Integrated Drip Irrigation and Temperature Control System for Strawberry Cultivation in Tabio, Cundinamarca

Sistema integrado de control de temperatura y riego por goteo para el cultivo de fresas en Tabio, Cundinamarca

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Abstract

This research paper explores the problem of strawberry crop losses caused by frost in specific areas of Tabio, Cundinamarca (Colombia), which leads to a significant decrease in both production and fruit quality. The primary objective is to design and implement an integrated drip irrigation and temperature control system that protects strawberry crops against low temperatures, thereby enhancing their productivity and sustainability.

The project development included a review of existing solutions, interviews with strawberry cultivation experts, and an analysis of farmers' perceptions regarding the adoption of new agricultural technologies. Additional challenges related to market acceptance of the product were identified, including competition, customer-perceived value, and logistical difficulties in implementing technologies across different regions. Based on the collected information, an automated system was designed that integrates temperature and humidity sensors, drip irrigation, and thermal control, with its performance evaluated through tests under simulated frost conditions. The results showed potential improvements in plant protection and greater efficiency in water use. It is concluded that the implementation of this system can help reduce frost-related losses and increase agricultural productivity, representing a technologically viable and easily adoptable alternative for local farmers.

Keywords
Agricultural automation, temperature control, strawberry cultivation, frost, agricultural IoT, drip irrigation, environmental sensors, agricultural technology

Resumen

Este trabajo de investigación explora el problema de las pérdidas en cultivos de fresa causadas por heladas en áreas específicas de Tabio, Cundinamarca (Colombia), lo que provoca una disminución significativa tanto de la producción como de la calidad de la fruta. El objetivo principal es diseñar e implementar un sistema integrado de riego por goteo y control de temperatura que proteja los cultivos de fresa frente a las bajas temperaturas, mejorando así su productividad y sostenibilidad. El desarrollo del proyecto incluyó una revisión de las soluciones existentes, entrevistas con expertos en el cultivo de fresa y un análisis de las percepciones de los agricultores sobre la adopción de nuevas tecnologías agrícolas. Se identificaron desafíos adicionales relacionados con la aceptación del producto en el mercado, como la competencia, el valor percibido por los clientes y las dificultades logísticas para implementar tecnologías en diferentes regiones. Con base en la información recopilada, se diseñó un sistema automatizado que integra sensores de temperatura y humedad, riego por goteo y control térmico, cuyo rendimiento se evaluó mediante pruebas en condiciones de escarcha simulada. Los resultados mostraron mejoras potenciales en la protección de los cultivos y una mayor eficiencia en el uso del agua. Se concluye que la implementación de este sistema puede ayudar a reducir las pérdidas por escarcha y a aumentar la productividad agrícola, lo que representa una alternativa tecnológicamente viable y fácilmente adoptable por los agricultores locales.

Palabras clave:
Automatización agrícola, control de temperatura, cultivo de fresas, heladas, IoT agrícola, riego por goteo, sensores ambientales, tecnología agrícola

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Introduction

Strawberry crops in the Bogotá savanna, particularly in the municipality of Tabio, face significant challenges due to extreme climatic phenomena such as frost and events associated with the "El Niño" phenomenon, which reduce water availability and lead to substantial agricultural production losses [1]. These factors are compounded by traditional, inefficient irrigation practices and a low level of technological advancement in the region, which increases the risk of economic losses and decreases farmers' productivity [1].

Over the past decade, several studies have developed automated irrigation systems and IoT-based agricultural technologies to optimize water resource usage and improve production efficiency. For example, Guale [2] designed a prototype of an automated irrigation system that utilizes a sensor network to measure soil moisture and control water consumption, employing the Scrum methodology as an agile development approach. Similarly, Valenzuela and Ojeda [3] developed an intelligent prototype for automated irrigation control in potato crops, achieving a significant reduction in water consumption without compromising soil moisture. Other studies, such as Pérez Monsalve's [4], have demonstrated that implementing IoT technologies in greenhouses can optimize critical factors, including temperature and lighting, thereby enhancing crop productivity.

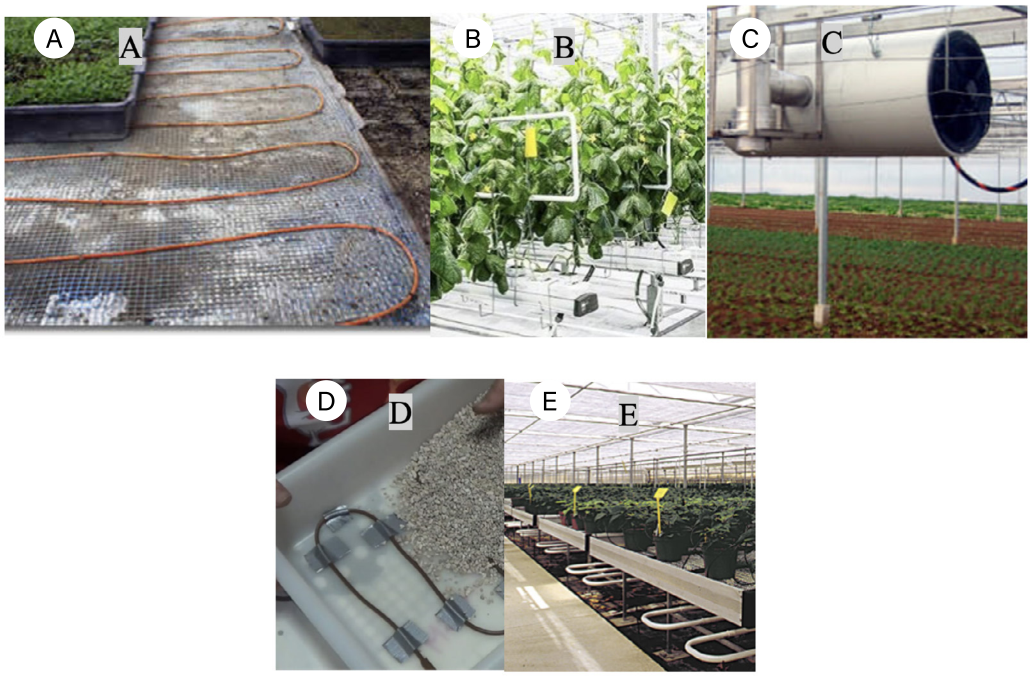
Specifically in strawberry cultivation, multiple projects have incorporated monitoring and automated control technologies. Recent studies [5], [6] have implemented wireless sensor networks to measure environmental variables such as humidity, temperature, pH, and conductivity, demonstrating improvements in irrigation efficiency and strawberry production in regions of Ecuador and Colombia. These advances highlight the positive impact of using microcontrollers, solenoid valves, and sensors for agricultural process automation, with results that include productivity increases of up to 50% and water consumption reductions exceeding 40% [7].

In addition to academic solutions, numerous patents focus on frost prevention and improving crop productivity in cold climates. These include plant-based compositions to protect crops against low temperatures [8], hot-air blowing systems [9], [10], trellis structures for irrigation and thermal control [11], [12], and methods for periodically heating the air in crops to enhance fruiting [13]. These innovations demonstrate the diversity of available approaches, ranging from the use of protective nanoparticles to mechanical heating devices and cold-air barriers [14].

During the development of this research, the main agricultural heating methods used worldwide were analyzed, as shown in Fig. 1: (A) radiant soil heating, using buried polyethylene pipes with water temperatures up to 40 °C; (B) crop heating, with steel or aluminum pipes suspended above the plants, reaching up to 50 °C; (C) greenhouse air heating, based on overhead steel pipe networks at temperatures up to 90 °C; (D) bed heating, with pipes placed on the ground to radiate heat to the roots and aerial parts of the plant; and (E) bench heating, used in potted crops on aluminum supports, with polyethylene pipes reaching up to 79 °C.

Additionally, the optimal conditions for strawberry cultivation were reviewed, which include well-drained soils, temperate climates resistant to frosts as low as –20 °C, and the need to avoid excessive rainfall during the harvest season.

Figure 1. Agricultural Heating Methods Used Worldwide: (A) Radiant Soil Heating, (B) Crop Heating, (C) Greenhouse Air Heating, (D) Bed Heating, (E) Bench Heating



These research efforts and technological developments have led to significant advances in agricultural automation and frost mitigation; however, most focus on partial solutions or on contexts different from strawberry cultivation in the Bogotá savanna. Therefore, there is a clear need for an integrated system that combines drip irrigation with an efficient and adaptable thermal control mechanism tailored to the specific conditions of Tabio, enabling crop protection against frost while sustainably improving agricultural productivity.

