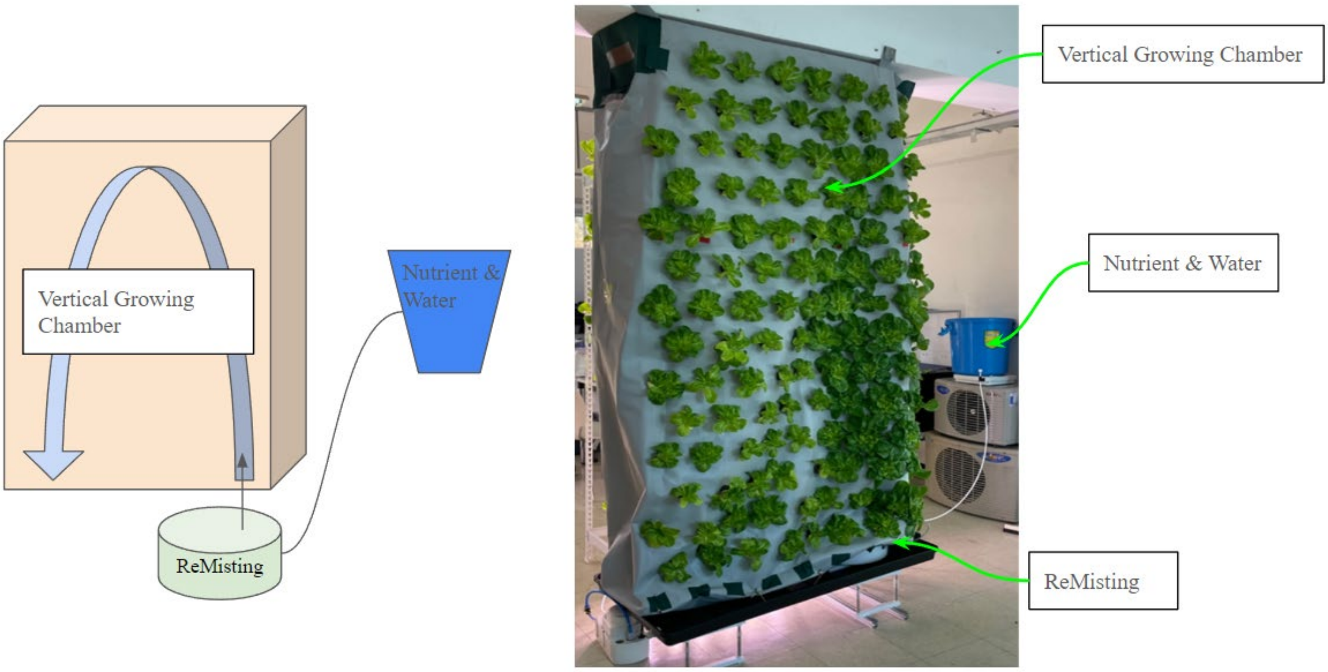


Figure 7. Performance testing of the new drainage manager in vertical cultivators. The **left** diagram illustrates the vertical growing chamber and the remisting system. The **right** image displays the actual vertical growing chamber with plants.

3. Experimental Results

3.1. Innovative Nutrient Mixer Cartridge System

The Nutrient Mixer system developed in this research focused on precise nutrient dilution control. Experimental results demonstrated that the Nutrient Mixer could accurately control dilution amounts down to nanoliter precision when combining six primary fertilizers with water. The precise dilution and combination of fertilizers within the cartridge did not directly deliver nutrients to plant roots but were controlled accurately during the dilution process. As depicted in Figure S8, this process achieved an effect resembling a fine mist dispersion.

This system, as shown in Figure S9, was able to precisely control the necessary concentration of fertilizers through nanoliter-scale dilution. This capability of precise dilution control demonstrates the potential to scientifically adjust and optimize the nutrients required by plants in hydroponic cultivation. The data obtained from the experiments confirmed that this system could very precisely control and provide the trace nutrients needed for plant growth. This represents a potential in smart farm technology to implement customized nutrient supply schedules tailored to different plant species.

However, during the experiment, as shown in Figure S10, clogging of the print head nozzles occurred due to crystallization reactions in the nutrient solution, which disrupted the normal operation of the system. This issue highlights the structural vulnerabilities of the nozzles and calls for experimental modifications in the composition and concentration of the nutrient solution under various conditions to minimize nozzle clogging. These results underscore the need for further research and development to solve potential issues in nutrient mixer technology while significantly enhancing the ability to micro-manage nutrients in smart farms.

