Analysis and Simulation of an IoT System for Measuring Soil Moisture in Avocado Plantations

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Abstract. Modern technologies have benefited agriculture and are used in various agricultural activities, mainly irrigation, to mitigate water scarcity problems. Water scarcity is of particular concern in avocado cultivation due to its water-intensive nature. This study proposes the use of an Internet of Things (IoT) system for avocado cultivation to enable farmers to identify problems and take preventive measures, thus improving crop productivity. The IoT system used data collected from an avocado plantation in Chile. Factors affecting the yield of this crop were studied to validate the proposed system, in addition to simulating harvesting operations, thus demonstrating the relevance of this technology for modern agriculture. This study demonstrates the feasibility of using a low-cost IoT architecture in precision agriculture, thus improving its performance, as well as the importance of collecting data that affect this agriculture in order to support the development of crops through simulations. The conclusions show the need to create an ecosystem that allows the implementation of these technologies, which implies strengthening capacities in terms of knowledge and communication infrastructure, especially considering the rugged terrain of avocado plantations in Chile.

Keywords: Smart Water Management · Smart Agriculture · Precision Irrigation · IoT Platform

1 Introduction

Agricultural activities primarily consume largest amounts of freshwater globally [1], making water scarcity a social and political problem that strongly impacts rural areas in particular [2]. In Chile, this consumption reaches approximately 80%, making it one

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of the 30 countries with the highest risk of water scarcity in the world [3]. Thus, water usage in irrigation must be optimized, particularly when the exact amount of water consumption for each planting line remains unknown.

Avocado farming occupies approximately 32,000 ha (10.8%) of the cultivated area and yields 220 thousand tons of crop, making it one of the most important fruit trees in Chile [4]. The avocado crop maintains high-quality standards, and various technological innovations, as well as drip or sprinkler irrigation are used in their farming [5].

Pruning, soil quality, climate, irrigation, and fertilization are some factors that directly affect the quality and yield of avocados. Therefore, significant efforts, including the use of technology, have been made to improve and optimize these processes to cater to the conditions of each field and facilitate optimal use of resources. Avocados are cultivated mainly in flat areas and on hillsides. In general, the soils where avocado trees are planted are shallow, with very variable textures, low organic matter content, and medium fertility [6]. In terms of climate, frost affects the growth of fruit and shoots on the tree, whereas high temperatures, particularly during the flowering period or when the fruit begins to grow, cause flower drop and fruit burn [7]. Moreover, avocado farming is a highly water- and energy-intensive process and consumes between 7 and 13 thousand cubic meters of water per hectare per year and approximately 400 L of water for each kilo of avocado produced [8].

Avocado trees are sensitive to excess and/or lack of water, and the size of the fruit is proportional to the amount of water consumed. Therefore, the amount of water available for irrigation must be quantified and optimized to meet the characteristics and needs of each crop [9]. Intelligent or precision irrigation (PI) systems are fundamental to guaranteeing good crop harvests [10, 11]. PI is an irrigation management approach, wherein crops are supplied with the required nutrients and water at the desired time, frequency, duration, and volume, thereby improving the crop yield and ensuring efficient water use [12]. This is achieved via data collection (weather, soil type, irrigation, etc.), information processing, efficient irrigation management, and technologies for online detection of problems and automatic control [13].

The Internet of Things (IoT) can be suitably used to address the issues with PI; however, the solution depends on each context and available resources [14].

Herein, an IoT system is proposed to detect the soil moisture content within 1 m of soil depth using moisture sensors that are installed in a trial pit created near the root of the plant and at different depths of 30, 60, and 90 cm. Farmers can proactively identify issues using a mobile application and/or web system and take preventive measures in areas with higher and lower water retention throughout the season. Accordingly, irrigation can be controlled or ceased, as the soil temperature and moisture change linearly over time. Thus, water consumption can be reduced and crop yield per season can be improved. The aim is to investigate whether crop productivity can be improved by monitoring the soil conditions using underground sensors with IoT technology taking into account the climatological aspects of the agricultural sector.

The importance of communication in IoT systems has been recognized [14, 18], but previous research has not considered the specific needs of these configurations, especially in rough terrain or on hillsides [23]. Thus, the implementation required the

incorporation of technologies that would allow for better communication performance with lower data latency. This situation should be considered in future research.