Based on the problem described, the following research question is posed: How does an integrated system of soil temperature control, automated irrigation, and IoT-based monitoring affect strawberry cultivation compared to conventional farming practices that do not incorporate these technologies?

General Objective

To develop and implement a comprehensive and sustainable technological solution that enhances the growth of strawberry crops in Tabio by means of an automated irrigation system equipped with sensors for continuous monitoring and optimization of crop conditions to maintain an optimal temperature.

Specific Objectives

- To conduct a state-of-the-art review on crop condition optimization, particularly on methods to maintain adequate temperature in strawberry crops monitored with various sensors and the use of drip irrigation.
- To diagnose the main climatic and operational issues that affect strawberry crop productivity.
- To design an irrigation system that integrates appropriate technologies for the precise and efficient distribution of water throughout the strawberry crop, minimizing water waste.
- To implement an efficient agricultural heating mechanism based on water vaporization or superheated water.
- To design a thermal control system that maintains a suitable temperature throughout the year using implemented sensors.
- To adapt the irrigation system for combined use with the heating system, utilizing the same pipelines for fluid circulation.
- To build a prototype of the irrigation system in a pilot area of the crop in Tabio and conduct tests to evaluate its efficiency and effectiveness.
- To evaluate the impact of the system on harvest quality, productivity, and efficient use of water resources.
- To analyze the thermal, hydraulic, and energy performance of the system through simulations, pilot tests, and loss studies.
- To document the entire process of system design, development, and implementation, providing a benchmark for similar projects in other regions.
- To assess the use of renewable energy sources, such as solar panels, to ensure a sustainable supply of electrical power.
- To validate the effectiveness of the system in the field through a pilot test on a strawberry crop plot.
- To establish technical guidelines that enable the replicability of the system in other regions.

Materials and Methods

The project was carried out in the municipality of Tabio, Cundinamarca (Colombia), an agricultural area with high strawberry production, characterized by a cold climate and frequent exposure to frost. In the initial stage, a literature review was conducted on drip irrigation technologies and temperature control systems applied to crops sensitive to low temperatures. This phase was complemented with semi-structured interviews and surveys directed at local producers and strawberry management experts to identify the main technical and economic needs related to the implementation of automated agricultural technologies.

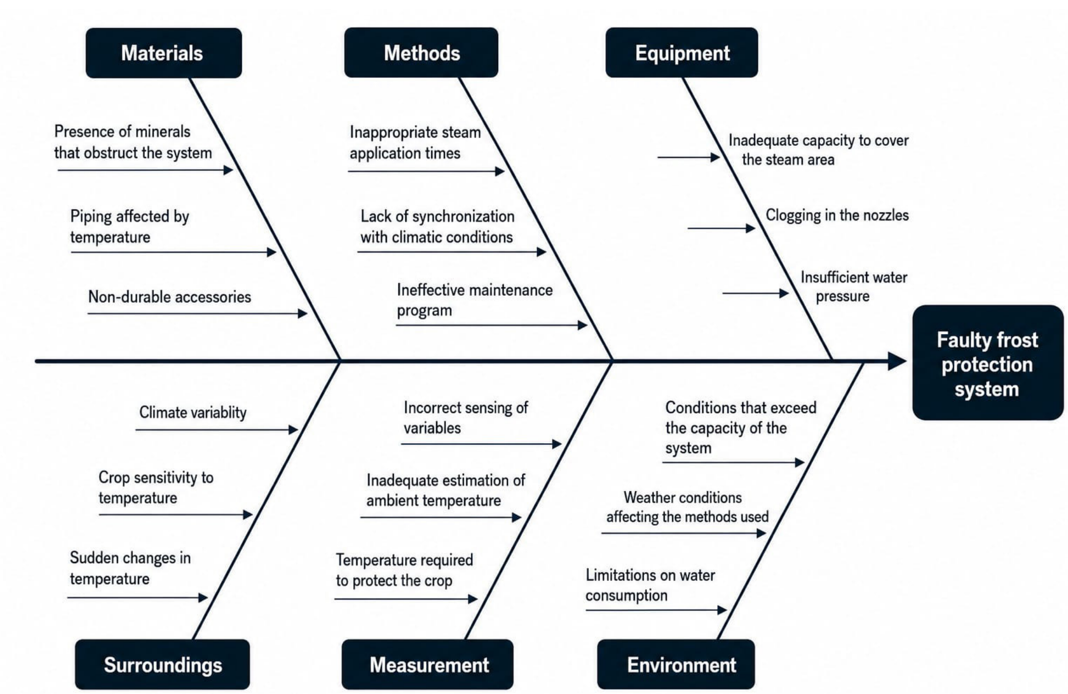
The designed system integrates soil temperature and humidity sensors connected to a programmable ESP32 microcontroller, which is responsible for data acquisition and actuator management. Drip irrigation was implemented using PVC pipes and electronically controlled valves, while the thermal control mechanism consisted of a water vaporization system designed to increase soil temperature during frost events.

For the design stage, a general system diagram was developed, incorporating component selection based on efficiency, cost, and availability, as well as programming a control algorithm that utilizes predefined temperature and humidity thresholds. The system performance was tested under simulated low-temperature conditions, recording variations in soil temperature and actuator responses.

The study did not involve experimentation with humans or animals; therefore, informed consent was not required. Surveys conducted among farmers helped identify barriers and opportunities for adopting the proposed technology, including investment costs, the need for technical training, and the perceived added value in agricultural production.

Failure Analysis and Action Plan. To identify critical factors that could affect the operation of the frost protection system, a cause–and–effect diagram (Fig. 2) and a Pareto chart (Fig. 3) were developed. Factors considered included system design, quality of materials and components, operating procedures, preventive maintenance, and staff training. The analysis revealed that approximately 20 % of the causes were responsible for 80 % of the consequences, highlighting the importance of proper operation, constant supervision, and preventive maintenance of the system.

Figure 2. Cause-and-Effect Diagram



To identify irregularities and areas for improvement, and define an action plan to prevent economic or productive losses caused by failures or malfunctions in the agricultural heating system, a Pareto chart was developed. The 80/20 principle states that 20 % of the causes are responsible for 80 % of the consequences (Table 1).

Table 1. Pareto Chart

Causes	Frequency	Cumulative Frequency	Percentage	Cumulative Percentage
1. System design	51	51	39.84 %	39.84 %
2. Materials and components	33	84	25.78 %	65.63 %
3. Operating procedures	23	107	17.97 %	83.59 %
4. Preventive maintenance	18	125	14.06 %	97.66 %
5. Staff training	3	128	2.34 %	100.00 %

The selected categories are based on both the Ishikawa diagram and the analysis of the surveys conducted:

System Design refers to the configuration and layout of the pipes and devices in the heating system. Design errors may result in poorly heated areas or inefficiencies in heat distribution.

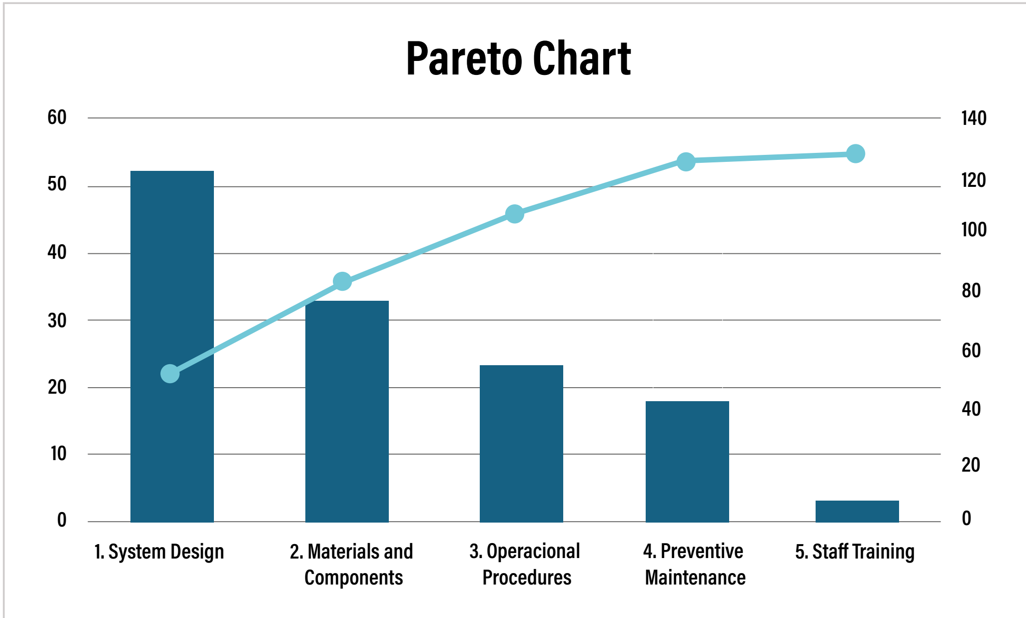
Materials and Components reflect issues related to the quality of the materials used in pipes and equipment, such as corrosion resistance or seal failures that may cause steam leaks or pressure loss.

