Frost Prevention in Vineyards Powered by Renewable Energy

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Abstract

Recent extreme climate events across Europe have highlighted the critical need for innovative frost mitigation strategies in agriculture. This study presents a practical evaluation of a targeted heating wire system, powered by a low-power electrical setup, designed to protect a small vineyard plot during a vulnerable late spring frost. Heating wires were strategically installed along the vine rows to provide direct warmth to the young plants. The effectiveness of this system was rigorously assessed using real-time microclimate monitoring, employing remote and ground-based IoT sensors to track canopy-level air temperature, humidity, and frost occurrence within both the treated area and a control plot. Preliminary results from this case study demonstrate a clear increase in canopy-level temperatures within the heated zone, which significantly correlated with a reduction in frost severity observed on the vines compared to the unheated control. To further explore sustainable energy solutions, we developed and tested a prototype energy harvesting system, integrating a small Darwin wind turbine and a solar panel, coupled with a battery storage unit. Moreover, we designed and evaluated a gravity battery system to showcase an alternative method for storing the harvested renewable energy. This practical investigation offers valuable insights into the immediate impact and future potential of combining localized heating solutions with diverse green energy harvesting and storage technologies to bolster agricultural resilience against increasing climate variability.

Keywords: Climate change, Monitoring Solutions, IoT, Frost Prevention, Energy harvesting, Agricultural Resilience, Agriculture, Renewable energy

Introduction

The impact of climate change on agriculture is becoming more apparent, with shifting weather patterns and extreme events like frost increasingly threatening crop yields and food security (Wheeler & Von Braun, 2013a). While agriculture is a key contributor to greenhouse gas emissions (Tubiello et al., 2013), it also faces the brunt of climate-related challenges, necessitating the adoption of climate-resilient mitigation and adaptation measures (Anwar et al., 2012). Mitigation efforts in agriculture typically focus on reducing emissions and enhancing carbon sequestration (U.S. Department of Agriculture, 2024; Grigorieva et al., 2023), but there is an urgent need to address immediate risks, such as frost, that can devastate crops. Traditional methods of frost protection, however, often fall short due to their high costs, environmental impact, and limited effectiveness. In light of this, our study investigates the potential for integrating cutting-edge technologies—such as IoT-based digital monitoring and renewable energy solutions—to foster microclimates that help mitigate frost damage. Specifically, we assess the effectiveness of active frost protection techniques, including infrared (IR) lights, heating wires, and wind towers, to determine their feasibility in protecting crops. This research aims to provide key insights into developing sustainable, technology-driven strategies to safeguard agriculture from the growing challenges posed by climate variability.

Materials and methods

To assess the performance of electric heating for frost protection in agriculture, we deployed a network of specialized sensors. Milesight EM300 LoRaWAN temperature-and-humidity probes delivered continuous environmental readings in both heated and control plots, while Milesight WS52x Smart LoRaWAN sockets tracked power consumption and enabled remote switching of the heaters. All devices were linked to the TELOS remote-monitoring platform through Milesight LoRaWAN base stations, which provided reliable data transmission over distances of up to 7 km. A custom sensor module with a Mobotix thermal camera complemented the network by supplying thermal imagery for deeper insight into heat distribution. By positioning sensors at multiple heights and locations, the study captured fine-scale temperature gradients and produced a comprehensive evaluation of the electric frost-protection system's effectiveness.

Figure 1: Milesight UG65 Figure 2: Milesight WS52 Figure 3: Milesight EM300

Figure 4: CAD drawing Figure 5: MOBOTIX thermal camera with dedicated electronics

Frost prevention

Frost can severely reduce crop yields, especially when temperatures dip during sensitive growth phases. To address this risk, we examined a heating wire system, widely used to keep water lines from freezing as a direct frost protection strategy for plants. In a controlled field trial, we compared plots equipped with heating wires to unheated controls, continuously logging microclimate data and the system's energy use. This approach allowed us to quantify how effectively the wires moderated near plant temperatures and prevented frost injury. Our results provide practical evidence that localized, wire heating can be a viable tool for reducing frost damage in agricultural production.

Heating wire

We conducted two heating wire experiments. One in a vineyard and another in an apple orchard at Estate Zobec in Slovenia's Štajerska (Steyer) wine-growing region (46.3575 °N, 15.6324 °E). Both experiments were run on 22 April 2024.

