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Article

Water efficiency in polycultures for small-scale agriculture

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Abstract

The adoption of irrigation technologies in small-scale crops faces economic barriers that hinder their implementation. This research developed, implemented and assessed an automated irrigation system for polyculture based on an open-source platform. In September 2023, the system was installed in the Orquiazul® greenhouse, Veracruz, Mexico, being applied to orchids of the *Phalaenopsis*, *Dendrobium* and *Vanda* species. Equipped with substrate moisture, temperature and relative humidity sensors and controlled with an Arduino-R1®, it automatically regulates the water supply according to the needs of each plant. Between September and December 2023, it reduced water consumption by 94%, going from 90 L biannually with manual irrigation to only 5 L with the automated system. In addition, it decreased weekly supervision from 10 to 2 h and achieved a 100% survival rate. Its modular design and low cost favor its adoption in rural communities without requiring advanced technical knowledge. Although the results are promising, it is recommended to evaluate its performance in different crops and climates to ensure its economic viability and long-term sustainability, reinforcing the potential of accessible technologies in small-scale agriculture.

Keywords:

agricultural sustainability, automated irrigation, backyard agriculture, polycultures, precision agriculture.

Introduction

Mexican agriculture faces critical challenges in water management. Its availability is irregular: in abundance, it is wasted; and in scarcity, farmers depend on rain. In Mexico, 76% of fresh water is used in agriculture, with more than 50% being lost due to inefficiencies (CONAGUA, 2023), coupled with the decrease in groundwater sources of up to 30% in two decades (SIAP, 2024), compromising the country’s sustainability and food security.

In this context of water scarcity and climate unpredictability, agricultural practices supported by the Internet of Things (IoT) and artificial intelligence (AI) have been shown to improve agricultural productivity (Qazi *et al*., 2022) and make better use of water use (Al-Hazmi *et al*., 2023). This challenge of efficient water use in agricultural systems is today a constant in rural communities (Statista, 2024).

In Mexico, 21% of arable hectares have technified irrigation and less than 5% of small farmers use digital tools for water management (CONAGUA, 2023; FAO, 2023). Irrigation modernization faces economic, cultural, and technical barriers, limiting agricultural sustainability (Brahmanand and Singh, 2022). To reduce this gap, financing strategies, training and accessible technologies are included, optimizing the use of water and strengthening the resilience of the sector.

Small farmers combine crops with growth cycles subject to poor water management, which can reduce agricultural yields by up to 40% (Juárez and Agudelo, 2021). Researchers such as Lu *et al*. (2022) have developed sensors and the internet of things to optimize irrigation water use and improve crop management. However, their high cost excludes small producers and its design focuses mainly on monoculture systems.

Despite the impossibility and economic resistance of small farmers to adopt crop management technologies (Dahane *et al*., 2022), automated irrigation systems based on open-source platforms emerge as an economical and adaptable alternative (Carrera *et al*., 2021). Their flexibility to integrate with local networks and mobile devices makes them ideal solutions for small-scale and family agriculture (Lucín and Torres, 2023).

In addition to the economic resistance of the small producer to adopt crop management technologies (Barnes *et al*., 2019), their implementation requires investment in learning for installation and operation, creating a gap between technology, purchase and use (Klerkx and Rose, 2020). To reduce this barrier, Kamienski *et al*. (2019) have developed accessible, simple and efficient technological solutions, allowing their adoption by small producers without compromising functionality.

To this end, the research that precedes this article had the main objective of designing, implementing and evaluating an open-source automated polyculture irrigation system (APIS) to improve water efficiency in small-scale agriculture. This article contributed to the design of irrigation systems that allow real-time monitoring of soil moisture and ambient temperature.

It is ideal for small rural producers and polycultures with independent irrigation lines adjusted to the needs of crops in greenhouses, tunnels and backyard orchards, improving efficiency in the use of water and reducing its consumption. The usefulness of the APIS is evaluated in the Orquiazul® orchid greenhouse, located in a community in Mexico.

Materials and methods

Traditional management and problems in Orquiazul®

The research was established at the Orquiazul® greenhouse in San Rafael, Veracruz in Mexico (20° 10’ 07.0” north latitude, 96° 54’ 48.4” west longitude), which grows *Phalaenopsis*, *Dendrobium* and *Vanda* orchids. The plants arranged in five production lines with 15 specimens of the same species per line are managed by two workers under constant supervision in morning and afternoon shifts, they carry out the irrigation, causing fungal problems and root rot, with 13% to 20% mortality per line, affecting the economic viability of the greenhouse. In response to these limitations, an automated polyculture irrigation system (APIS) was implemented, designed to fine-tune the water supply to the specific needs of each orchid species through the use of programmable sensors and controllers.