Operating Procedures refers to the management and operation of heating system control techniques. Errors in operating methods may cause overheating, pipe damage, or failures in heat distribution.

Preventive Maintenance refers to the maintenance of system components, including mechanical, electrical, and steam flow control aspects. Lack of proper maintenance can lead to unplanned shutdowns and costly downtime.

Staff Training represents issues related to improper system handling due to inadequate training. Poorly trained staff may fail to recognize or prevent critical situations, such as overheating or leaks.

Figure 3. Pareto Chart



The design and implementation of the system were organized using a Gantt chart (Fig. 4), in which the project stages were scheduled: research on agricultural heating methods, analysis of alternatives (hot water spray vs. superheated water vapor), system design in CAD software, material acquisition, assembly, sensor integration, testing, adjustments, and optimization. The critical path (Fig. 5) was identified as the sequence of activities with zero slack that determines the total duration of the project.

Figure 4. Gantt Chart

Weeks	1–2	3–5	6–8	9–11	12–13	14–17	18–20	21–26	27–30
Task 1 Brainstorming		Agricultural heating methods							
Task 2 Option Research			Analysis of methods: hot water spray vs. superheated water vapor						
Task 3 System Design (CAD)			System design of pipelines, mechanisms, and control systems in CAD software						

Weeks	1–2	3–5	6–8	9–11	12–13	14–17	18–20	21–26	27–30
Task 4 Material Acquisition			Strawberry crop planting	Materials and components required for system construction					
Task 5 System Assembly	Prototype development and initial results collection				Mounting of pipelines, mechanisms, and control systems				
Task 6 Sensor Integration						Mounting of pipelines, mechanisms, and control systems			
Task 7 System Testing					Fluid flow testing		Evaluation of system performance and effectiveness under real conditions		
Task 8 Adjustments and Optimization								Document preparation	
Task 9 System Evaluation									System testing

Finally, a flowchart (Fig. 6) was designed to describe the process of verification and automatic control of the system. The software enables the input of predefined limit values for strawberry cultivation, provides real-time monitoring of temperature and humidity, and activates control valves to maintain optimal operating conditions.

Figure 5. Critical Path

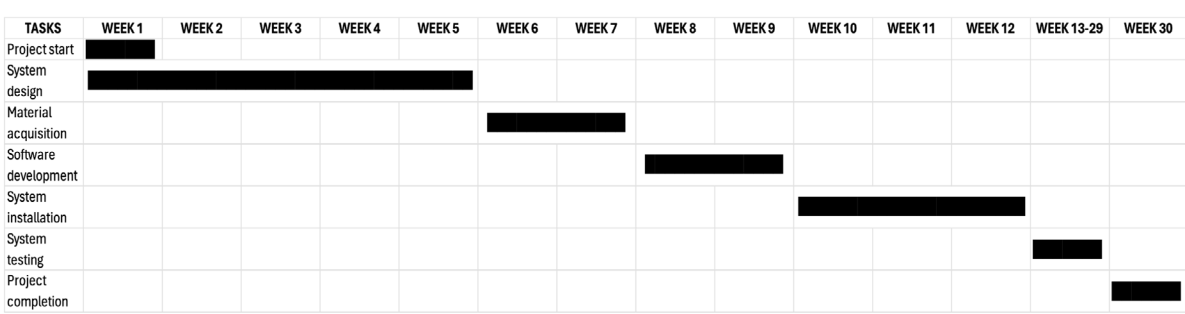
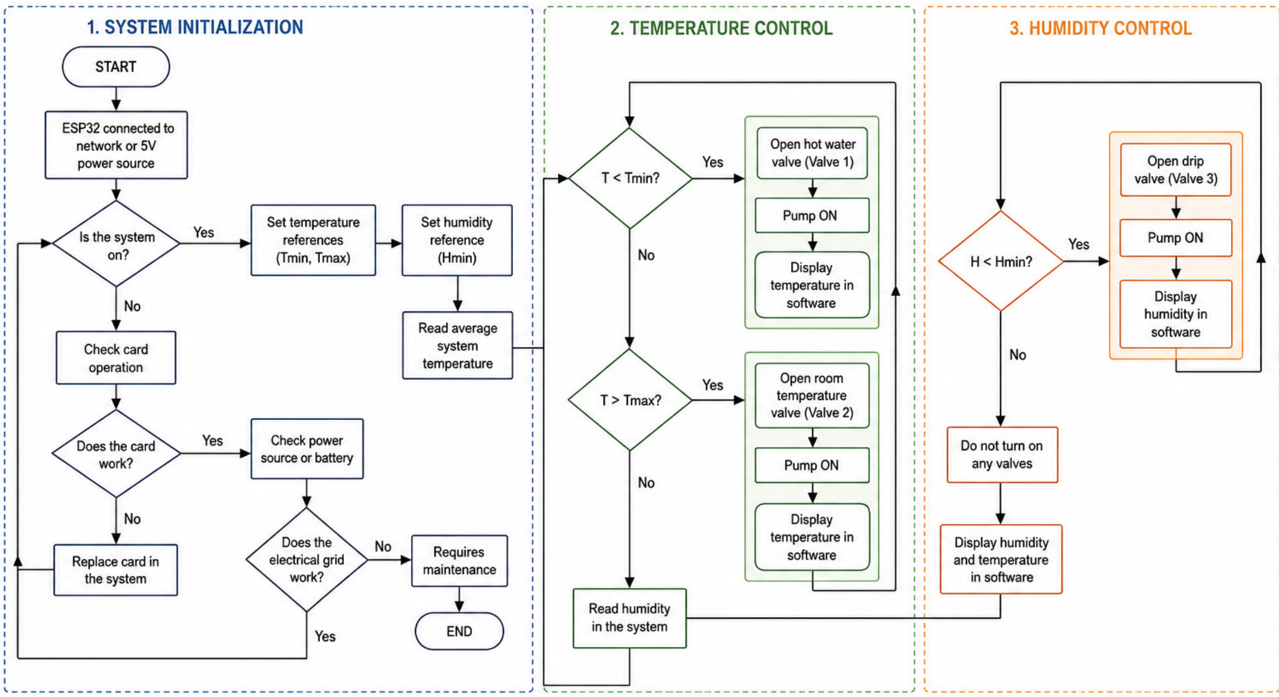


Figure 6. System Flowchart



The first part shows that when the system is turned on, a functionality check is performed. Once verified, the designated software for the system allows the input of permitted values. It was designed this way to be used for any type of crop; however, the software includes initial data with predefined limits for strawberry crops, which are the focus of this research. The same process applies to the system's humidity. Once the system maintains an optimal temperature, it continues to update. If any irregularity occurs, the system activates one of the three valves to control the desired variable temperature or humidity.

Results and Analysis

The development of the integrated irrigation and thermal control system was validated in three main phases: (i) surveys of users and experts, (ii) design, calculations, and simulations, and (iii) implementation of a field pilot to evaluate performance.

Surveys for Users and Experts

Two data collection instruments were applied, targeting different stakeholder groups:

Survey for farmers (users): It was administered to strawberry producers from the municipality of Tabio and its surrounding areas, who represent the potential end-users of the system. The questionnaire included 39 Likert-scale questions (1 = strongly disagree, 5 = strongly agree) regarding ease of use, economic feasibility, expected benefits, and willingness to adopt automated irrigation and thermal control technologies. Figs. 7 and 8 show some of the results obtained from these surveys.