Custom 3-D-printed clips (Figure 6) were designed to secure the wire directly to the plants (Figure 7); the same fixtures were used in both crop types. In each plot, the wire was stretched roughly 60 cm above ground—aligned with the height of the buds targeted for frost protection. Drawing only 20 $W\ m^{-1}$, the wire offered a straight forward yet energy-efficient means of delivering localized heat to vulnerable tissues.

Figure 6: CAD drawing of clamp

Figure 7: Installation in vineyard

The second iteration of the same system presented in *Figure 8* implemented a slightly newer version of the heating wire that draws 25 W per meter. The newer system also featured a controller to enable the user of easily and instantly turning the system on and off during extreme climactic events.

Figure 8: Heating wire system with controller

Renewable energy solutions

To advance sustainable agriculture, we explored ways to harvest and store renewable energy on-site. Several small-scale harvesting setups—solar, wind, and kinetic—were built to power our IoT sensor network. Although sized for low-power devices, these prototypes demonstrate pathways for scaling the technology to run higher-load equipment, including future frost-protection systems. Our approach aligns with findings by De Jesus Acosta-Silva et al. (2019), which highlight the viability of distributed energy harvesting for agricultural applications.

The Hybrid Darwin Wind Turbine (HDWT) system is primarily designed to harness wind power and convert it to electrical energy. But in our case, it was upgraded to include also photovoltaics to harvest solar energy to provide a renewable, portable power source for agricultural workers / tasks. The system's core components include small solar panels, a simple wind turbine, a 3D-printed housing, and various DC/DC voltage converters to stabilize energy flow.

The materials used for the Hybrid Darwin Wind Turbine (HDWT) system included 1 kg of PLA white plastic, utilized for 3D-printing the housing; three solar panels, each rated at 6 V and 1 W, for harvesting solar energy; and a wind turbine rated at 5 V and 3 W to convert wind energy into electricity. To ensure stable voltage output, a 5 A DC/DC step-down converter and a 2 A DC/DC step-up converter were incorporated. Additionally, a 20 Ah rechargeable battery was included to store the generated energy and provide consistent power output.

Figure 9: Hybrid Darwin Wind Turbine

Energy storage solutions

This demonstration project investigates a gravitational hydro battery (GHB) as an on-farm renewable-energy solution, aimed especially at running automatic heating systems. The prototype stores surplus power by pumping water to an elevated reservoir and later generates electricity by passing the water through a micro-hydro turbine as it descends. The study's primary goal is to evaluate how effectively this height-based water storage can deliver reliable, renewable electricity for agricultural operations. The experimental setup involved a 4-meter height difference between water storage tanks, a water pump to move water to the upper tank (potentially powered by renewable sources like solar), and a hydro generator to convert the falling water's kinetic energy back into electricity. To keep the technology affordable and easy to replicate, the prototype was built exclusively from low-cost, off-the-shelf parts. A self-contained monitoring module logs both the electricity required to pump water uphill and the power produced when the water drives the turbine. These data make it possible to calculate the system's round-trip efficiency and verify its practicality as a renewable energy option.

Figure 10: Gravitation battery setup

The gravitational hydro battery (GHB) demonstration underscores its potential as a sustainable power source for agriculture. By harnessing water's gravitational potential energy, the GHB provides a viable, renewable alternative to conventional farm-energy solutions. The use of low-cost components further enhances the accessibility and feasibility of this approach for the agricultural sector. While the initial demonstration utilized a modest 4-meter height, the concept can be scaled based on available infrastructure or landscape. Future research should concentrate on optimizing the efficiency of the GHB system, exploring integration with various renewable energy sources (like solar) to power the water pump, and investigating its long-term reliability and cost-effectiveness in diverse agricultural settings. The successful implementation of water-based energy storage and generation systems like the GHB could play a key role in lowering agriculture's carbon footprint while enhancing on-farm energy self-sufficiency. This approach supports the transition toward more sustainable and resilient agricultural practices.

Results and discussion

1. Heating Wire

Visual observations revealed that the heating wire generated warmth within only a narrow radius, offering minimal protection against frost. This limited heating effect proved insufficient for the broader canopy of the apple orchard. In the vineyard, where the buds were more closely aligned with the wire, the results were moderately encouraging, suggesting some potential for targeted protection in specific crop configurations.

