INTEGRATION OF SMART TRAPS AND WEATHER SENSORS INTO A DIGITAL PRECISION AGRICULTURE SYSTEM
/
INTEGRAREA CAPCANELOR INTELIGENTE ȘI A SENZORILOR METEO ÎNTR-UN SISTEM DIGITAL PENTRU AGRICULTURA DE PRECIZIE

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ABSTRACT

Precision agriculture requires advanced digital solutions capable of continuously monitoring environmental conditions and pest dynamics in orchard ecosystems. This paper presents the development, integration, and experimental validation of a digital system dedicated to orchard crop monitoring. The proposed system integrates a smart pheromone trap equipped with an HD camera, a meteorological monitoring station, an autonomous photovoltaic power supply system, and a wireless communication module for real-time data transmission. The experimental model was designed to support automatic pest detection and continuous acquisition of climatic parameters associated with pest and pathogen development. The monitoring architecture combines environmental sensing, image acquisition, local data processing, and cloud-based communication. Functional testing was conducted under controlled orchard conditions over a 30-day monitoring period. The obtained results demonstrated stable autonomous operation, reliable wireless communication, and accurate environmental monitoring. The average deviations compared with a reference meteorological station were within ±0.4 °C for air temperature, ±2.5% for relative humidity, and ±0.3 m/s for wind speed. The smart trap achieved pest identification accuracy higher than 90% for target species. The photovoltaic system ensured autonomous operation for more than 72 h without direct solar radiation. The developed digital platform represents a scalable solution for integrated pest management and precision orchard monitoring applications.

REZUMAT

Agricultura de precizie necesită soluții digitale avansate, capabile să monitorizeze continuu condițiile de mediu și dinamica dăunătorilor din ecosistemele pomicole. Lucrarea prezintă dezvoltarea, integrarea și validarea experimentală a unui sistem digital destinat monitorizării culturilor pomicole. Sistemul propus integrează o capcană inteligentă cu feromoni, echipată cu cameră HD, o stație meteorologică, un sistem autonom de alimentare fotovoltaică și un modul de comunicație wireless pentru transmiterea datelor în timp real. Modelul experimental a fost proiectat pentru detectarea automată a dăunătorilor și achiziția continuă a parametrilor climatici asociați dezvoltării dăunătorilor și patogenilor. Arhitectura sistemului combină senzori de mediu, achiziție de imagini, procesare locală a datelor și comunicație prin platformă cloud. Testarea funcțională a fost realizată în condiții controlate de livadă, pe o perioadă de monitorizare de 30 zile. Rezultatele obținute au demonstrat funcționare autonomă stabilă, comunicație wireless fiabilă și monitorizare meteorologică precisă. Abaterile medii față de o stație meteorologică de referință au fost de ±0,4 °C pentru temperatura aerului, ±2,5% pentru umiditatea relativă și ±0,3 m/s pentru viteza vântului. Capcana inteligentă a obținut o precizie de identificare a dăunătorilor mai mare de 90% pentru speciile țintă. Sistemul fotovoltaic a asigurat funcționarea autonomă timp de peste 72 h fără radiație solară directă. Platforma digitală dezvoltată reprezintă o soluție scalabilă pentru managementul integrat al dăunătorilor și monitorizarea de precizie a culturilor pomicole.

INTRODUCTION

The transition toward precision agriculture has accelerated the development of intelligent monitoring systems capable of continuously evaluating environmental conditions and phytosanitary risks in orchard ecosystems. Modern orchard management requires rapid access to accurate information regarding climatic variability, pest dynamics, and pathogen development in order to optimize crop protection strategies and reduce production losses (*Nicolì et al., 2024; Yakovenko et al., 2023*).

Conventional monitoring methods are generally based on manual field inspections and periodic observations performed by specialists. These approaches require significant labor resources, generate delayed responses, and are strongly influenced by operator experience. In addition, traditional monitoring does not provide continuous data acquisition, which limits the possibility of identifying early infestation stages and accurately predicting pest evolution (*Karar et al., 2021; Rustia et al., 2023*).

Recent advances in digital agriculture enabled the integration of environmental sensors, wireless communication technologies, artificial intelligence, and image processing systems into autonomous monitoring platforms. These technologies support real-time acquisition and analysis of environmental and biological data, allowing rapid identification of critical conditions associated with pest outbreaks and disease development (*Fuentes-Peñailillo et al., 2024; Karunathilake et al., 2023; Masi et al., 2023; Zude-Sasse et al., 2021*).