Figure 7. Summary of the Responses to Questions 1–6

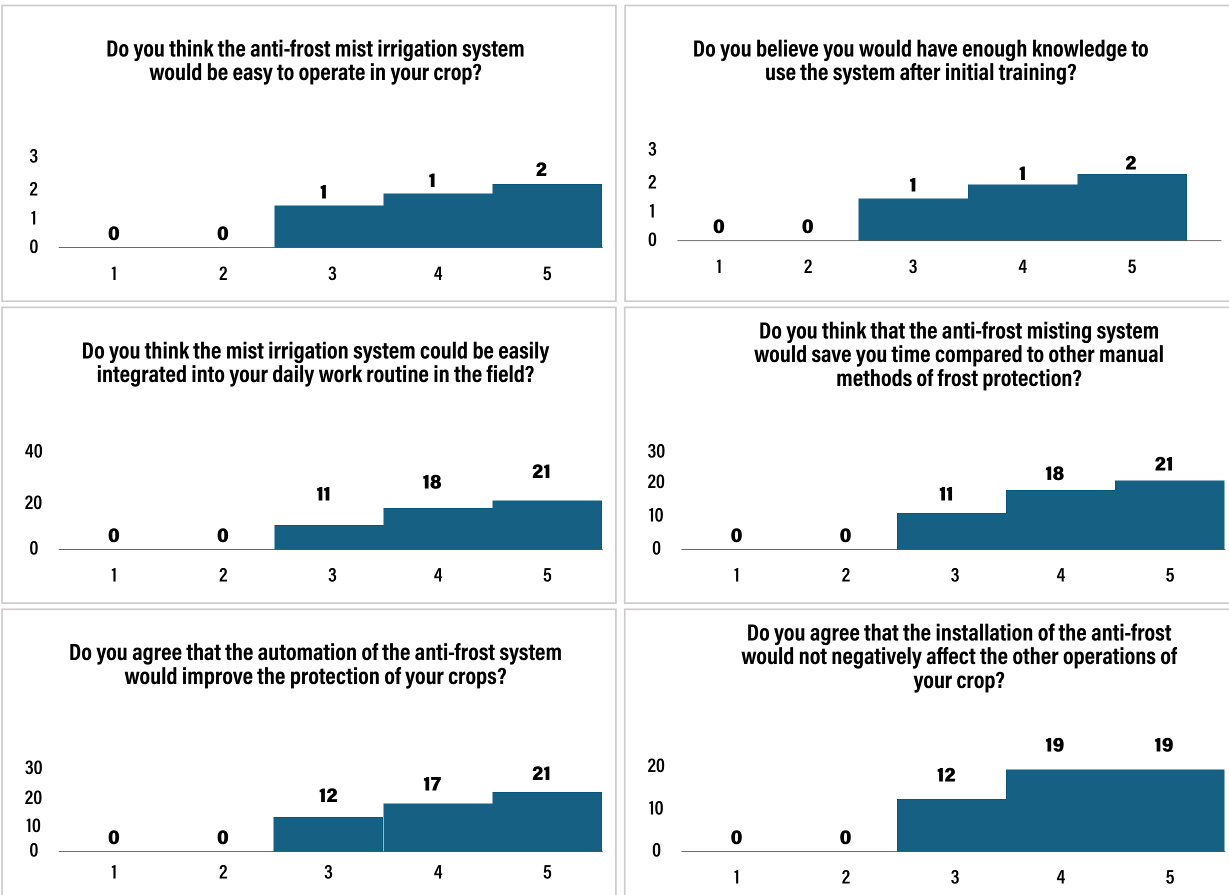
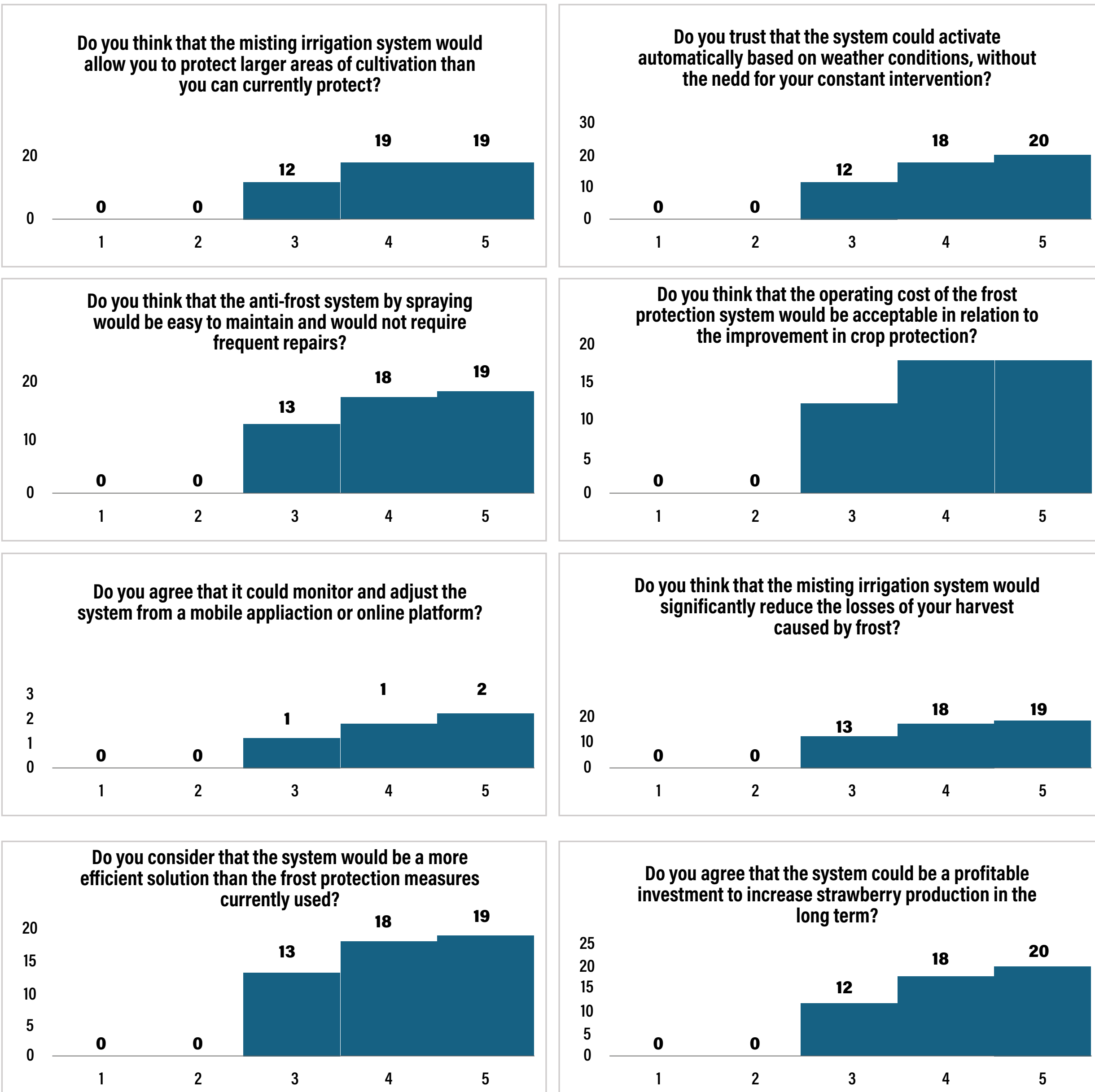


Figure 8. Summary of the Responses to Questions 7–14

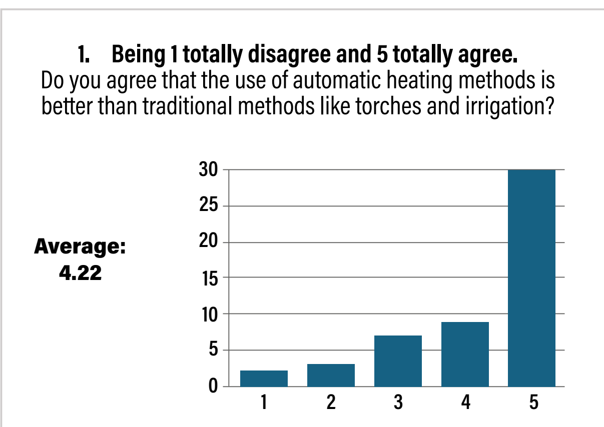


The results showed high acceptance of the automated system, with more than 80 % of respondents considering it easy to operate and compatible with their agricultural routines. Additionally, 78 % stated that automation would improve frost protection and reduce crop losses. Regarding economic feasibility, 75 % believed that the operating cost was acceptable in relation to the productivity benefits. However, 42 % expressed some uncertainty about using mobile applications for monitoring, highlighting the need to provide digital training to facilitate the adoption of technology.