Figure 11: Thermal image of the heating wire captured by MOBOTIX depicts a thermogram taken by our thermal camera and shows the heating element evenly radiating heat. To further explore the potential of this crop protection method, additional experiments are warranted, given its low energy consumption and straightforward design, which make it a promising solution.

Figure 11: Thermal image of the heating wire captured by MOBOTIX combined with an RGB image

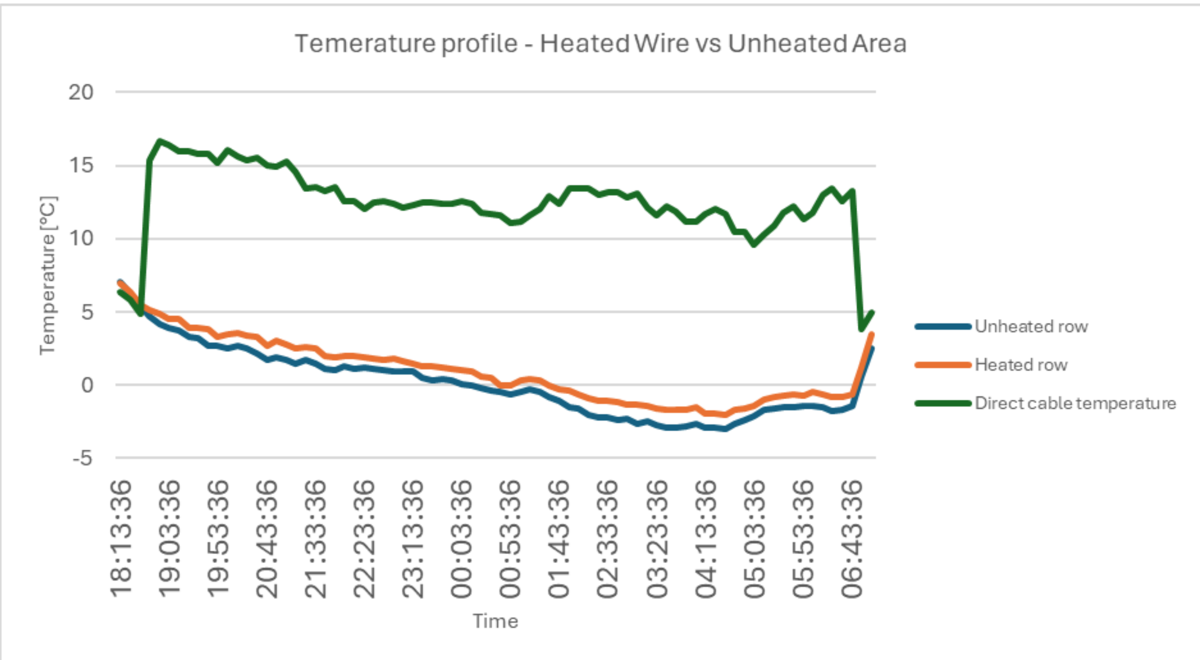

Figure 12: Temperature profile, Heated Wire vs. Unheated Area

This graph illustrates temperature readings taken from a heating wire system, measured at three distinct points to assess the system's effectiveness. The first location is directly on the wire itself, representing the core heating zone. The second, labeled as the "heated row," is positioned nearby—within the intended area of influence. The third, the "unheated row," acts as a control point, situated at a similar distance but without any active heating. The sensor was placed at *10* cm from the wire. In the case of direct wire temperature measurements, the sensor was placed directly on the heating wire. As a result, we see a drop in temperature.

The data clearly show that the temperature directly on the wire remains consistently higher than at the other points, demonstrating a stable and concentrated heating effect. In the heated row, a modest rise in temperature is observed, though the warming influence noticeably decreases with distance from the wire. Meanwhile, the unheated row consistently registers the lowest temperatures, often approaching or dipping below freezing.

These observations underscore the localized nature of the heating wire's effect. While it offers effective protection against frost in its immediate vicinity, its influence fades quickly beyond a limited radius, but can provide a limited protective effect against frost. For optimal frost prevention, it would be beneficial to place the wire densely or position it closer to vulnerable areas—such as wrapping it along branches or aligning it directly under sensitive crop zones.