Smart pheromone traps represent one of the most important technological solutions currently used for integrated pest management in orchard crops. By combining pheromone attraction systems with digital imaging and automated analysis algorithms, these devices can continuously monitor insect populations and reduce the dependence on manual observations. Studies demonstrated that machine vision and neural network approaches can significantly improve pest identification accuracy and increase monitoring efficiency in orchard ecosystems (*Čirjak et al., 2022; İtmeç and Zorlu, 2025; Kumar et al., 2025; Suto, 2022*).

Meteorological parameters also have a major influence on pest and pathogen activity. Air temperature, relative humidity, precipitation, solar radiation, and wind conditions directly affect insect development cycles, infection risks, and migration intensity. Consequently, integrating weather monitoring with automatic pest detection provides a more accurate basis for predictive phytosanitary management (*Rajput et al., 2024*; *Tudi et al., 2021; Yeshiwas et al., 2026*).

Experimental studies conducted in precision horticulture demonstrated that intelligent monitoring systems based on environmental sensors, wireless communication modules, and automated image acquisition can provide accurate and continuous information regarding pest activity and orchard microclimate conditions. Field experiments performed in orchard ecosystems confirmed that integrating meteorological monitoring with digital pest detection improves the efficiency of phytosanitary management and supports early identification of infestation risks (*Łągiewska and Panek-Chwastyk, 2025; Pascoal et al., 2024; Wang et al., 2025*).

Developments in Internet of Things technologies and cloud-based agricultural platforms also demonstrated the applicability of autonomous monitoring infrastructures in orchard crops. The integration of wireless sensor networks, automated image acquisition systems, and real-time communication platforms enables continuous monitoring over extended agricultural areas while reducing labor requirements and operational costs. Several studies reported that intelligent monitoring architectures contribute to improved pest surveillance efficiency, optimized pesticide application, and increased sustainability of horticultural production systems (*Liakos et al., 2018; Pivoto et al., 2021; Talaviya et al., 2020; Verdouw et al., 2021*).

The main objective of the research was the realization of a functional experimental model capable of continuously monitoring environmental parameters and pest activity under orchard conditions. The study also aimed to evaluate the operational stability, energy autonomy, communication reliability, and monitoring accuracy of the developed system. The proposed monitoring platform contributes to the implementation of precision horticulture technologies by supporting real-time decision-making, reducing manual intervention, and improving the efficiency of integrated pest management strategies in orchard ecosystems.

MATERIALS AND METHODS

1. General architecture of the experimental monitoring system

The experimental model was developed as an integrated digital system dedicated to continuous monitoring of orchard crops. The monitoring platform combined environmental sensing modules, smart pest detection equipment, autonomous energy supply, and wireless communication infrastructure within a unified operational architecture.

The developed system included the following main components:

- intelligent meteorological station;
- smart pheromone trap equipped with HD camera;
- electronic acquisition and control module;
- autonomous photovoltaic power supply system;
- wireless communication infrastructure;
- cloud-based monitoring platform.

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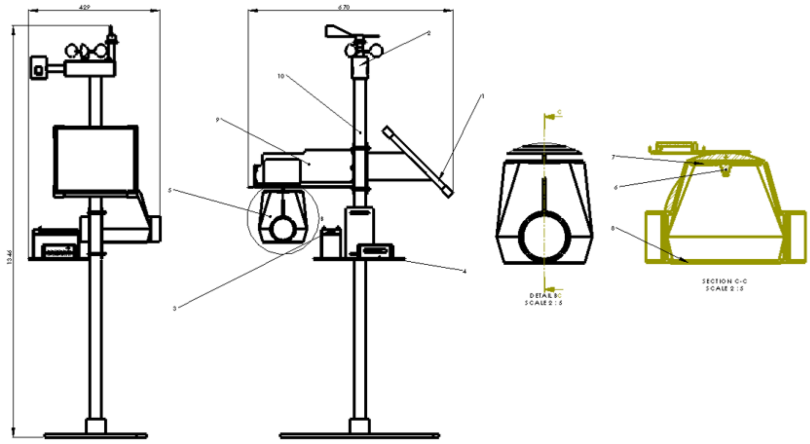

Fig. 1 – General architecture of the experimental orchard monitoring system

1 – solar panel with support arm; 2 – smart meteorological station; 3 – 12 V battery; 4 – support plate for the control unit; 5 – pheromone insect trap; 6 – pest monitoring camera; 7 – LED strip; 8 – adhesive pheromone plate; 9 – pheromone trap mounting arm; 10 – support pipe structure

2. Smart meteorological station

The meteorological station was designed for continuous monitoring of climatic parameters associated with pest activity and pathogen development in orchard ecosystems.