Furthermore, participants believed that the system could protect larger cultivation areas, improve strawberry quality, and significantly reduce frost-related losses, while also representing a profitable long-term investment. Nevertheless, some farmers expressed concern about the use of mobile applications or online platforms due to limited connectivity and the lack of digital tools in rural areas, indicating the need for additional training and simpler control alternatives. Overall, respondents appreciated that the system creates a favorable microenvironment without negatively affecting other agricultural tasks and can be adapted to different terrains and climatic conditions, making it an efficient and technologically viable solution for their crops.

Survey for experts: It was administered to agricultural engineers and technicians specialized in cold-climate crops, with experience in strawberry cultivation management and the implementation of agricultural technologies. This survey, comprising 20 questions, assessed the technical feasibility, efficiency, and safety of various agricultural heating methods, as well as the relevance of integrating automated systems with renewable energy sources (Figs. 9 and 10).

Figure 9. Summary of the Responses to Questions 1 and 2



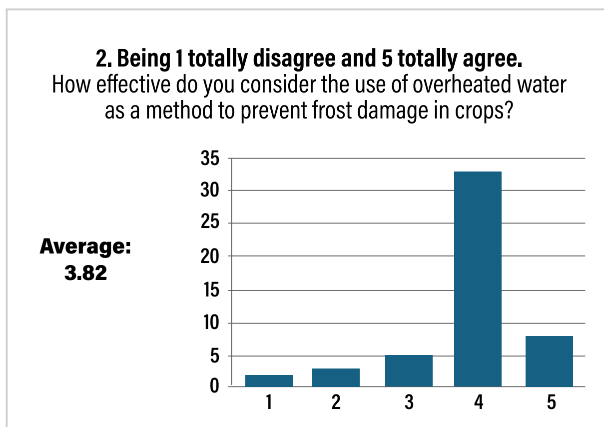
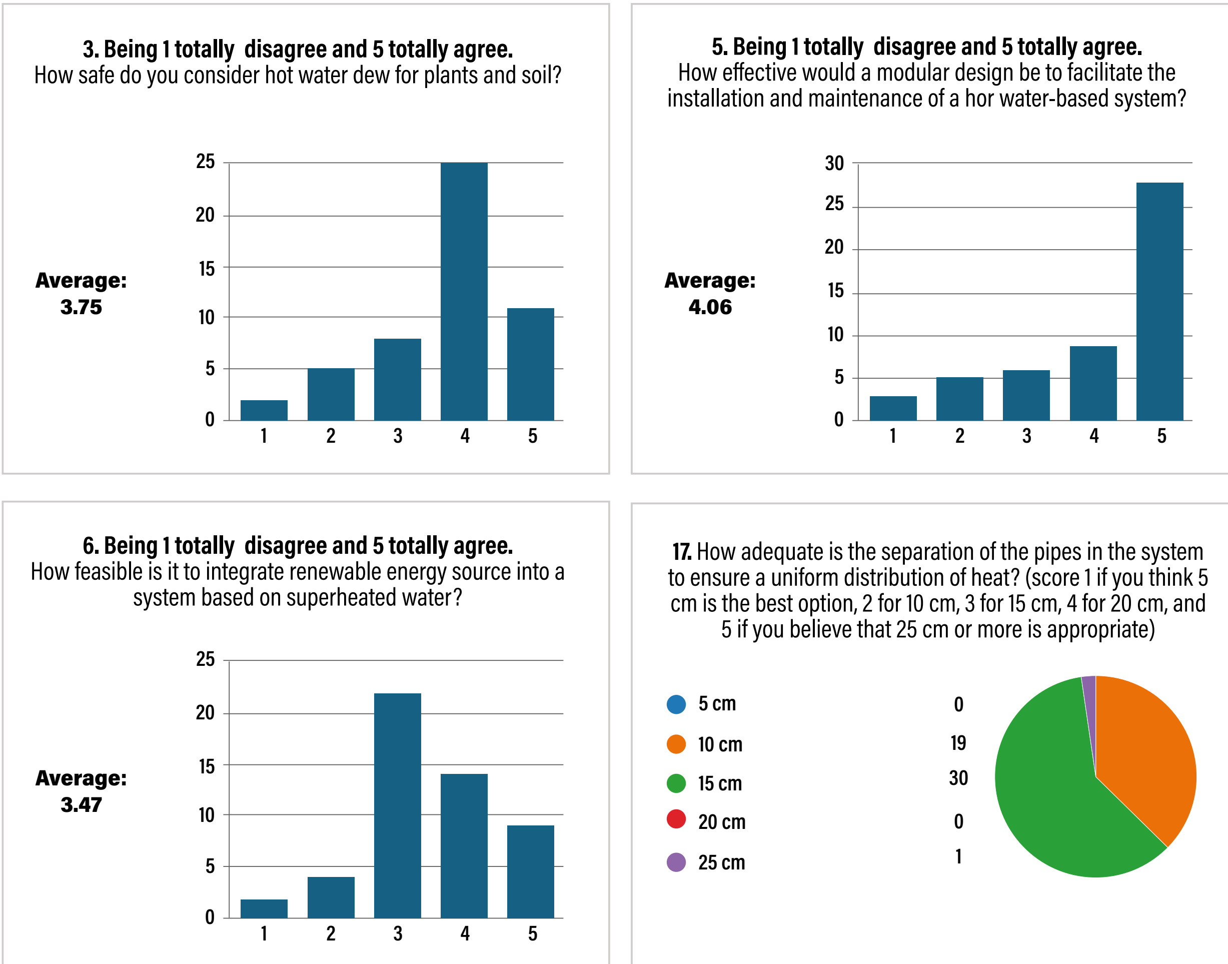


Figure 10. Summary of the Responses to Questions 3, 5, 6, and 17

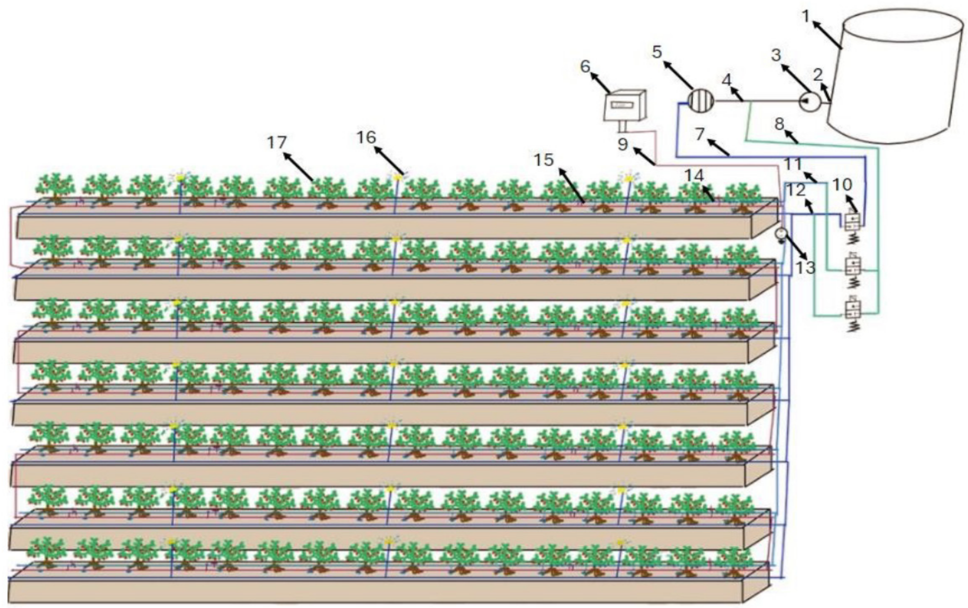


The results of the survey conducted among agricultural engineers and crop management experts showed a clear preference for implementing automated technologies for frost protection. A total of 78 % of participants stated that automatic heating methods are more efficient than traditional ones, indicating a positive attitude toward adopting innovative solutions. Additionally, the use of superheated water was considered effective and safe by 80 % and 70 % of respondents, respectively, reinforcing its viability as a technical alternative. The modular design of the system received an average rating of 4.2, while the integration of renewable energies obtained a score of 3.5, showing interest in scalable and sustainable solutions. Moreover, most experts agree that a pipe spacing of around 15 cm provides better thermal distribution, a key aspect for system efficiency. Among the improvement suggestions, proposals such as using biodegradable thermal sheets and geotextiles to cover the soil stood out, reflecting a concern for sustainability and efficiency in crop protection.