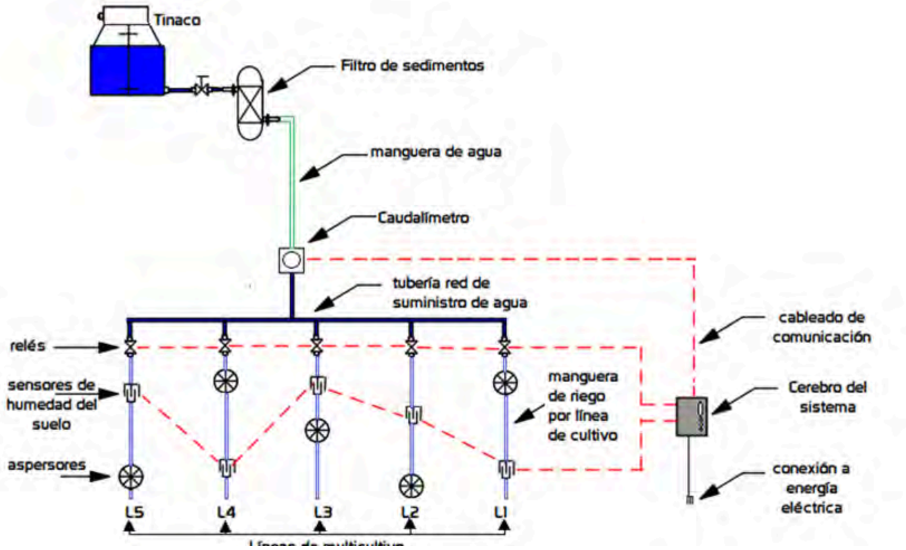
Method

The APIS, programmed in Arduino-R1® (Indautor-Mexico registration number: 03-2023-071911280500-01), operates with independent irrigation lines for each orchid species. It reduces manual monitoring with visual and audible alerts: a green light indicates irrigation in progress, whereas a red light and flashing alert indicate a lack of water after five minutes, with pauses of 30 seconds. It monitors the moisture of the substrate and activates irrigation when it falls below the established threshold. In addition, it stores temperature, relative humidity and substrate moisture data on an SD card, with the option of export to Excel® or Minitab®.

Materials: irrigation system architecture

The APIS, based on Arduino-R1®, uses anti-corrosion capacitive sensors to measure soil moisture and automatically activates each irrigation line according to specific parameters for each species. Its components include soil moisture sensors, ambient temperature (AT), relative humidity (RH), flowmeters, valves, visual (LED) and audible (buzzer) alerts, relays, a Wi-Fi module (ESP32) for remote monitoring, and an SD card for data storage (Figure 1).

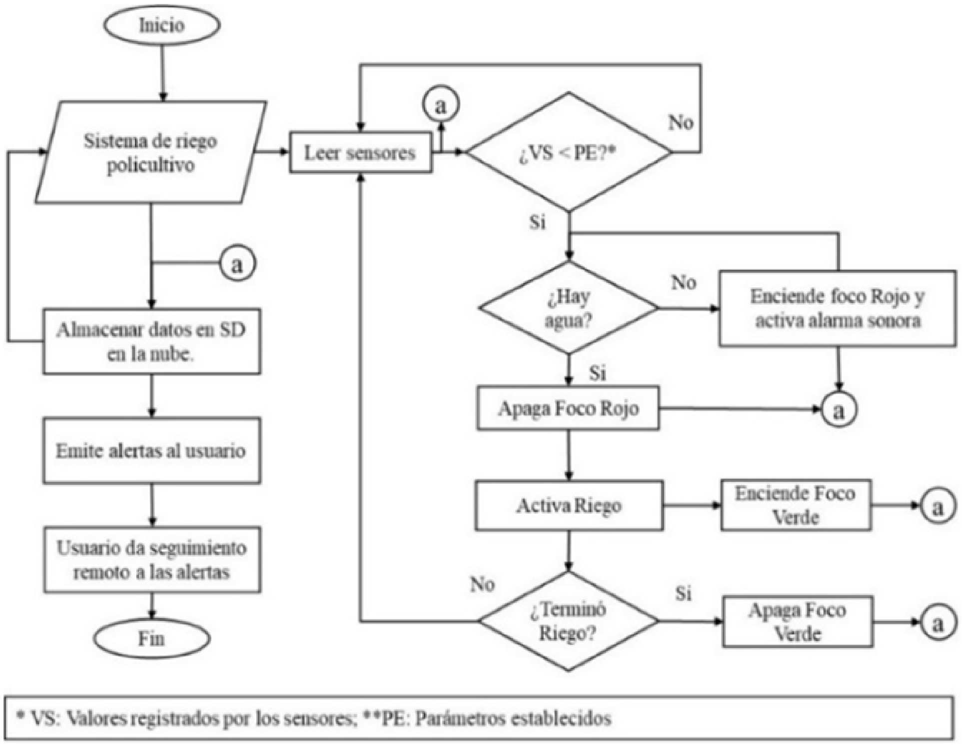
Figure 1. Infrastructure of the polyculture irrigation system (APIS).