The monitoring station integrated: air temperature sensor; relative humidity sensor; anemometer; wind direction sensor; rainfall sensor; solar radiation sensor.

The sensors were mounted on an anodized aluminum support structure resistant to corrosion and outdoor environmental exposure.

The monitored parameters included: air temperature, °C; relative humidity, %; wind speed, m/s; precipitation intensity, mm/h; solar radiation, W/m².

Fig. 2 – Experimental meteorological station used for continuous orchard environmental monitoring

The experimental meteorological station was installed under orchard field conditions and connected to the acquisition and communication module for real-time environmental monitoring. Table 1 presents the main climatic parameters monitored by the experimental meteorological station together with the corresponding measurement units and sensing components used within the developed monitoring platform.

Table 1

Climatic parameters monitored by the experimental station

Parameter	MU	Sensor type
Air temperature	°C	Digital thermal sensor
Relative humidity	%	Capacitive sensor
Wind speed	m/s	Anemometer
Wind direction	°	Wind vane
Precipitation	mm	Rain gauge
Solar radiation	W/m²	Pyranometer
Parameter	Unit	Sensor

3. Smart pheromone trap

The smart pheromone trap represented the central monitoring component of the experimental system. The trap was designed for automatic detection and monitoring of orchard pests, especially Lepidoptera and Diptera species. The trap structure included: UV-resistant polymer housing; pheromone compartment; HD digital camera; LED illumination system; support and suspension elements.

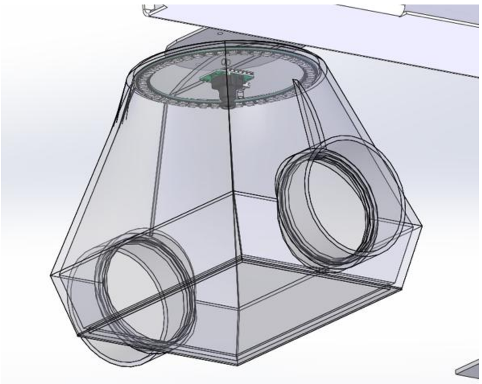

Fig. 3 – Smart pheromone trap integrated into the monitoring system

The HD camera periodically captured images of the adhesive monitoring surface. The integrated LED system ensured uniform illumination during low-light acquisition conditions.

4. Electronic acquisition and control module

The electronic acquisition module coordinated all sensing, communication, and energy management operations within the experimental monitoring system.

The module performed: environmental data acquisition; image acquisition control; LED activation management; local data storage; wireless communication control; energy monitoring.

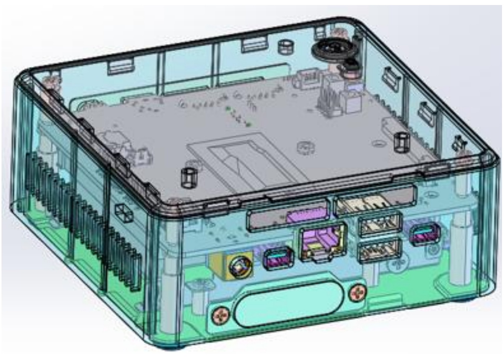

Fig. 4 – Electronic acquisition and control module integrating communication, sensing, and energy management subsystems

The electronic components were integrated into an IP65 protective enclosure to ensure operational stability under field conditions.

5. Autonomous photovoltaic power supply system

The developed monitoring platform used an autonomous photovoltaic energy system for continuous operation under orchard conditions.

The energy subsystem included: monocrystalline photovoltaic panel, 50 W; accumulator, 12 Ah; solar charge controller.