3.2. Misting System

3.2.1. Two-Fluid Nozzle Misting

In the experiments using the two-fluid nozzle for misting in a 6 m long cultivation bed, the feasibility of achieving a uniform mist distribution was assessed. The introduction of an external air injection misting method in an enclosed space aimed to enhance the efficiency of water, nutrients, and oxygen supply. However, difficulties were encountered in achieving uniform mist distribution across the entire cultivation bed. The primary issue arose from the backflow phenomenon, caused by injecting external air into a closed space. The two-fluid nozzle misting technique involves drawing in external air to finely atomize water into microscopic particles. With all four sides of the cultivation area sealed, continuous misting led to air blockage at the opposite end, as depicted in Figure S11, resulting in reduced misting efficiency and visibly wilting plants farther from the mist source.

Additionally, technical issues were identified with the compressor that supplied the air necessary for the continuous operation of the two-fluid nozzle. It was observed that oil leaking from the air compressor mixed with the air and was sprayed along with the mist onto the plant roots, as evidenced in Figure S12. This contamination significantly degrades the quality of the mist and poses a serious concern, being potentially harmful to plant health.

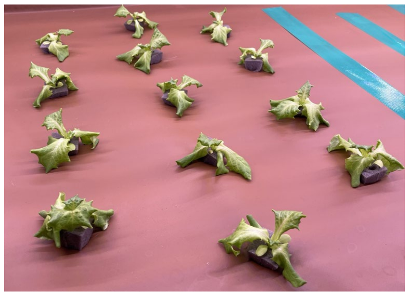
These findings underscore the critical design parameters and operational considerations necessary for misting system implementation and design. Specifically, managing contaminants within the system that could affect misting efficiency and plant health is highlighted as a vital area of research for optimizing cultivation systems.

3.2.2. Ultrasonic Transducer Mist Spraying

In this experiment, the efficiency of the ultrasonic transducer misting system was evaluated through tests designed to assess the difference in cultivation performance across a 6 m long growing area with and without the use of guiding tubes. As shown in Table 2, the setup including guiding tubes resulted in uniformly distributed misted nutrients across the cultivation area, leading to notably healthier plant growth.

On the other hand, in the scenarios without guiding tubes, plant growth significantly declined further away from the misting point, especially on the side opposite to the misting point where growth issues were prominently worse. These results suggest that even in ultrasonic misting systems, the introduction of external air can cause backflow issues, significantly obstructing the efficient delivery of nutrient mist across the growing area.

Table 2. Comparison of lettuce growth depending on the presence of ultrasonic atomizer induction ducts in ultrasonic atomizer mist spraying method.

	Overall View of Cultivation	Spray Start Position	Opposite the Spray Start Position
Guide Pipe (O)			
Guide Pipe (X)			

Nevertheless, the introduction of guiding tubes in the ultrasonic misting setup allowed for consistent and healthy plant growth throughout the cultivation area. This uniform nutrient distribution demonstrates the potential for enhanced cultivation performance through optimized control of growing conditions and nutrient solutions. Future research should explore fine-tuning the cultivation environment and optimizing nutrient mixtures to maximize growth efficiency based on these system configurations.

3.3. Drainage Manager

In this study, the performance of the drainage system utilizing a centrifugal humidifier was evaluated to minimize water circulation while enabling re-misting. This system was applied in a vertically constructed grow tent made from a regular tent fabric, and the experiment tested the minimum amount of water required for re-spraying and the viability of cultivation over the period. The experimental setup, as illustrated in Figure 7, involved a nutrient solution diluted with water in a reservoir, which was then sent to the humidifier and sprayed inside the vertical grow system, with the remaining solution not returning to the reservoir. The results demonstrated that the plants could be sustainably grown using only about 40 L of water over three weeks, highlighting the system's efficiency without the implementation of the air circulation detailed in Figure 3.

During this experiment, a new variable identified was the correlation between the amount of light provided by artificial sources and plant growth. As depicted in Figure 8, although Area A received more light compared to Area B under artificial lighting, the growth performance was notably poorer in Area A. This observation suggests that the amount of water absorbed by the plants through their roots is determined by the photosynthesis and transpiration processes, and insufficient water supply via misting can lead to plant dehydration. Plants located on the periphery, receiving less light, utilized more water for their growth and consequently showed better development. This result implies that optimizing the relationship between water supply to the roots and lighting in a hydroponic system using fine mist can establish an ideal cultivation environment.