2. Heating bulbs

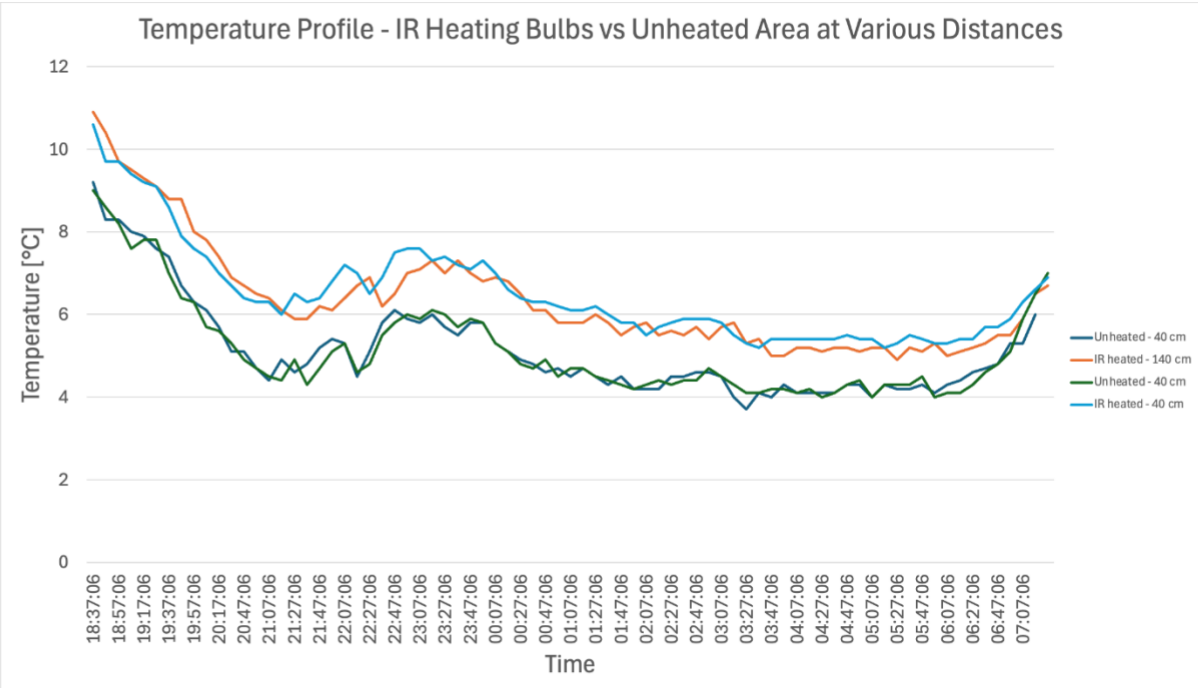

Figure 13: Temperature profile, IR Heating Bulbs vs Unheated Area at Various Distances

This graph illustrates the thermal behavior recorded at two distances (40 cm and 140 cm) in both heated and unheated rows, during a frost protection experiment using infrared heating bulbs mounted above trees. The experiment was done on the 20th – 21st of March 2025.

The experimental setup revealed clear differences in temperature across the heated and unheated rows. The row positioned 140 cm of height, pusitioned just beneath the infrared (IR) bulbs consistently exhibited the highest temperatures, suggesting a strong and effective heat transfer from the IR source when placed in close proximity. In contrast, the heated row at 40 cm showed a moderate temperature increase, indicating it received some benefit from the heat but to a lesser extent.

Meanwhile, both unheated rows—at 40 cm and 140 cm—remained significantly cooler throughout the observation period. This was especially evident at the 40 cm distance, reinforcing the conclusion that the presence and positioning of IR bulbs play a decisive role in elevating local temperatures.

From these findings, it's clear that IR bulbs provide a localized heating effect, with their warming influence confined to a limited horizontal and vertical range. To enhance frost protection in sensitive crops, such as those with vulnerable buds or blossoms, the bulbs must be positioned close to the target areas. Additionally, because infrared radiation is directional, achieving uniform heat coverage requires the use of multiple bulbs or careful strategic placement to ensure effective protection across the entire area.