Irrigation is adjusted according to pre-established parameters, optimizing water use and avoiding excesses, while allowing real-time monitoring through Wi-Fi with visual and audible alerts, reducing the need for on-site supervision (Figure 2).

Prior to installation, moisture sensors were calibrated with dry and wet substrates to determine specific limits for each species, and flowmeters were adjusted to deliver the precise flow of water according to the needs of the plants. The system was validated for three months, demonstrating its ability to maintain the moisture of the substrate in optimal ranges and operate autonomously, without direct intervention from the farmer.

Figure 2. Operation of the polyculture irrigation system (APIS).



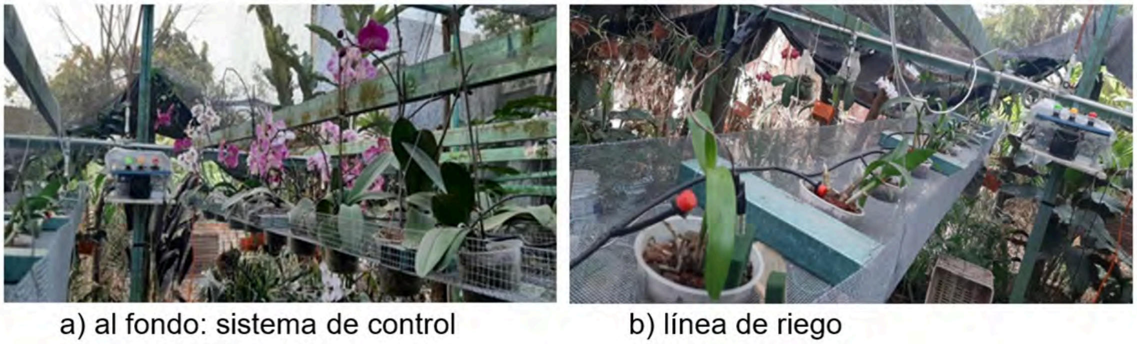
Automated system validation

The optimal ranges of moisture were calibrated by orchid and hourly data were recorded. Then, a Student's t-test was applied (Molina, 2022) and normality was verified with Shapiro-Wilk (Tapia and Ceballos, 2021). In addition, weekly inspections recorded survival and signs of stress. At 16 weeks, moisture, thermal stability, and irrigation efficiency were evaluated and the volume of water was compared between automated and manual irrigation. Finally, the data was analyzed in Minitab®.

Results

Figure 3 shows the irrigation system in operation. Between September and December 2023, hourly data on ambient temperature (AT), relative humidity (RH), and substrate moisture (SM) were recorded and analyzed in Minitab® to generate graphs of system behavior. Figure 4 presents values by production line (L1 to L5), highlighting irrigation (I) moments and upper (UL) and lower (LL) limits for Phalaenopsis (L1, L2), Dendrobium (L3) and Vanda (L4, L5).

Figure 3. Irrigation system in operation. Original photos Orquiazul®.