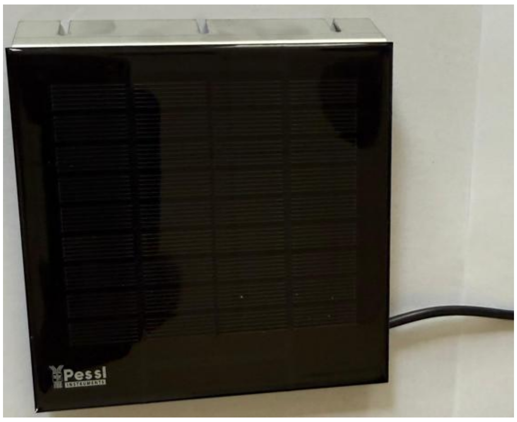

Fig. 5 – Monocrystalline photovoltaic panel integrated into the autonomous orchard monitoring system

The photovoltaic panel was mounted on an adjustable metallic structure oriented southward to maximize solar energy conversion efficiency.

6. Wireless communication and data transmission

The developed monitoring system used wireless communication technologies for remote data transmission and cloud synchronization.

The communication subsystem supported: Wi-Fi communication; 4G transmission; local data storage during signal interruption; automatic synchronization after communication recovery.

Table 2

Data acquisition and transmission configuration

Monitoring operation	Acquisition interval
Meteorological measurements	30 min
Automatic image acquisition	6 h
Data synchronization	12 h

The acquired environmental data and captured images were periodically transmitted to a cloud-based monitoring platform.

7. Experimental setup and monitoring procedure

The experimental monitoring system was installed in an apple orchard located in a lowland horticultural area. The monitoring campaign was conducted during the vegetation season over a period of 30 consecutive days.

Fig. 6 – Integrated experimental monitoring platform installed under orchard field conditions

The experimental monitoring campaign was conducted in an apple orchard at the Research Institute for Fruit Growing Pitești-Mărăcineni, Mărăcineni, Argeș County, Romania, over 30 consecutive days during the vegetation season. The meteorological monitoring unit incorporated Pessl Instruments sensors for air temperature, relative humidity, wind speed and direction, precipitation, and global solar radiation. Air temperature and relative humidity were measured using a HYT221-based sensor, with an operating temperature range of −40 to +125 °C and a relative humidity range of 0–100% RH; the nominal accuracies were ±0.2 °C within the 0–60 °C range and ±2% RH at 23 °C within the 0–90% RH range. Wind speed was measured using a three-cup anemometer with a measurement range of 0–30 m/s and a nominal tolerance of ±0.5 m/s for wind speeds up to 5 m/s and ±10% above 5 m/s. Wind direction was measured over a range of 0–359°, with a nominal tolerance of ±5°. Precipitation was recorded using a double tipping-bucket rain gauge with a resolution of 0.2 mm and a nominal accuracy of ±5%. Global solar radiation was measured using a Pessl Instruments IM506D pyranometer, based on a photodiode sensing element, with a measurement range of 0–2000 W/m², a spectral response of 300–1100 nm, and a maximum absolute error of ±5% (typically approximately ±3%).

The smart pheromone trap was equipped with a Raspberry Pi High Quality Camera based on a Sony IMX477R stacked, back-illuminated CMOS sensor, with a resolution of 12.3 megapixels (4056 × 3040 pixels), a sensor diagonal of 7.9 mm, and a pixel size of 1.55 × 1.55 µm. The camera was fitted with an 8 mm C/CS-mount lens, providing a fixed optical configuration for imaging the adhesive monitoring surface. Images of the adhesive plate were automatically acquired at 6 h intervals. An integrated LED illumination system provided uniform illumination of the monitoring area under low-light conditions, thereby reducing variations in image quality caused by ambient lighting conditions.

The smart-trap evaluation targeted the codling moth (Cydia pomonella) using a conventional pheromone trap with an adhesive plate and a species-specific pheromone lure. A total of 120 images acquired during the 30-day monitoring campaign were evaluated by comparing automatic detections with manual visual counts. Identification accuracy was calculated as the percentage of correctly identified target insects relative to the total number manually confirmed. Energy autonomy was evaluated with the 12 Ah battery fully charged and without direct solar radiation, while maintaining normal acquisition and communication intervals. The system remained fully operational for more than 72 h without external charging.

8. Functional performance evaluation

The environmental measurements obtained from the developed meteorological station were compared with the values recorded by a reference weather station installed in the same orchard area.