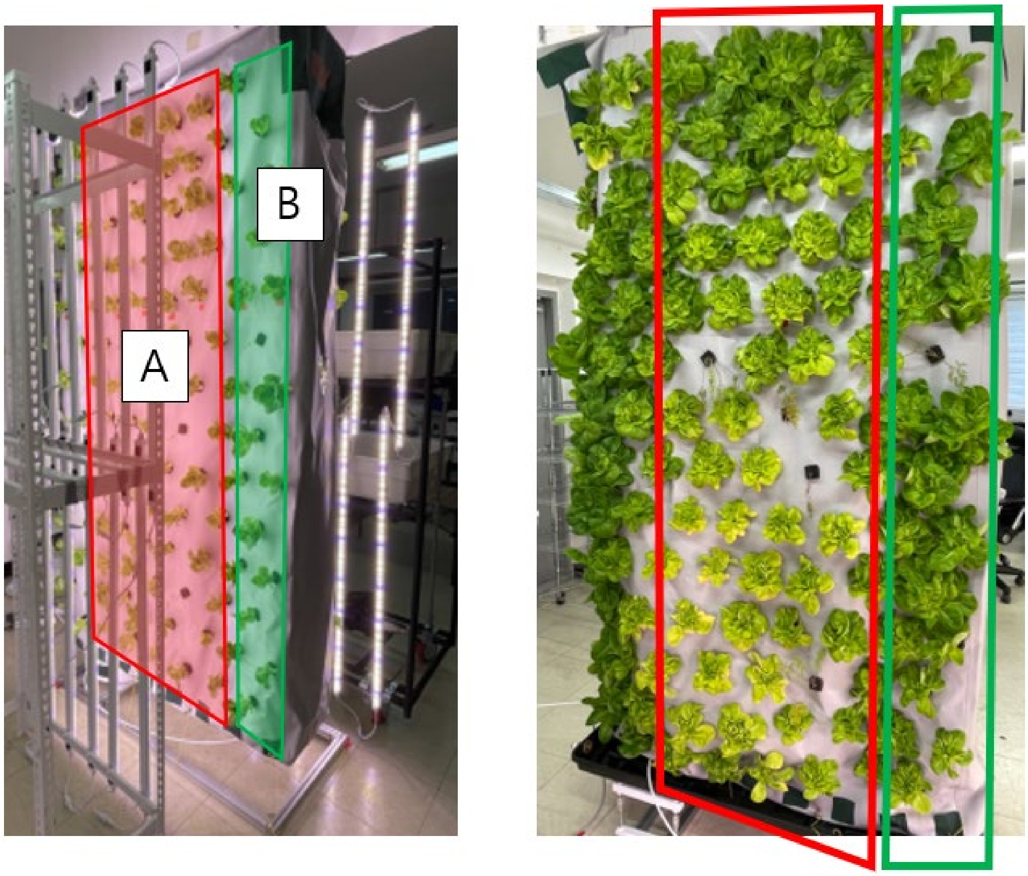


Figure 8. Representation of the difference in light supply quantity by color on one side of the vertical cultivation bed with installed artificial light in the vertical cultivator equipped with recirculation system. "A" Red indicates a relatively higher supply, while "B" green indicates a relatively lower supply of light.

The system tested in the experiment could accommodate a total of 250 crops and used about 40 L of water during the three-week cultivation period, equating to approximately 0.16 L per plant. Assuming a planting distance of 15 cm, it would be possible to cultivate 49 plants per square meter. Comparing this to traditional field cultivation data from the Jeju Agricultural Technology Center, where water usage is significantly higher, the system demonstrated a water savings of about 93.5%. Utilizing this system within an air-inflated enclosed smart farm allows for water harvesting through air circulation, projecting a 99% reduction in water usage compared to open-field agriculture.

3.4. *Air-Injected Enclosed Mist Spraying Smart Farm UAE Experiment Cultivation*

In this paper, compared to other cultivation methods such as nutrient solution culture and film culture, less water can be used, and the system is specialized for extreme outdoor environments with water scarcity and high adaptability. Therefore, experimental cultivation was conducted in the Middle East, in the United Arab Emirates, to confirm the cultivation potential, internal environmental control performance as shown in Figure 9, and water use efficiency. For this purpose, cultivation and nutrient solution data, electricity and water consumption data, and internal and external environmental data were collected. By analyzing the collected data, we aim to find more efficient environmental conditions. During the experiment, the entire system was set up as shown in Figure 1, and a Nutrient Mixer, Misting System, and Drainage Manager were installed using the existing method. Data were collected for one cultivation cycle of 21 days to analyze the efficiency of nutrient solution circulation and air circulation. As shown in Table 3, the total amount of water collected and reused from the air during one cultivation cycle was approximately 520 L, and the additional water required was measured to be 176 L.