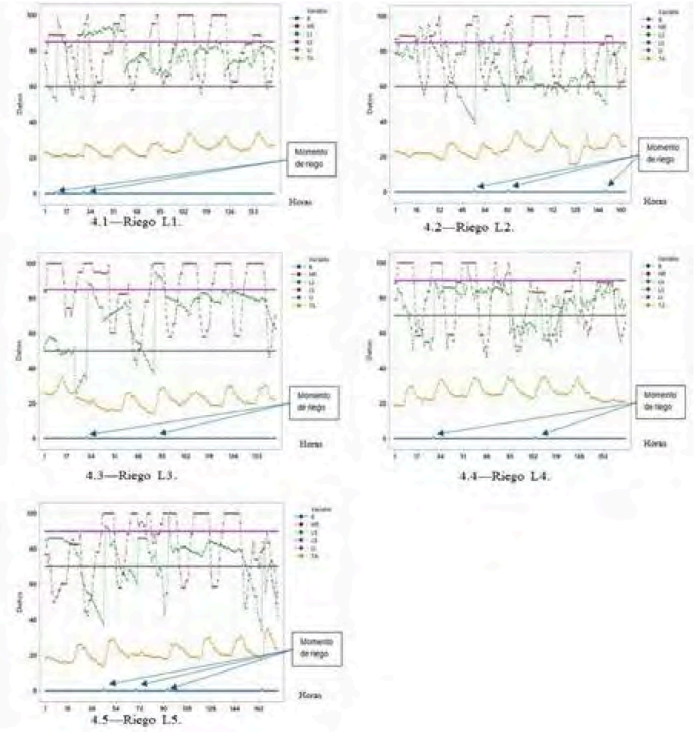
a) al fondo: sistema de control

b) línea de riego

Throughout the study, precipitation ranged from 34.2 to 71.9 mm, RH between 42.3% and 100% and AT between 14 °C and 35 °C (SMN, 2023) with warm humid weather, rainfall in summer and high relative humidity. The greenhouse soil is a mixture of coconut fiber and pine bark, a specialized substrate for orchids that reduces waterlogging and root diseases.

The APIS demonstrated activating irrigation by detecting low moisture. In lines 2 and 4 (Figure 4), irrigation was not activated when the substrate moisture fell below the lower limit, respecting the time and temperature restrictions. This prevented excess water and favored the health of the plants.

Figure 4. Behavior of irrigation lines.



4.1—Riego L1.

4.2—Riego L2.

4.3—Riego L3.

4.4—Riego L4.

4.5—Riego L5.

Table 1 details the parameters of soil moisture (SM), ambient temperature (AT) and relative humidity (RH), achieving 100% survival and keeping SM levels within the limits established for each orchid.

Table 1. Records of moisture and survival of the plants by cultivation line.

	Line		L1		L2		L3	L4	L5
SM (%)	LL	60	60	50		70	70		
	UP	85	85	85		90	90		
	SM (%) (min, max)		77.61 (52, 98)		69.43 (39, 95)		69.7 (26, 95)	75.75 (51, 98)	73.16 (34, 98)
	AT (°C) (min, max)		25.21 (20, 34)		24.63 (16, 34)		22.62 (14, 35)	26.22 (18, 35)	21.72 (14, 35)
	RH (%) (min, max)		94.64 (86, 95)		94.4 (92, 95)		93.96 (91, 95)	94.56 (81, 95)	93.72 (91, 95)
	Live plants (%)		100		100		100	100	100
	SM (average sensed)		77.61		69.43		69.7	75.75	73.16
	SM (SD)		6.25		6.25		8.75	5	5
	t-statistic		3.27		-1.964		1.002	-3.4	-5.47
	p-value		0.0051		0.06823		0.3305	0.00395	6.4346

L1= Phalaenopsis; L2= Phalaenopsis; L3= Dendrobium; L4= Vanda; L5= Vanda.

A t-test was applied to compare the sensed moisture with the operating range (Table 1), considering H0: the mean sensed moisture does not differ from the midpoint of the range and H1: there is a significant difference. With 95% confidence (α= 0.05), the results showed that the sensed moisture does not differ in five lines. Nevertheless, in L4 and L5 (Vanda), it is recommended to adjust watering, increase volume or frequency, and monitor temperature.

The APIS reduced water use by 95% compared to manual irrigation and weekly supervision from 10 to 2 h (Table 2). Before its implementation in Orquiazul®, manual irrigation, carried out three times a week, consumed 90 L per semester. The amount of water depended on the farmer's perception, generating variations in moisture, a mortality of 13%-20%, and favoring fungi and root rot.

Table 2. Comparison between manual and automated irrigation by semester.

Records	Irrigation method				
	Manual	Manual	Manual	Manual	Automated
Semester	2021-2	2022-1	2022-2	2023-1	2023-2*
Water consumption (liters-average)	100	80	100	90	5
Initial plants	35	30	30	40	75
Dead plants	6	4	5	7	0
Mortality rate (%)	20	13	16	17.5	0
Required supervision (hours/week)	10	12	10	16	2
Subjective water application	Yes	Yes	Yes	Yes	No

* = In all cases, the value of n= 16 was considered, which corresponds to the number of weeks in which the system was validated.

The Shapiro-Wilk test for water consumption, mortality rate, and required supervision showed (p> 0.05), indicating that the data do not present significant deviations from a normal distribution (Table 3). Therefore, Student's t-test was applied for independent samples with uneven variances (Welch's test) to evaluate the difference between manual and automated irrigation methods (Table 3).