The remainder of this paper is organized as follows. Section 2 presents the literature review and discusses some main existing applications. Sections 3 and 4 present the methodology and development. Section 5 cover preliminary results and discussion, and Sect. 6 concludes the study.

2 Related Work

IoT allows connecting physical elements via different devices to the Internet. It starts from simple things, such as light bulbs, doors, recording cameras, to more complex elements such as health devices, traffic lights, cars and even linking different devices to form smart cities [15]. This interconnectivity is achieved by integrating sensors that collect and transmit data to the Internet, generally via wireless networks [16]. IoT has been successfully implemented in different sectors such as logistics, transportation, health, homes, and agriculture [16–18]. Although its use in agriculture is recent, most IoT systems have focused on monitoring and controlling risks [19]. For instance, an IoT-based irrigation management platform [20] was developed to increase water productivity in main crops. Additionally, a platform for precision agriculture and ecological monitoring with private features was designed using several sensor nodes deployed in various facilities [21].

Another study also focused on improving the yield classification and prediction algorithms that use data obtained via IoT [22], thus realizing the potential of this technology.

A robotic system was also proposed in India to detect soil temperature and moisture [23] by transmitting these data via an IoT platform. Manual controls were employed using a mobile application and Bluetooth to control the robotic system in real-time. Other studies were also conducted to evaluate the benefits of using IoT in agriculture [24, 25].

Developing low-cost, more stable and efficient systems is now an opportunity for innovation [26, 27]. Integrating IoT into proprietary systems and/or public clouds is becoming more and more recurrent [28]. The integration of peripherals and other software components contributes to rapid prototyping in order to make informed decisions, both in terms of system quality and costs [29].

Table 1 shows different systems that are currently employed in the agriculture sector. Kilimo (https://kilimoagtech.com/) is an effective irrigation management platform that connects weather stations in an area with data entered by the user and calculates the evapotranspiration of plants to provide irrigation recommendations. Agri (https://www.agri.cl/) web application is used for managing agricultural activities; it contains modules on irrigation control, climate, and IoT. Instacrops (https://www.instacrops.com/) is a Chilean company oriented toward the development of hardware and software for agriculture by integrating different data sources, artificial intelligence, and computer vision to collect information on key crop parameters. Netafim (https://www.netafim.cl/) focuses on precision irrigation and highlights its own weather stations together with irrigation system sensors. Hermisan (https://hermisan.com/) offers irrigation solutions,

with proprietary plant development by integrating various modules. Agrapp (https://agrapp.cl/) is an application that ensures crop management and works offline; it does not use sensors, climate measurements, or artificial intelligence. Irricontrol (http://www.irricontrol.com.uy/) is a platform that manages a database in real-time using IoT systems and facilitates irrigation planning by running a program selected by the user that indicates the irrigation threshold by permanently updating the soil moisture balance. Aquadaia (http://www.aquadaia.com/) reports on the amount of water needed for the optimal growth of a crop by connecting to the nearest weather station and incorporating various data mining techniques to recommend irrigation options. Orionis (https://orionis-iot.com/) offers products focused on crop management and point solutions for remote irrigation control. Agricultic (https://agricultic.net/) is an IoT platform comprising hardware, software, and applications developed for data acquisition, monitoring, and control of agribusiness processes. It uses multispectral image analysis, data analytics, and field sensors, which together allow the system to monitor climate, soil, and water quality, among other factors.

Table 1. Analysis and comparison of current IoT platforms on the market.

Functional features	A	B	C	D	E	F	G	H	I	J
Web access	X	X	X	X	X	X	X	X	X	X
APP version	X	X	X		X	X	X	X	X	X
Desktop version				X	X					X
Role and profile management	X	X	X	X	X	X	X	X	X	X
Real-time information	X		X	X	X		X	X	X	X
Creation/modification of customized measurements	X	X		X	X	X	X	X	X	X
Customized reports	X	X		X	X	X	X	X	X	X
IoT		X	X	X	X		X	X	X	X
Climate information analysis	X		X	X	X		X	X	X	X
Support	X	X	X	X	X	X	X	X	X	X
Non-functional features										
Customer registration	X	X	X	X	X	X	X	X	X	X
24/7 access	X	X	X	X	X	X	X	X	X	X
Database access	X	X				X	X	X		X
Backups	X	X	X	X	X	X	X	X	X	X
Data download from the cloud	X		X		X	X	X		X	X
99.9% uptime	X	X	X	X	X	X	X	X	X	X
Data import from external files			X	X	X					

Note: A: Kilimo; B: Agri; C: Instacrops; D: Netafim; E: Hermisan; F: Agrapp; G: Irricontrol; H: Aquadaia; I: Orionis; J: Agricultic. Source: Own elaboration based on information from websites

These aforementioned solutions were developed on complex architectures using applications oriented toward irrigation systems for large-scale farming. They also have high implementation costs because of the use of weather stations, telemetry for controlling irrigation and fertilizer supply based on the chemical content in the soil.