The transmission efficiency was evaluated using the relation:

$$\eta = \frac{N_r}{N_t} \cdot 100 \ \ [\%] \tag{1}$$

where:

η – transmission success rate, [%];
N_r– received data packets, [-];
N_t – transmitted data packets, [-].

The mean deviation of environmental measurements was calculated using:

$$MAD = \frac{1}{n} \cdot \sum_{i=1}^{n} |x_i - x_{ref}| \tag{2}$$

where:

MAD – mean absolute deviation, [°C, m/s, mm, W/m²];
x_i– measured value, [°C, m/s, mm, W/m²];
x_{ref} – measured value, [°C, m/s, mm, W/m²].
n – number of measurements, [-].

The pest detection accuracy of the smart trap was evaluated by comparing automatically detected insect counts with manual observations performed during the experimental monitoring campaign.

RESULTS

1. Functional validation of the experimental monitoring system

The developed experimental system operated continuously during the monitoring campaign under orchard environmental conditions. The integrated platform successfully performed simultaneous acquisition of meteorological parameters and automatic pest monitoring using the smart pheromone trap equipped with HD image acquisition capabilities.

The experimental model demonstrated stable operation during continuous field deployment, while the wireless communication subsystem ensured periodic transmission of environmental and biological data to the cloud-based monitoring platform. No significant interruptions of operation were observed during the experimental period.

The modular architecture of the developed monitoring system also facilitated rapid installation, maintenance operations, and reconfiguration according to orchard monitoring requirements.

2. Environmental monitoring results

The environmental monitoring subsystem continuously recorded climatic parameters associated with pest activity and pathogen development during the experimental orchard monitoring campaign.

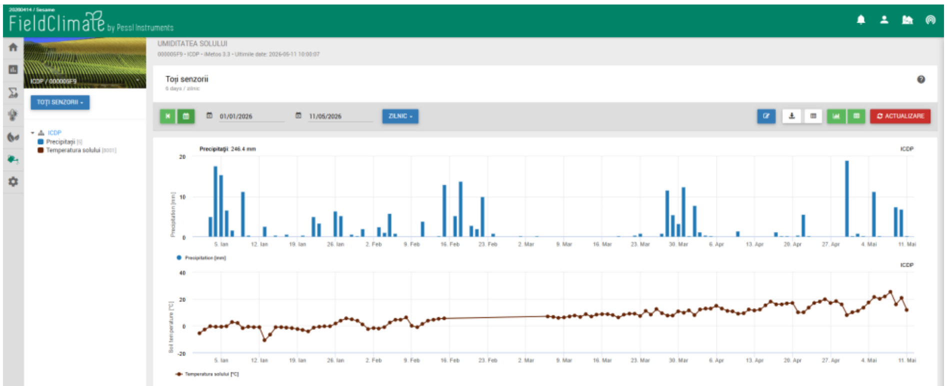

Fig. 7 – Cumulative precipitation recorded during the experimental orchard monitoring campaign

The cumulative precipitation values progressively increased throughout the monitoring campaign, exceeding 120 mm during the analyzed period. Several rainfall accumulation intervals above 15-20 mm were recorded during short time periods, generating elevated humidity conditions within the orchard ecosystem. These environmental conditions favored fungal pathogen development and increased the phytopathological vulnerability of monitored crops.

The environmental monitoring results demonstrated significant climatic variability during the experimental campaign. The cumulative precipitation exceeded 120 mm, while accumulated chilling units surpassed 800 units and accumulated degree-days exceeded 250 °C above the 10 °C thermal threshold. The recorded temperature values varied between approximately -4 °C and 28 °C, with several daily thermal amplitudes above 12 °C. These environmental conditions generated favorable intervals for pest biological activity and phytopathological development. The continuous monitoring platform successfully identified critical climatic periods associated with increased infestation and infection risks, confirming the applicability of the developed system for predictive orchard management and precision phytosanitary monitoring.

3. Monitoring pest activity in pome fruit crops

The developed monitoring platform successfully identified the correlation between environmental conditions and phytopathological risks in orchard crops during the experimental campaign. The recorded climatic data indicated cumulative precipitation exceeding 120 mm, accumulated degree-days above 250 °C, and temperatures ranging from approximately -4 °C to 28 °C. Under these conditions, the estimated aphid attack risk exceeded 60% during intervals characterized by temperatures above 18 °C and relative humidity values higher than 70%, while codling moth activity intensified at temperatures between 20 °C and 24 °C. The monitoring system also detected increased fire blight and apple scab infection risks following precipitation accumulation periods above 5-10 mm and relative humidity levels exceeding 80%, confirming the applicability of the developed platform for predictive phytopathological monitoring and precision orchard management.