3. Mobile wind turbine

Our experiments with the ventilator system demonstrated that directing air from elevated positions had minimal effect on temperatures at ground level. The airflow failed to meaningfully alter the thermal conditions in the crop zone, indicating limited effectiveness for frost protection. The fan system did not cause significant changes in temperature either relatively or absolutely. Confirming the statement of Tadić, et al. 2023 that the performance of wind machines is low. Sensor temperatures remained largely unaffected before and after the fan was turned on.

Looking at the data, there was a high correlation with ground temperature. All temperature sensors showed a strong correlation with the reference ground temperature, indicating consistent thermal patterns across the field unaffected by the fan. Minimal changes in extreme temperatures were observed, with only slight variations in the minimum and maximum temperatures recorded after the fan was activated, further suggesting limited influence on frost prevention. This is demonstrated in Graph 2.

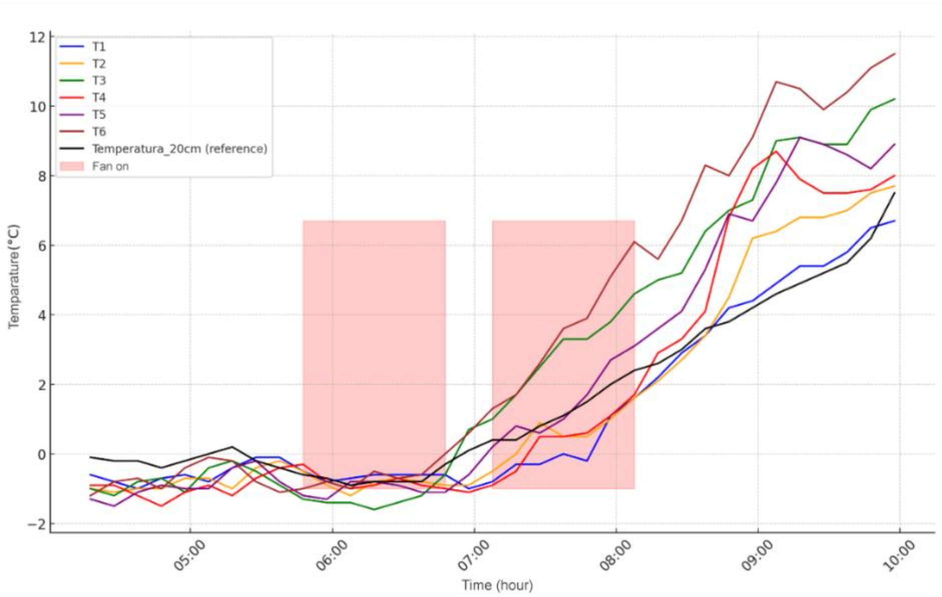

Figure 14: Comparison of temperatures from 4:00 a.m. to 10:00 a.m

Further thought experiments investigated the effectiveness of capturing warm air from higher altitudes to improve frost prevention. Measurements at different heights: 0.2 m, 5 m and 10 m, revealed a consistent temperature gradient of approximately 0.3 °C across 10 meters. The results, shown in Figure 15 and Figure 16, suggest that while warm air is present at higher altitudes, the current height of 5 m is insufficient for effective warm air capture.

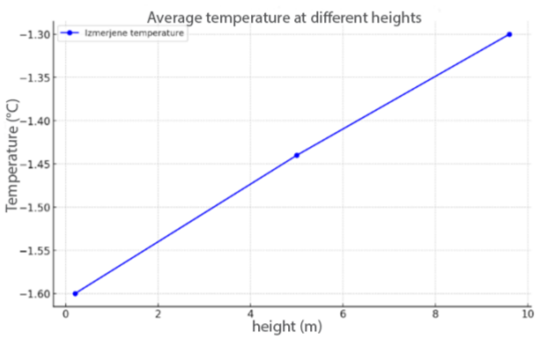

Figure 15: Measured temperatures

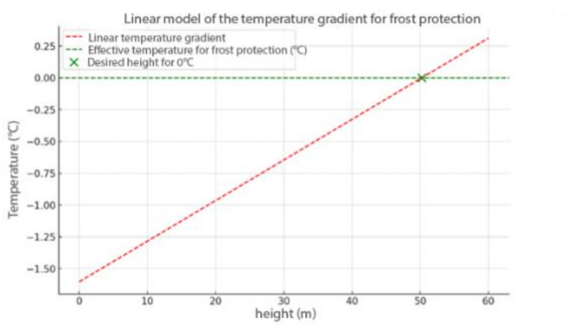

Figure 12: Linear regression model of the temperature gradient

A linear regression model (Figure 16) demonstrates that increasing the system height to at least 10 m is required to achieve meaningful temperature improvements near ground level. This finding highlights the need to redesign ventilation systems to take advantage of the temperature gradient. To enhance the performance of ventilation systems for frost prevention we would recommend increasing the system height from 10 to 20 meters to better utilize the observed temperature gradient.