In contrast, the solution proposed herein can be modified to suit varying needs and enables the configuration of main parameters based on the geographical characteristics of crops. They are economical and developed using opensource technologies as well as stable and quality components. Thus, it provides farmers with relevant information, using which ideal irrigation and water supply measures can be taken.

3 Methodology

The methodology used for developing the proposed IoT system is designed using metrics that validate the previously defined objectives [30, 31]. The data to be analyzed were obtained from an avocado plantation in the central zone, near the town of Quillota. These data were the actual measurements of soil relative humidity, UV intensity, ambient temperature, and wind speed and direction recorded from August 2019 to March 2020 from a weather station. The avocado plantation spanned 2.5 ha, with approximately 500 avocado trees per ha, with an age of 15 years of maturity. The crop is harvested annually. The land is sandy and irrigated every two days, once or twice a day, using water obtained from a well and an irrigation canal.

This investigation focuses on a specific type of avocado cultivation, with characteristics such as climate and soil type different from those of other regions. Therefore, the factors associated with these regions have been thoroughly studied.

Quality assessment was performed based on the ISO 25000 standard to measure aspects of the product such as data, crop life cycle, and metrics [32–34]. 60% of the established quality attributes in ISO25000 were achieved.

4 Development Process

The methodology used for meeting the proposed objectives is discussed in subsequent sections.

4.1 Relevant Literature Review

A systematic literature search [35–38] was conducted using Google Scholar to incorporate white and gray literature. The inclusion criteria were articles published since 2000, the complete process of avocado cultivation, the influence of land use, determinants of avocado growth, and the use of computer simulation and precision agriculture. Exclusion criteria were articles published before 2017, not considering avocado cultivation, referring to a particular software, and oriented to a particular market (country). The initial search resulted in 918 articles. 37 articles were selected based on the inclusion and exclusion criteria were applied, as shown in Table 2.

Table 2. List of articles analyzed and their corresponding research areas.

Research area	Reference
Avocado tree cultivation	[9, 39–41]
Avocado irrigation	[42, 43]
Irrigation automation	[5, 44, 45]
Precision agriculture	[46–51]
Irrigation technologies	[12, 52–54]
Internet of Things	[18, 19, 37, 38, 55–58]
Telemetry	[59–64]
Machine learning smart irrigation	[65–68]

Three lines of research were identified: automated drip risk systems, water efficiency based on agriculture 4.0, and precision agriculture. Figure 1 shows the sub-areas.

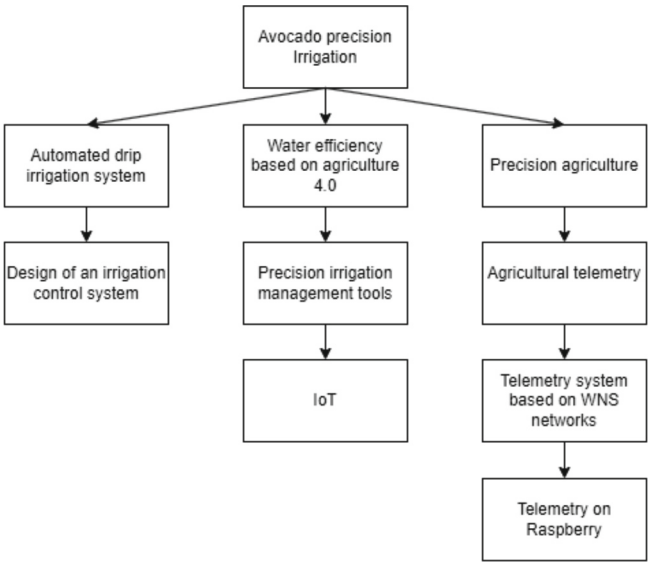


Fig. 1. Main research areas. Source: Own elaboration

The following influencing factors were identified:

Pruning: This process is used to improve productive capacity and fruit size and quality. During the initial years of development, main branches are shaped using three types of pruning: training, fruiting, and restoration.