System Design, Calculations, and Simulations

Based on the results obtained, a hydraulic and thermal system was designed, consisting of 21 nebulizers and 192 drippers, sized to maintain the soil temperature above 4 °C during frost events. The initial sketch is shown in Fig. 11.

Figure 11. System Sketch



No.	Item
1	Water tank
2	Pipe connecting the tank to the pump
3	Pump
4	Pipe connecting the pump to the heater
5	Heater
6	Control panel
7	Pipe connecting the heater to the solenoid valves
8	Pipe connecting the pump to the solenoid valves
9	Control line and sensors
10	Solenoid valve
11	Drip irrigation pipe
12	Nebulization pipe
13	System power supply
14	Humidity sensor
15	Temperature sensor
16	Nebulization nozzle
17	Strawberry plant

- A minimum flow rate of 1.38 m^3/h (1385 L/h) was calculated for the efficient operation of the system (Eqs. 1–19).

$$h = a\left(\frac{|T_\alpha - T_o|}{H}\right)^{0.25} * P_{atm}^{0.5}\left[\frac{w}{m^2 * C}\right] \quad (1)$$

$$h = 111.3\left(\frac{|20 - 0|}{0,6}\right)^{0.25} * 0.737^{0,5} \quad (2)$$

$$h = 229.6\left[\frac{w}{m^2 * C}\right] \quad (3)$$

$$\frac{1}{u} = \frac{1}{229.6 * 1} = \frac{1}{\left[\frac{w}{m^2 * C}\right]} \quad (4)$$

$$u = 229.6\left[\frac{w}{m^2 * C}\right] \quad (5)$$

$$Q = u * A * \Delta T * E \quad (6)$$

$$Q = 229.6 * 35 * 20 * 7200 \quad (7)$$

$$Q = 1.1572 * 10^9 J \quad (8)$$

$$Q_s = C * m * \Delta T \quad (9)$$

$$Q_s = 4181 * 3.785 * 20 \quad (10)$$

$$Q_s = 316502 \frac{J}{gal} \quad (11)$$

$$Q_L = L * m \quad (12)$$

$$Q_L = 334 * 3.785 \quad (13)$$

$$Q_L = 1264190 \frac{J}{gal} \quad (14)$$

$$Q_T = Q_L + Q_s \quad (15)$$

$$Q_T = 1580692 \ \frac{J}{gal} \tag{16}$$

$$C = \frac{\frac{Q}{Q_T}}{Time} \tag{17}$$

$$C = \frac{\frac{1.1572 * 10^9 \ J}{1580692 \ J \ \frac{J}{gal}}}{2 \ H} = \frac{732 \ gal}{2 \ H} \tag{18}$$

$$C = 332 \ \frac{gal}{Hour} = 1385 \ \frac{L}{H} \tag{19}$$

- The hydraulic and thermal design included the analysis of head losses (Eqs. 20–51) and the selection of a pump with a power of 0.34 HP (Eqs. 52–63).

$$Cross\text{ - }Sectional\ area = \pi \left(\frac{\text{Diameter}}{2}\right)^2 \tag{20}$$

$$A_T = 0{,}0001775 \ m^2 \tag{21}$$

$$Flow\ Rate = \frac{Q}{A_T} \tag{22}$$

$$V = 1{,}9718 \frac{M}{Seg} \tag{23}$$

$$R_e = \frac{V * D}{\mu} \tag{24}$$

$$R_e = 23954{,}26 \quad Turbulent\ Flow \tag{25}$$

$$Friction\ Factor(f) = \frac{0.25}{\left(log_{10}\left(\frac{rugosity\ /\ D}{3.7} + \frac{5.74}{Re^{0.9}}\right)\right)^2} \tag{26}$$

$$f = 0{,}02495 \tag{27}$$

$$Elbows\ 90°\ (1) = 0{,}6 * \left(\frac{V^2}{2 * 9.81}\right) \tag{28}$$

$$Elbows\ 90°\ (1) = 0{,}07861 \ m \tag{29}$$

$$T(6) = 0,4 * \left(\frac{V^2}{2 * 9.81}\right) \tag{30}$$

$$T(6) = 0,0524\ m \tag{31}$$

$$Friction\ Losses(hl) = f\left(\frac{L}{D}\right)\left(\frac{V^2}{2 * 9.81}\right) \tag{32}$$

$$hl = 2,354\ m \tag{33}$$

$$Total\ Losses = hl + Elbow\ 90° + 6 * T \tag{34}$$

$$Total\ Losses = 2,747421\ m \tag{35}$$

$$\text{Cross-Sectional area} = \pi\left(\frac{\text{Diameter}}{2}\right)^2 \tag{36}$$

$$A_T = 0,0001767\ m^2 \tag{37}$$

$$Flow\ Rate = \frac{Q}{A_T} \tag{38}$$

$$V = 0,3\ \frac{M}{Seg} \tag{39}$$

$$R_e = \frac{V * D}{\mu} \tag{40}$$

$$R_e = 4507,47 \quad Flow\ in\ transition \tag{41}$$

$$Friction\ Factor(f) = \frac{0.25}{\left(log_{10}\left(\frac{rugosity / D}{3.7} + \frac{5.74}{Re^{0.9}}\right)\right)^2} \tag{42}$$

$$f = 0,03919 \tag{43}$$

$$Elbows\ 90°\ (1) = 0,4 * \left(\frac{V^2}{2 * 9.81}\right) \tag{44}$$

$$Elbows\ 90°\ (1) = 0,002783\ m \tag{45}$$

$$T(6) = 0{,}4 * \left(\frac{V^2}{2 * 9.81}\right) \quad (46)$$

$$T(6) = 0{,}001855\ m \quad (47)$$

$$Friction\ Losses(hl) = f\left(\frac{L}{D}\right)\left(\frac{V^2}{2 * 9.81}\right) \quad (48)$$

$$hl = 0{,}145454\ m \quad (49)$$

$$Total\ Losses = hl + Codos\ 90° + 6 * T \quad (50)$$

$$Total\ Losses = 0{,}15937\ m \quad (51)$$

$$HB = \frac{P_2}{\gamma} + \left(\frac{V^2}{2 * 9.81}\right) + z_2 + h_p - z_1 \quad (52)$$

$$V_2 = 1.9718\ \frac{m}{sec} \quad (53)$$

$$hp = 2.747421\ m \quad (54)$$

$$z_2 = 0.6\ m \quad (55)$$

$$z_1 = 1.7\ m \quad (56)$$

$$P_2 = 200\ K\,Pa \quad (57)$$

$$\gamma = 9980\ N / m^3 \quad (58)$$

$$HB = \frac{200\ K}{9980} + \left(\frac{1.9718^2}{2 * 9.81}\right) + 0.6 + 2.74 - 1.7 \quad (59)$$