4. Renewable energy solutions

Figure 17 illustrates that our small-scale, theoretical model of the HDWT system shows promise for low-power, short-duration applications in agriculture. While these findings are preliminary, they suggest that, with further refinement, the system could evolve into a sustainable and cost-effective solution for targeted use. Similar findings of Mohammed, 2024 provide us with insight that further research would be beneficial.

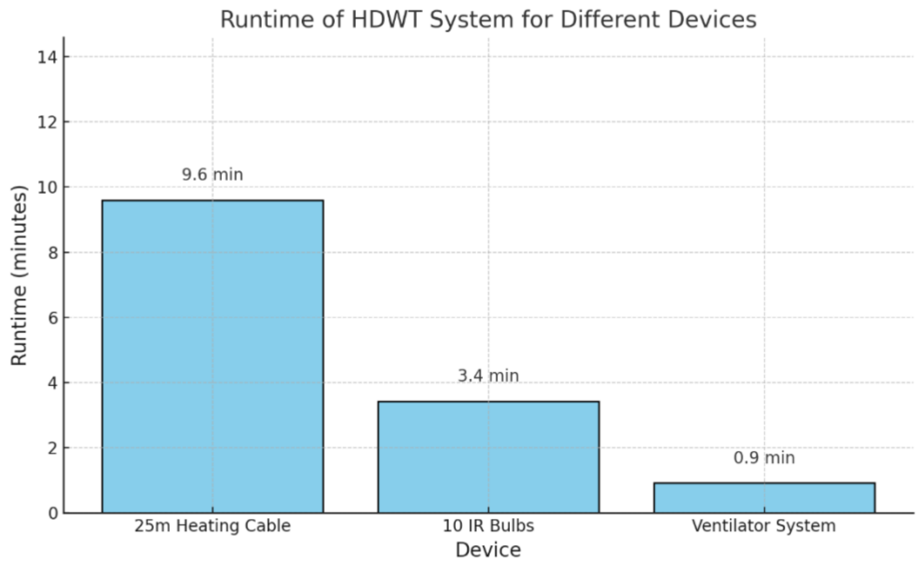

Figure 17: Runtimes of different active measures presented in a chart.

Conclusions

Our field tests of the heating wire system did not yield the level of success we initially anticipated. Due to its low cost and ease of implementation, we plan to continue research in this area, shifting our focus toward its potential effects on root-zone temperatures and root system development.

We concluded that using of IR light bulbs commonly used in animal husbandry proved successful in plant protection. They are easy to install, trigger and provide a way to target the necessary area and prevent frost. They downside is their high-power consumption and energy that is not transferred into heat on the plants, but in the surrounding area.

The ventilator system experiment concluded that the fan system did not significantly impact ground or near-ground microclimatic conditions in this setting, as confirmed by the negligible temperature differences before and after fan operation. High correlations between sensor readings and limited shifts in extreme temperatures support this finding. A linear regression analysis of temperature gradients at various heights indicated that the current fan height of 5 meters is insufficient for effective warm air capture, suggesting that increasing the system height could enhance its efficacy in frost prevention.

Future research could investigate methods for capturing and repurposing the excess heat emitted by infrared light bulbs used in plant heating. By integrating a heat recovery system with targeted ventilation, it may be possible to redirect this otherwise lost thermal energy toward areas in need of protection. Such an approach could significantly improve the overall efficiency of frost prevention strategies, reduce energy waste, and support the development of more sustainable and cost-effective solutions for agricultural use.

The HDWT system presents a promising, portable, and cost-effective energy solution for localized frost protection. Although its current energy storage capacity restricts its suitability for large-scale applications, future improvements—such as integrating higher-capacity batteries, adopting modular configurations, or incorporating more efficient technologies—could significantly expand its potential. Such advancements would strengthen the system's alignment with the increasing need for sustainable and adaptable solutions in modern agriculture.

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