Irrigation: Avocado farming consumes large amounts of water throughout the year following the water demand curve of the growing area. In Aconcagua Valley, Chile, with a Mediterranean climate, the annual water consumption of the adult avocado trees irrigated

using micro sprinklers varies between low and high localities, fluctuating between 7,000 and 16,000 m^3/ha/year, if a Kc of 0.72 and an Efa of 85% are considered. In this region, part of the water demand is covered by rainfall in June, July, and August. However, 80% of the water demand is covered between October and March.

Soil: The most recommended soils for avocado farming are light-textured, deep, and well-drained. However, clay or clay loam soils can also be used as long as good drainage is ensured. Excess moisture fosters physiological root diseases such as root asphyxia and fungal diseases such as phytophthora cinnamomi [5]. Avocado trees thrive in soils with neutral to slightly acidic pH (5.5–7), as long as salt or sodium accumulation can be prevented. Such accumulations considerably affect crop yield and commonly result in micronutrient deficiencies.

Fertilization: Fertilizers can be used four times during avocado farming, particularly during flowering, fruit setting, and after harvest. This prevents common symptoms caused by nutrient deficiencies such as blackening of vascular bundles in avocados due to lack of potassium, browning of mature leaves due to lack of phosphorus, and yellowing and premature leaf drop due to lack of nitrogen. The crop yields can be improved by addressing nutritional deficiencies or stress as they impact the foliage or leaves of the tree.

Climate: Climate is a vital factor for improved avocado production, both in terms of potential possibilities as well as quality and yield. Frost can cause damage to fruits and trees. During its vegetative development, avocados cannot withstand temperatures below −1.1 °C. However, during winter, they can withstand up to −2 °C or −4 °C depending on the age of the trees. To avoid frost in Chile, avocados are cultivated in soils located on hills with steep slopes, preferably with northern exposure. During flowering and fruit setting, which occur between September and November, daytime temperatures are $\geq$20 °C and >10 °C at night. Lower temperatures during the day or night cause a reduction in fruit setting, particularly in orchards closer to the sea. The base temperature for avocado growth is 12.5 °C–36 °C. The average maximum winter temperatures should be >15 °C for continued growth of avocados. Another climatic factor that affects avocado trees is the wind, which causes fruit drop, breakage, and branch detachment.

Pests: Avocados in Chile are affected by a few diseases. Some isolated cases of fungal and bacterial damage to plants have also been observed. The main phytosanitary issue in Chile is caused by phytophthora cinnamomi, which causes root rot and progressive decay of the tree. Symptoms of such infestations involve the presence of small leaves, yellowish green foliage, leaf drop, semitransparent trees, small fruits, and sunstroke. If the infection is severe, trees may eventually die. This fungus infestation is observed in areas with high soil moisture content and the presence of wounds in the roots.

The irrigation process is simulated, and artificial validation scenarios are created based on parameters such as soil moisture, ambient temperature, avocado tree development stage, soil characteristics (moisture and pH, among others), and irrigation equipment characteristics (actual precipitation intensity of the equipment and percentage of soil wet by the emitters).

4.2 Technological Architecture

Figure 2 shows the proposed IoT architecture comprising a device that collects data related to soil moisture and temperature. These data are then sent to a database in the cloud and processed for visualization by farmers.

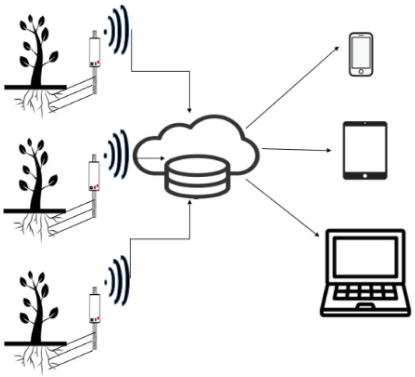


Fig. 2. Proposed architecture. Source: Own elaboration

Python batch processing is performed for transferring information to a new server, from which reports are extracted. Then, simulations are performed, and management reports are delivered using Power BI, Python, and R (Fig. 3).