$$HB = 21.878\ m \quad (60)$$

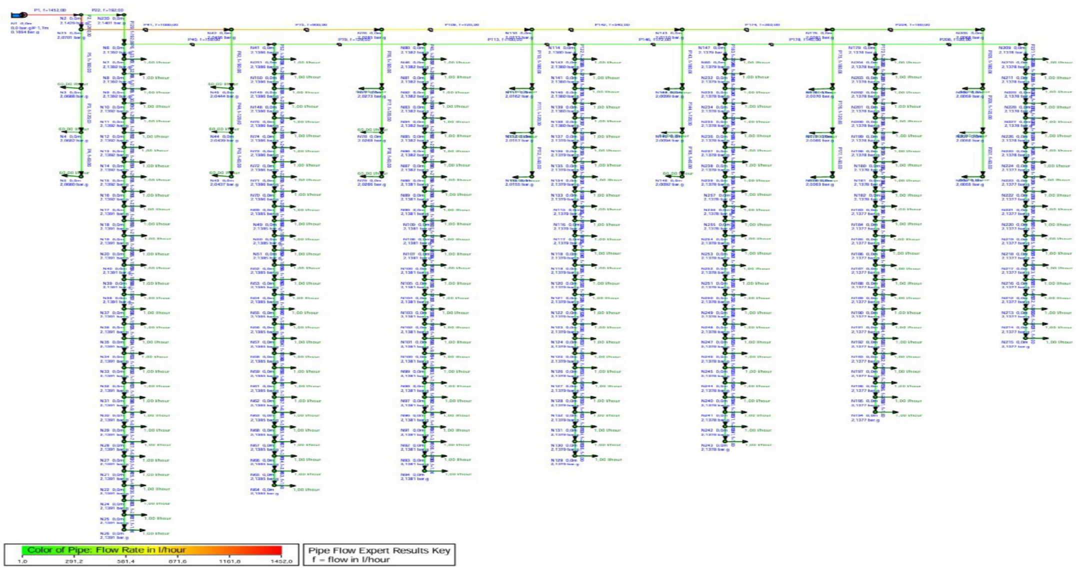
$$Efficiency\ (n) = 30\,\% \quad (61)$$

$$Power = \frac{Pump\ Head * Flow * Specifict\ Weight}{n} \quad (62)$$

$$Power = 254.738\ W = 0.3416\ HP \quad (63)$$

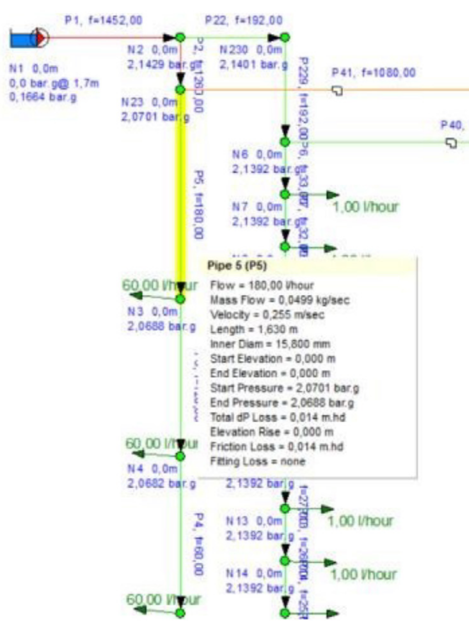
The simulations conducted in Pipe Flow confirmed that the selected pump meets the flow and pressure requirements, and that the losses at the last nebulizer are minimal (Figs. 12–13).

Figure 12. Full View of the System Simulation



From the illustration above, the system to be implemented can be observed with its respective drip points and nebulizers distributed along each of the desired rows. Most of the flow runs through the nebulization lines, as expected, to regulate the temperature of all the crop plants during a frost event. Additionally, the drip lines contain a limited amount of flow, which allows the soil to be moistened and facilitates irrigation.

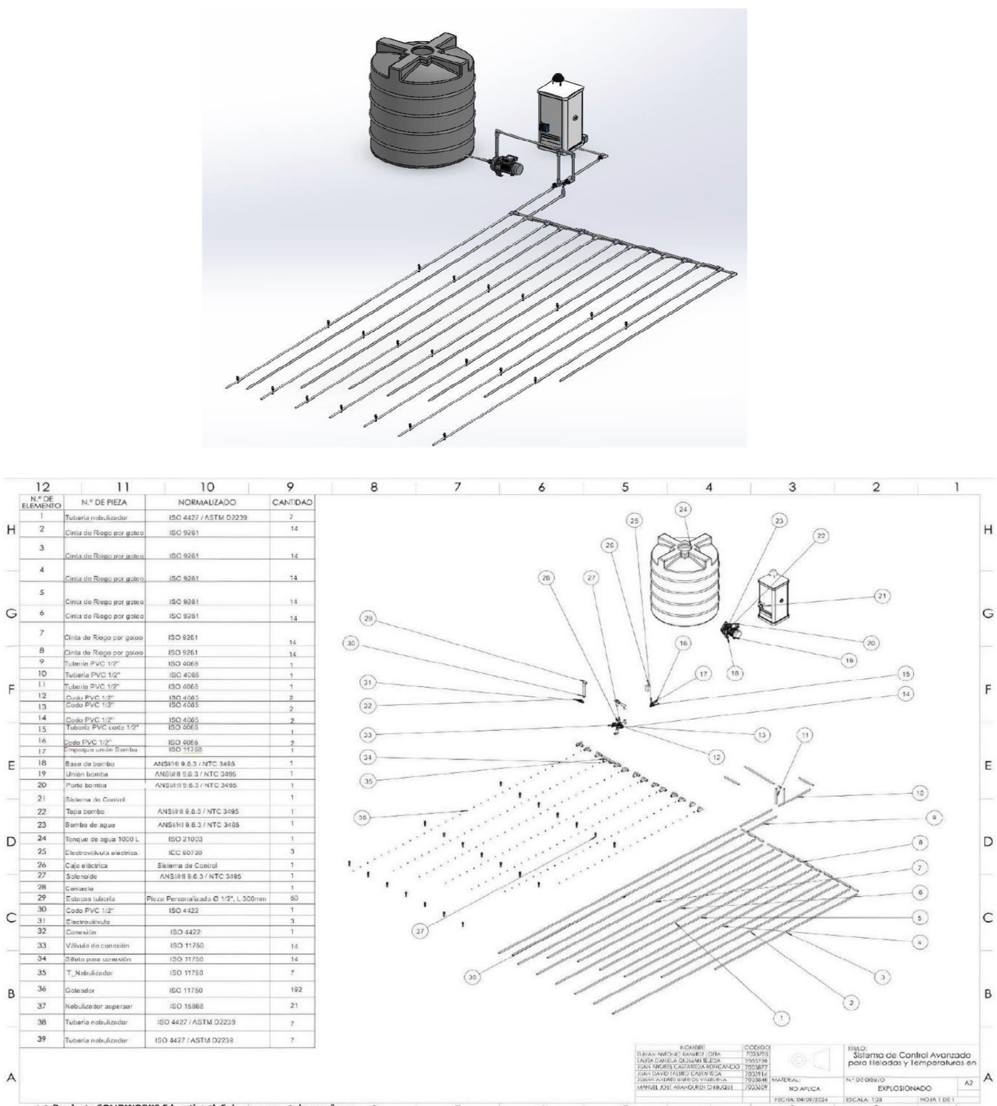
Figure 13. Results of a System Nebulizer



On the other hand, when analyzing one of the system's nebulizers, it is evident that it achieves the required pressure and flow to cover a radius of 1.5 m. When this is extended to all the nebulizers in the system, it can be observed that they can easily cover the cultivated area. With the total flow they can provide at the simulated pressure, the system temperature can be effectively controlled.

- The three-dimensional design in SolidWorks made it possible to optimize the layout of pipes and valves, reducing thermal losses through insulation and efficient component distribution (Fig. 14).

Figure 14. System CAD and Exploded View of the System



N.º DE ELEMENTO	N.º DE PIEZA	NORMALIZADO	CANTIDAD
1	Tubería nebulizador	ISO 4427 / ASTM D2239	7
2	Cinta de Riego por goteo	ISO 9261	14
3	Cinta de Riego por goteo	ISO 9261	14
4	Cinta de Riego por goteo	ISO 9261	14
5	Cinta de Riego por goteo	ISO 9261	14
6	Cinta de Riego por goteo	ISO 9261	14
7	Cinta de Riego por goteo	ISO 9261	14
8	Cinta de Riego por goteo	ISO 9261	14
9	Tubería PVC 1/2"	ISO 4065	1
10	Tubería PVC 1/2"	ISO 4065	1
11	Tubería PVC 1/2"	ISO 4065	1
12	Codo PVC 1/2"	ISO 4065	2
13	Codo PVC 1/2"	ISO 4065	2
14	Codo PVC 1/2"	ISO 4065	2
15	Tubería PVC corta 1/2"	ISO 4065	1
16	Codo PVC 1/2"	ISO 4065	2
17	Empaque unión Bomba	ISO 11750	1
18	Base de bomba	ANSI/HI 9.6.3 / NTC 3495	1
19	Unión bomba	ANSI/HI 9.6.3 / NTC 3495	1
20	Porte bomba	ANSI/HI 9.6.3 / NTC 3495	1
21	Sistema de Control		1
22	Tapa bomba	ANSI/HI 9.6.3 / NTC 3495	1
23	Bomba de agua	ANSI/HI 9.6.3 / NTC 3495	1
24	Tanque de agua 1000 L	ISO 21003	1
25	Electroválvula eléctrica.	IEC 60730	3
26	Caja eléctrica	Sistema de Control	1
27	Solenoide	ANSI/HI 9.6.3 / NTC 3495	1
28	Contacto		1
29	Estacas tubería	Pieza Personalizada Ø 1/2", L 300mm	60
30	Codo PVC 1/2"	ISO 4422	1
31	Electroválvula		3
32	Conexión	ISO 4422	1
33	Válvula de conexión	ISO 11750	14
34	Silleta para conexión	ISO 11750	14
35	T_Nebulizador	ISO 11750	7
36	Goteador	ISO 11750	192
37	Nebulizador aspersor	ISO 15886	21
38	Tubería nebulizador	ISO 4427 / ASTM D2239	7
39	Tubería nebulizador	ISO 4427 / ASTM D2239	7

As shown, the implemented system corresponds to the one designed in the sketch, where each row has two pipes: one for nebulization and the other for irrigation. The tank, pump, heater, and solenoid valves are also included, each with its corresponding connection. Additionally, an exploded view of the system is presented, displaying all the components—excluding the electronic section—that were included in the sketch, as well as certain standardized elements that are essential to the system. The applicable standards for each component and the quantity of each part are also specified.