Fig. 8 – Peach leaf curl infection risk estimated during the experimental monitoring campaign

The obtained results demonstrated that continuous acquisition and integration of climatic and biological data enabled rapid identification of critical environmental intervals associated with increased pest activity and pathogen infection probability in orchard ecosystems.

4. Monitoring phytopathological risks in stone fruit crops

The developed monitoring platform successfully identified the correlation between environmental conditions and phytopathological risks in orchard crops during the experimental campaign. The recorded climatic data indicated cumulative precipitation values exceeding 120 mm, accumulated degree-days above 250 °C, and temperatures ranging from approximately -4 °C to 28 °C. Under these environmental conditions, elevated pest activity and increased pathogen infection probability were observed, especially during intervals characterized by relative humidity values higher than 70-80% and moderate temperatures favorable for biological development.

Table 3 presents the main environmental conditions recorded during the experimental campaign together with the estimated phytopathological and pest infestation risks identified using the developed digital monitoring platform.

Table 3

Estimated phytopathological risks identified during the experimental monitoring campaign

Monitored parameter	Observed condition	Estimated risk level
Aphid infestation risk	RH > 70%; T > 18 °C	Moderate to high
Codling moth activity	T = 20-24 °C	High
Fire blight infection risk	Precipitation > 10 mm	Moderate to high
Apple scab infection risk	RH > 80%	High
Shot-hole disease risk	Prolonged humidity	Moderate
Moniliosis infection risk	T = 17-23 °C; RH > 75%	High
Peach leaf curl infection risk	T = 10-18 °C	Moderate to high

The obtained results demonstrated that increased humidity conditions, precipitation accumulation above 5-10 mm, and temperatures between 18 °C and 24 °C generated favorable environments for pest biological activity and pathogen development. The developed monitoring platform successfully identified critical phytopathological risk intervals and enabled continuous evaluation of orchard environmental conditions during the experimental campaign.

5. Communication performance and operational stability

The wireless communication subsystem ensured stable transmission of environmental and biological data throughout the experimental campaign. The transmission success rate exceeded 99% under stable communication conditions and remained above 90% in areas characterized by reduced signal intensity.

The implemented retransmission mechanism prevented significant data losses during temporary communication interruptions. The photovoltaic energy subsystem also ensured continuous autonomous operation for more than 72 h without direct solar radiation exposure.

The obtained results confirmed the operational stability, autonomous capability, and applicability of the developed digital monitoring platform for long-term precision orchard management applications.

CONCLUSIONS

The developed platform combined environmental sensing technologies, smart pheromone traps, autonomous photovoltaic energy supply, wireless communication infrastructure, and cloud-based data visualization within a unified precision agriculture architecture.

The experimental results confirmed stable and reliable operation of the monitoring system under orchard field conditions during the 30-day monitoring campaign. The environmental monitoring subsystem successfully recorded climatic parameters associated with pest activity and pathogen development, while the smart pheromone trap enabled automatic monitoring of insect population dynamics.

The obtained results demonstrated that cumulative precipitation values exceeding 120 mm, accumulated degree-days above 250 °C, and relative humidity values higher than 70-80% generated favorable environmental conditions for increased pest activity and phytopathological risk development. Elevated codling moth activity was observed at temperatures between 20 °C and 24 °C, while fungal infection risks intensified following precipitation accumulation periods above 5-10 mm.

The wireless communication subsystem ensured reliable real-time data transmission, with transmission success rates exceeding 99% under stable signal conditions. The photovoltaic power supply system also demonstrated high operational autonomy, maintaining continuous system functionality for more than 72 h without direct solar radiation exposure.

The developed digital monitoring platform proved suitable for predictive phytopathological management and precision orchard monitoring applications. The integration of climatic monitoring, automated pest detection, and real-time communication technologies enabled rapid identification of critical environmental intervals associated with increased infestation and infection probability.

The obtained results confirmed the applicability of the proposed monitoring architecture for modern precision horticulture systems, contributing to improved crop protection efficiency, reduced manual intervention, and enhanced sustainability of orchard management practices.

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