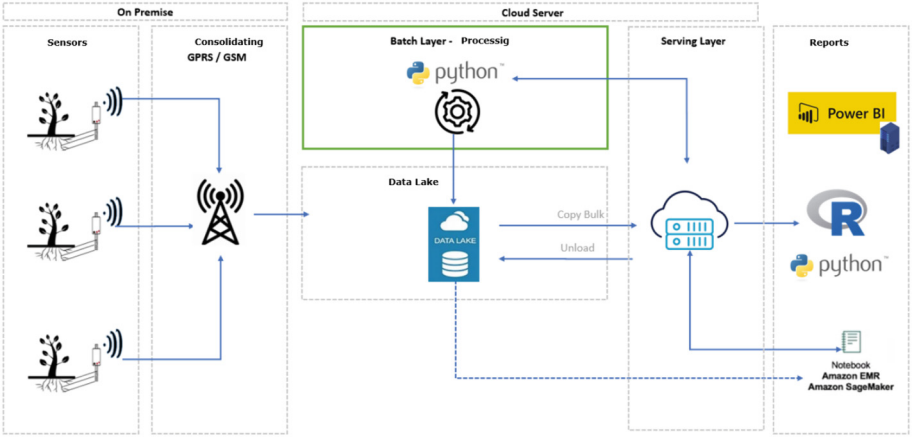


Fig. 3. Technology architecture diagram. Source: Own elaboration

For validation, use cases, specifications, class diagrams, sequence diagrams, and entity-relationship models are generated based on the different software development practices [30, 31] (Figs. 4 and 5).

The following IoT components are considered: Arduino UNO, soil moisture sensor (YL-69), ambient temperature and humidity sensor (DTH11), SIM900D wireless card, and polycrystalline solar panel solar cell.

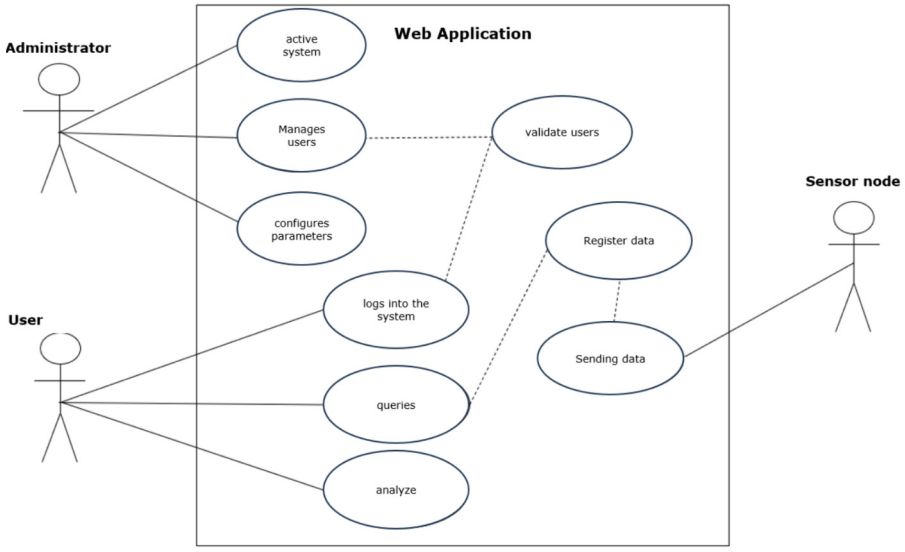


Fig. 4. Example use cases. Source: Own elaboration

4.3 Validation by Discrete Simulation

Discrete simulation reduces the high uncertainty of using various exogenous variables such as environmental variables, weather, frost, and rainfall [69].

Selection of Artificial Validation Scenarios. Seventeen elements are considered essential for the growth and production of all cultivated crops, including avocados [5, 8]. The three essential macronutrients for fruit biomass (roots, trunk, branches, leaves, and fruit) are carbon (C), hydrogen (H), and oxygen (O), and represent 90% of the dry matter of trees. Of these, C is supplied from the atmosphere, which is transformed into carbohydrates via photosynthesis. H and O are provided by water. The essential mineral nutrients for the plant are categorized into macronutrients and micronutrients. Among the macronutrients found in plants, nitrogen (N), potassium (K), and calcium (Ca) are considered primary, whereas phosphorus (P), magnesium (Mg), and sulfur (S) are secondary. Micronutrients include zinc (Zn), manganese (Mn), copper (Cu), iron (Fe), boron (B), molybdenum (Mo), chlorine (Cl), and nickel (Ni). This criterion for differentiating nutrients can lead to confusion, as in extreme cases, the deficit of a given micronutrient can become more important than a macronutrient [5].