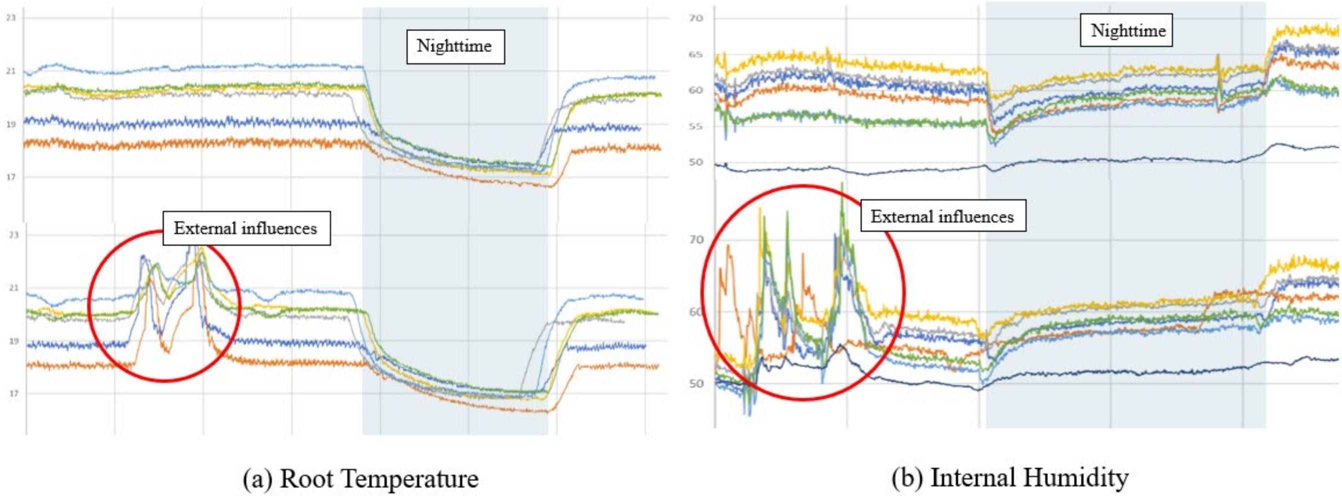


Figure 9. Monitoring system comparison graphs: These graphs demonstrated that, in the absence of external factors, the system maintains stable environmental conditions within the sealed system. The lines in different colors represent the data from six different growing beds.

Table 3. Water usage.

Air Circulation: Water Harvest	Usage of Water
521 L	176 L

Assuming an average biomass of 100 g per plant and considering that leafy vegetables consist of 95% water in their bodies, the total number of crops that can be cultivated in an air-injected enclosed smart farm is calculated to be 1100 plants. Therefore, during the cultivation period, leafy vegetables would absorb approximately 105 L of water. The remaining 70 L can be attributed to water loss due to internal and external air circulation and system ingress. Minimizing such water loss could lead to innovative advancements in water efficiency, as only the water needed for absorption into plant bodies would be required, eliminating the need for further additional water. This demonstrates the potential for revolutionary advancements in water efficiency through innovative technologies.

4. Discussion

While the enclosed smart farming system shows great promise, several technical issues must be addressed to maximize its potential. These include nozzle clogging in the nutrient solution head, difficulties in achieving uniform mist distribution, and the physical limitations of devices hindering precise control of the nutrient solution. Future research should focus on refining the nutrient cartridge design to address nozzle clogging and accommodating actual water and dilution needs.

The misting system's oiliness issue also requires attention, as it hinders nutrient and moisture absorption by the roots. Research should explore methods to thoroughly remove oiliness and develop fine particle circulation misting methods for enclosed spaces. These innovations would significantly reduce water usage and simplify installation processes.

Addressing environmental pollution in smart farming involves minimizing water circulation and exploring mechanical and biological methods for redistributing water within the cultivation area through a drainage system. Additionally, further research on airflow circulation methods is needed to optimize performance and efficiency based on differences in plants' respiratory rates [45]. Studies on fluid dynamics to create gas flow within the enclosed smart farming system will ensure consistent internal environments and increase water usage efficiency by recycling atmospheric water.