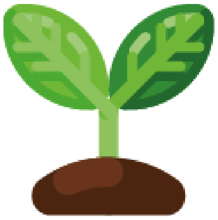


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Table 3. Comparison of irrigation methods.

Irrigation method	Water consumption (L)	Mortality rate (%)	Required supervision (hours/week)
Average (manual)	96.62 ±7.6843	15.91 ±1.8777	13.68 ±2.05
Average (automated)	4.56 ±1.1528	0.98 ±0.5455	2.05 ±0.5123
Shapiro-Wilk	0.9194	0.9507	0.8976
p- value	0.1655	0.5015	0.0737
t-statistic	47.3913	30.5587	22.8843
p- value	0	0	0

In all cases, the value of n= 16 was considered, which corresponds to the number of weeks in which the system was validated.

Student’s t-test shows significant differences ($p < 0.001$) between irrigation methods. With the APIS, water consumption decreased by 94% (90 to 5 L per semester) without affecting the development of orchids. There were no fungal diseases or mortality, achieving 100% survival, compared to the mortality observed with manual irrigation.

Irrigation supervision decreased from 10 to 2 h, optimizing labor effort and redistributing resources to other agricultural activities. The economic benefits per cultivation line increased from 4 000 to 12 000 MXN, depending on the species. The Arduino-R1-based® APIS improves water efficiency, plant health, and agricultural productivity.

Advantages and disadvantages of the APIS

The APIS improves irrigation, preventing waterlogging and root rot, preventing diseases and improving water use. However, the initial investment of 19 000.00 MXN and annual maintenance of 2 500.00 mxn to 3 000.00 mxn can be a complication for small producers. In addition, electrical components require careful handling, and the farmer must understand how they work in order to operate it properly.

Technical implications

The technical implications of the APIS operation include ensuring a continuous water supply, conducting regular inspections of sensors, valves, relays, and connections, and incorporating electrical protection. Training staff in the operation of the APIS and preserving the system periodically are essential for its proper functioning.

Discussion

The APIS improved water efficiency, reducing consumption by 95% and eliminating the subjectivity of manual irrigation, achieving 100% survival. The savings of 85 L per semester are significant due to the total volume of water used in Mexican agriculture; on a larger scale, it would improve the water resilience of rural agricultural systems by optimizing the available resource.

This confirms the effectiveness of automated systems in optimizing irrigation and crop health (Brahmanand and Singh, 2022; García-Salazar *et al*., 2023). In lines 4 and 5 (Vanda), irrigation was adjusted to guarantee the moisture of the substrate, improving the efficiency of the system and reducing root rot and fungal diseases through the APIS.

Compared to other automated irrigation systems, the Arduino R1-based® APIS stands out for its accessibility and water efficiency (Akter *et al*., 2018). Although advanced technologies, such as AI or IoT, reduce water consumption by 30% to 80% (Dahane *et al*., 2022), their costs and complexity limit their adoption in rural communities (Qazi *et al*., 2022).

Although commercial systems are effective on a large scale (Al-Hazmi *et al*., 2023), their high cost limits their adoption by small producers. Automated irrigation systems with commercial controllers offer similar efficiencies, but with higher operating costs (Brahmanand and Singh, 2022). The open-source, low-cost, Arduino-R1®-based APIS is a viable alternative for producers in rural contexts (García-Salazar *et al*., 2023).

This study has important limitations. Although the four-month experiment showed initial benefits, it is not enough to assess long-term performance. Prolonged studies are required in various climatic conditions. In addition, the results, focused on greenhouse orchids, are not generalizable to other species or agricultural configurations (González-Lorence *et al*., 2024).

Conclusions

The results show that the Arduino R1-based® automated polyculture irrigation system (APIS) significantly improves water efficiency in small-scale agriculture. Its implementation in the Orquiazul® greenhouse reduced water consumption by 95%, going from 90 to only 5 L per semester, and guaranteed 100% survival in orchid plants, eliminating the mortality recorded with manual irrigation. In addition, it optimized operational management by reducing irrigation supervision from 10 to 2 hours per week, allowing an efficient redistribution of working time and available resources.

From an economic perspective, the reduction of losses due to plant mortality represented benefits of between 4 000.00 mxn and 12 000.00 mxn per cultivation line and reduced the costs associated with water consumption and manual supervision. The APIS is presented as an accessible and profitable solution for small farmers, promoting sustainable and efficient agricultural practices. Nonetheless, the study was limited to a period of four months, which makes it impossible to evaluate its performance in the long term and in various climatic conditions. It is recommended that additional studies be carried out to validate its operational stability and analyze its economic impact in scenarios with longer periods.

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