Some of the 14 essential mineral elements are supplied via fertilizers due to soil weakness and erosion. Such nutritional deficit is accentuated when the nutrient is not

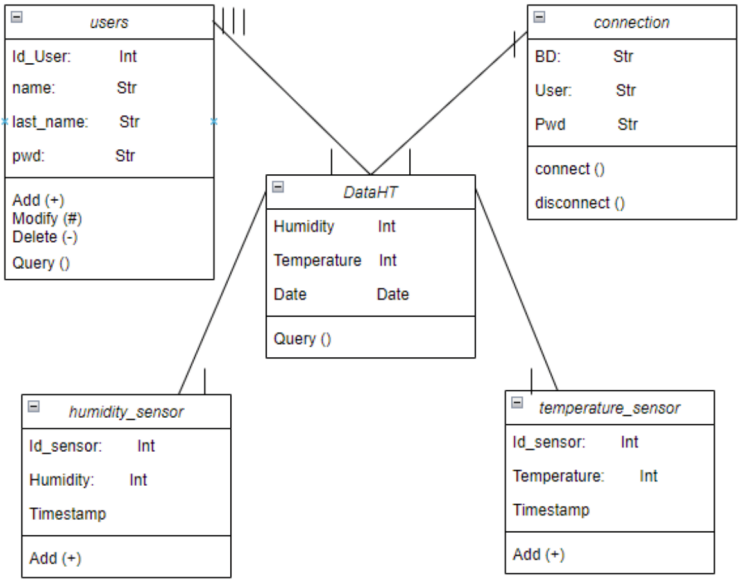


Fig. 5. Example of a class diagram. Source: Own elaboration

sufficiently mobile within the plant and does not reach the strategic site of action, such as buds, flowers, or recently set fruit. In either case, the nutrients will have to be replenished via soil or foliar fertilization. The soils of areas containing avocado plantations, such as the Valparaíso Region, are fertile but lack micronutrients such as Zn, B, and Fe. The aim is to simulate data collection from different IoT devices using simulators in the field of electronic circuit generation and computational systems, and an electrical prototype was developed.

5 Preliminary Results and Discussion

The proposed IoT architecture was developed by modifying a previously reported methodology [70] or via software simulation. The architecture was evaluated based on the ISO 25000 for software quality.

Although a standard IoT infrastructure has not been established [18] such systems are used in avocado agriculture to reduce and optimize water consumption and reduce operating costs. However, their implementation is difficult in terms of infrastructure and trained personnel [71], accounting for a gap in terms of capacity building in this aspect.

The advantage of this IoT system is that it allows real-time data collection for informed irrigation decisions based on the requirements of each farm [24], thus improving performance.

The ability to remotely monitor water usage provides the opportunity to identify potential problems early, such as water stress or leaks in the irrigation system, allowing to anticipate water shortage problems [12, 13].

This paper identifies patterns and trends in PI for establishing long-term farming strategies and planning future farm expenditures related to labor or logistics [10, 11], which have been reviewed in previous literature.

6 Conclusions

The use of IoT in precision agriculture enables irrigation optimization and fosters cost reduction and strategic production planning. However, robust methodologies are required for software simulations, so that the process can be iterated and accurately documented. The planning of crop harvesting process can be simulated using large amounts of data.

The proposed architecture is economical and can therefore be installed in small- and large-scale farms. However, their implementation is limited by communication infrastructure and lack of knowledge regarding its use. In future studies, precision agriculture with IoT can be explored on other crops to compare the effectiveness of methodology and simulations. The scalability of the infrastructure will also be evaluated to enhance the accuracy of conclusions.

To increase the confidence level, larger amounts of data will be required for performing complex simulations. This study focused only on a specific type of avocado crop, with characteristics such as climate and soils different from those of other regions; therefore, an exhaustive review of the factors associated with these regions will be required to replicate the current study.

The limitations of this study are related to the type of avocado chosen and the region in which the implementation was carried out, which, given its specific conditions, does not allow the generalization of the results.

There are also limitations related to the communication infrastructure, which should be considered in the process of implementing these technologies, considering, among other things, the limitations of connectivity and the ruggedness of the terrain.

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