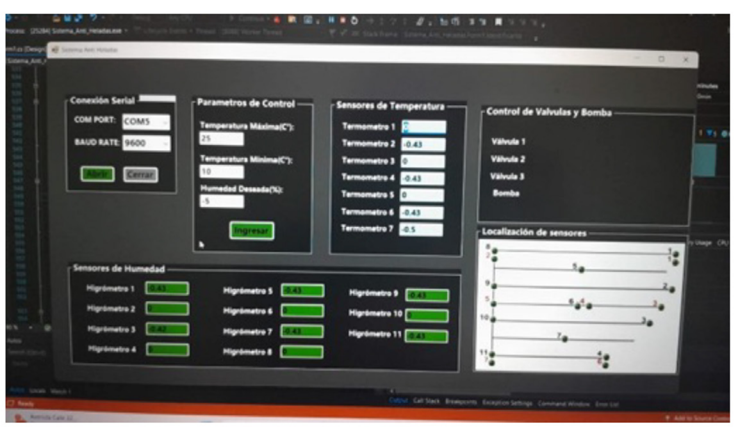
System Implementation and Field Evaluation

The system was installed on a 35 m² plot with 200 Monterrey strawberry seedlings distributed in seven rows (Fig. 15). Drip tapes, nebulizers, temperature and humidity sensors, and an IoT interface for remote monitoring were integrated (Fig. 16).

Figure 15. Implemented System

Subsequently, the complete irrigation and nebulization system was implemented. Drip tapes were installed to efficiently distribute water directly to the root zone, along with a properly positioned pipe network for mist dispersion, aimed at controlling ambient temperature during cold nights. Additionally, a user interface application was developed, allowing real-time monitoring of critical crop variables through integrated sensors, remote activation or deactivation of the irrigation and nebulization system, and access to historical records to evaluate the system's performance.

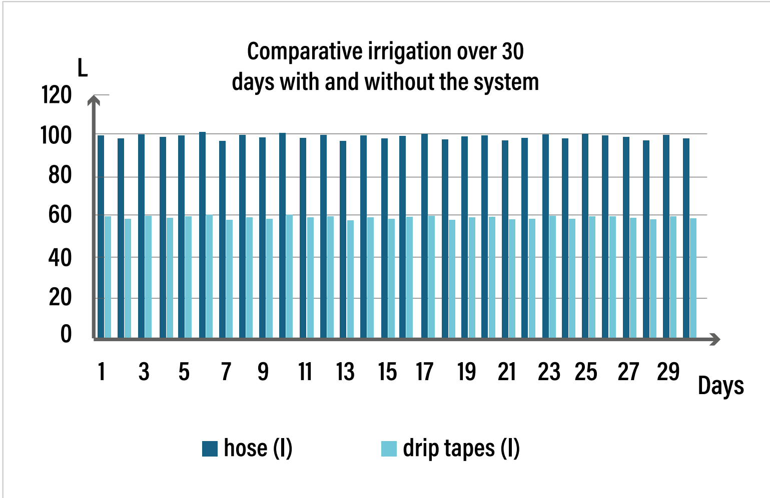
Figure 16. Local Application Implemented with Internet Access for Data Monitoring



Most Relevant Quantitative Results

- A 40 % reduction in water consumption compared to traditional irrigation methods (Fig. 17)

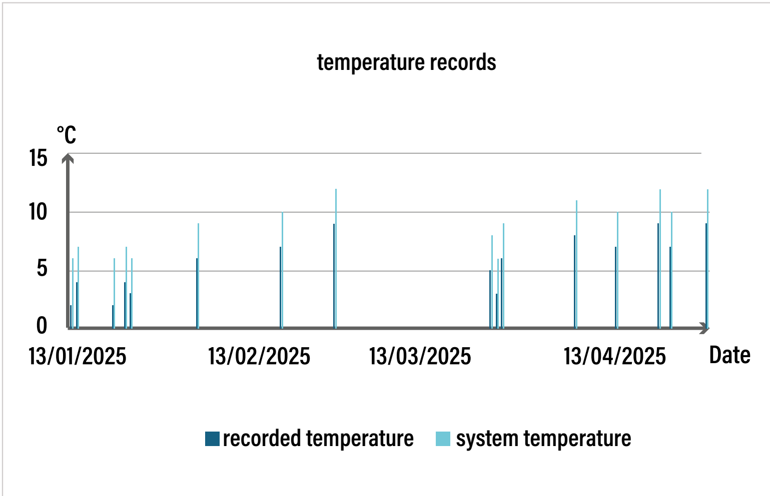
Figure 17. Comparison of Water Consumption in Liters



A 40 % reduction in water consumption was achieved through the implementation of drip irrigation and sensor-controlled nebulization, which optimized irrigation distribution and frequency. This was calculated using a flow meter over a 30-day period, comparing traditional hose irrigation with the implemented system during different months: hose irrigation was evaluated in November 2024, and the system in December 2025.

- Maintenance of an ambient temperature > 4 °C on frost nights with an external temperature < 10 °C (Fig. 18)

Figure 18. System Temperature



- A 30 % increase in plant survival rate compared to manual methods
- Average production of 2.5–3 kg of fresh strawberries every five days, with additional generation of new seedlings (Fig. 19)

Figure 19. Last Crop Yield in April 2025

Identified Limitations:

- During periods of heavy rainfall, excess humidity favored the appearance of fungi, highlighting the need to integrate automatic humidity control.
- An increase in monthly electricity consumption (37,000 COP) was recorded, suggesting the convenience of incorporating renewable energy sources (solar panels) in future versions.

Summary of Findings

The results confirm that the system:

- optimizes water use, reducing consumption by up to 40 %.
- mitigates the effect of frost by maintaining safe temperatures for the crop.
- increases fruit productivity and quality compared to traditional methods.
- is technically and economically viable, although improvements are recommended in energy management through renewable sources and in optimizing humidity control.

Discussion and Conclusions

The results obtained validate the technical and economic feasibility of an automated drip irrigation and thermal control system for strawberry crops in Tabio, Cundinamarca. The designed prototype optimized water use, reducing consumption by 40 % compared to traditional irrigation methods, and mitigated the effects of frost by maintaining an ambient temperature above 4 °C during cold nights with external temperatures below 10 °C. These improvements were reflected in a 30 % increase in plant survival rate and an increase in the average production of fresh strawberries.

Surveys of farmers confirmed a high level of acceptance of the system, with more than 80 % of participants considering it easy to operate and integrate into their daily activities. However, 42 % expressed uncertainty regarding the use of digital platforms, highlighting the need for prior training to ensure successful technology adoption.

Agricultural engineering experts agreed that automatic heating methods are more efficient than traditional ones and rated the use of superheated water positively as an effective (80%) and safe (70%) option. They also emphasized the importance of a modular design (average rating 4.2) and the potential integration of renewable energies (average rating 3.5), demonstrating interest in the scalability and sustainability of the system. Among the suggested improvements were alternatives such as the use of biodegradable thermal sheets and geotextiles to cover the soil, reflecting a concern for more sustainable solutions.

Despite the observed benefits, some limitations were identified, including increased electricity consumption (~37,000 COP per month) and the appearance of fungi during periods of high humidity. This suggests the need to incorporate renewable energy sources and automatic humidity control in future versions of the system.

In summary:

1. The proposed system is technically and economically feasible, improving water efficiency and frost protection.
2. Its adoption by farmers is feasible, although it requires prior training and accessible control alternatives for areas with low connectivity.
3. The use of superheated water and automation represents innovative and efficient solutions, supported by the opinions of experts and potential users.
4. The integration of renewable energy and additional humidity control strategies would increase sustainability and reduce operating costs.
5. The modular design and replicability of the system make it a scalable alternative adaptable to other frost-sensitive crops in different regions of the country.

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