To provide a comprehensive understanding of its economic viability, we conducted a cost comparison between our inflatable smart farm system and traditional container farms. The analysis included initial setup costs, operational expenses, and yield outputs. The Table 4 highlights the differences.

Table 4. Comparison of cost and operational efficiency between container farms and inflatable smart farm systems.

Comparison	**Container Farms**	**Inflatable Smart Farm**
Water Requirement	4 tons/month (Soil-based)	0.2 tons/month (Aeroponics)
Installation Location	Requires substantial infrastructure; not feasible for indoor installation	Operable without substantial infrastructure; feasible for any indoor space
Weight	Approximately 8 tons	Approximately 0.4 tons
Installation Time	Approximately 3 months	Installable within 0.5 days
Cost	Approximately USD 80,000	Approximately USD 25,000
Installation Costs	Additional costs for transportation (trucks, cranes), site preparation, and infrastructure	No additional installation costs
Additional Costs	High, due to land preparation, building permits, and infrastructure setup	No additional costs

It is challenging to compete with open-field crops in terms of cost under normal conditions because crops grown in indoor environments are significantly more expensive. However, considering the increasing frequency of extreme weather events and environmental pollution, the interest in indoor smart farms is rising. Despite the ongoing costs for maintenance and research, our proposed system offers a unique solution. It can be folded and stored in places like warehouses and deployed during emergencies. In situations where traditional farming is not feasible, the higher cost of crops grown in our system becomes justified as it ensures food production during crises.

In practical terms, the competitive advantage of our system lies in its flexibility and rapid deployment capability, making it a critical tool for food security in crisis situations. By addressing both environmental sustainability and emergency readiness, our inflatable smart farm system presents a viable alternative when outdoor farming is compromised. Furthermore, additional validation will be conducted in Jordan as part of a KOICA ODA project.

5. Conclusions

In conclusion, our study successfully developed an enclosed smart farming system aimed at addressing the challenges of traditional hydroponic systems by utilizing a misting-based approach. This system facilitates the efficient cultivation of high-value crops while optimizing water and nutrient usage, making it particularly suitable for urban environments with architectural constraints. The experimental results demonstrated the system's effectiveness in optimizing water circulation efficiency and precisely controlling the trace elements required by plants. Additionally, its mobility and spatial efficiency were highlighted as significant advantages.

Furthermore, we validated the system's potential in extreme environments, such as water-scarce regions, by maintaining optimal conditions for crop cultivation through indoor environmental control. This underscores the significant contribution of smart farming technology to sustainable agriculture and water conservation efforts. Future research should continue to refine these technologies, ensuring their applicability across diverse settings and enhancing their contribution to global food security.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14114931/s1, Figure S1. Shape of the Air Structure Before and After Air Injection. Volume decreases by approximately 17.25 times. Figure S2. Air Structure Formed by Connecting Five Panels of Drop-Stitch fabric to Form a Container-shaped Cuboid. Figure S3. Air Structure Shelf Frame Maintaining a Slope of Approximately 1 Degree to Facilitate Drainage Functionality of the Cultivation Tier, connected to the Ceiling to Maintain the Slope. Figure S4. A View of the Cultivation Tier from the Ceiling, Showing the Cultivation Surface. The Holes with Openings at the Top and Bottom Represent Each Cultivation Tier, with Two Tiers Visible in this Image. Figure S5. Output File Design for the Nutrient Cartridge Operation. Figure S6. Installation of Ultrasonic Vibrator Sprayer in the Cultivation Tier, with Flow Tubes Installed Inside to Ensure Uniform Spraying. Figure S7. Fabrication of the Biofilter. Figure S8. Verification of Normal Operation of Nutrient Cartridges. Figure S9. Nanoliter Spray Volume for Each of the 6 Fertilizers Controlled via Cartridges. Figure S10. Clogging of the Solution Cartridge Head Nozzle. Figure S11. Test Results of Mist Spraying Cultivation Using Impinging Nozzles Inside the 6m Wide Horizontal Cultivation Stage of the Airtight Type Smart Farm. Figure S12. Residual Oil Stains Inside the Cultivation Stage After Using Impinging Nozzle Spraying. The presence of oil residue is a crucial issue that must be addressed when cultivating plants using impinging nozzles, as oil residue can severely hinder the absorption of nutrients and moisture by the roots.

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