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Agro-productive impact of an experimental model for estimating pressure and flow rates in the micro-irrigation system of the 14 July organoponic farm

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Abstract

A theoretical–experimental model was validated to improve the estimation of pressure and flow rate in a low-pressure microirrigation system at the “14 de Julio” organoponic farm in Ciego de Ávila, Cuba. The model estimates hydraulic variables along pipelines with multiple outlets using the principle of energy conservation, the Bernoulli equation, the Darcy–Weisbach head-loss equation, and friction-factor relationships. A field experiment was conducted with two treatments and three replicates involving lettuce, Swiss chard, green beans, and cucumber during the 2021–2023 period. Treatment T-A represented normal operation, whereas treatment T-B incorporated the model, emitter flow-rate and pressure control, and corrective maintenance. Under T-B, the Christiansen uniformity coefficient increased from 87.76% to 93.30%, while the total flow-rate variation coefficient decreased from 0.17% to 0.09%, and flow-rate variation decreased from 34.09% to 9.13%. Crop yields increased by 19% for lettuce, 21% for Swiss chard, 15% for green beans, and 23% for cucumber. The use of rainfall also reduced irrigation requirements and enabled water savings. The results show that the model can support hydraulic diagnosis and the conservation of water and energy in low-pressure microirrigation systems.

Keywords: microirrigation; pipeline with multiple outlets; pressure; flow rate; irrigation uniformity; crop yield

INTRODUCTION

A theoretical–experimental model is a mathematical model constructed from theoretical principles and adjusted and validated using experimental results or field data to represent the actual behaviour of a system more accurately. It is a simplified representation, expressed through mathematical equations, functions, or formulas, of a phenomenon or of the relationship between two or more variables. Such models can represent graphically or visually facts, relationships, variables, parameters, or behaviours that are difficult to observe in reality (Dager et al. 2023; Rojas et al. 2023).

Theoretical–experimental models are important because they are applied in fields such as education, engineering, and the physical, biological, and social sciences. In education, mathematical modelling has become a teaching strategy for addressing mathematical concepts in the classroom (Molina 2017). In engineering education, mathematical modelling is

fundamental because it provides the modelling language used to express the laws governing the engineer's object of work (Sharhorodska et al. 2018).

The application of theoretical–experimental models makes it possible to explore, control, and predict phenomena or processes that may occur in practice. They are used in physics, economics, biology, engineering, and other fields to explain systems, study the effects of their components, and predict their behaviour. These models may take the form of dynamic systems, statistical models, or differential equations (Santos et al. 2018).

In this context, theoretical–experimental models are particularly relevant to the study of irrigation systems because they describe, analyse, and predict the behaviour of fundamental hydraulic variables, including pressure, flow rate, and water distribution. By combining a theoretical basis with validation against field data, these models provide a more accurate representation of actual system performance, which is essential for evaluating efficiency and operation.

Regression models can be used to obtain experimental design and management variables for irrigation systems. They have become an essential tool for integrated water-resource and environmental management, spatial precipitation prediction in watersheds, and the design and management of agricultural irrigation systems. Once calibrated under the specific conditions in which they were developed, they provide a valuable option for pressurised and gravity irrigation systems (Álvarez-Sevilla et al. 2021). Their simplicity and ability to predict the variables involved also make them useful for modelling forecasting problems in irrigation systems (Riveras-Hernández et al. 2023).

Accordingly, the objective of this study was to validate the theoretical–experimental model for estimating pressure and flow rate in the micro-irrigation system of the 14 July organoponic farm.

MATERIALS AND METHODS

Study site

The study was conducted in the micro-irrigation system of the 14 July organoponic farm, located at 21°51'41.9" N, 78°46'23.9" W, in the western part of Ciego de Ávila, Cuba, within the former Ricardo Pérez Alemán Park (Fig. 1).



Fig. 1 Location of the micro-irrigation system

Irrigation-system characteristics at the 14 July organoponic farm

The irrigation system covers 3955.40 m² and contains 144 beds, each 1.40 m wide, 19.62 m long, and 20.0 cm high. The beds are used for intensive production of horticultural crops, including beetroot, carrot, radish, chives, lettuce, Swiss chard, bean, cucumber, leek, aubergine, and others. The unit has one administrator and five production workers.

The evaluated irrigation system comprises a KAWAMOTO submersible pump from Japan with a flow rate of 10 L s⁻¹ (Fig. 2). The main PVC pipe has a diameter of 75 mm over its first 10 m, then decreases to 50 mm over 18 m and finally decreases to 40 mm, which is maintained to the end of the mainline. PVC distribution pipes with diameters of 25 and 40 mm are connected to this final section; polyethylene laterals with a diameter of 19 mm are connected to the distribution pipes at 2.42 m intervals. Each lateral contains nine micro-sprinklers spaced 2.40 m apart to distribute water to the crops (Fig. 3).



Fig. 2 Pumping system at the 14 July organoponic farm



Fig. 3 Distribution pipe and laterals at the 14 July organoponic farm

The system used low-pressure micro-irrigation with NaanDanJain micro-sprinklers comprising a bridge, rotor, anti-mist device, butterfly connector, stake, fine hose, and barbed connector. The emitter operated at an initial flow rate of 39.6 L h⁻¹ and a pressure of 1.7 bar (170 kPa), as shown in Fig. 4.

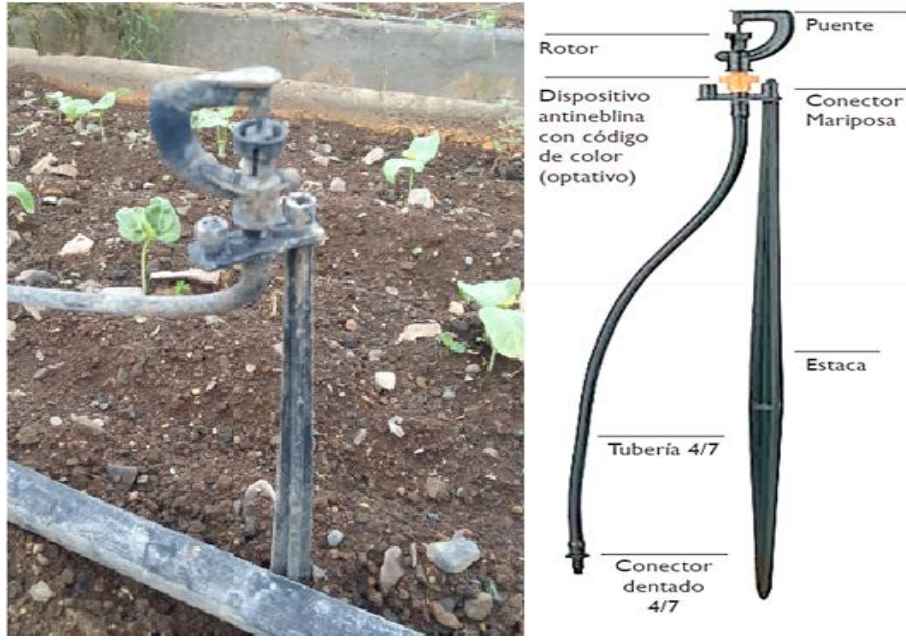


Fig. 4 NaanDanJain micro-sprinkler at the 14 July organoponic farm

Theoretical–experimental model for pressurised irrigation

The theoretical–experimental model (TEM) for pressurised irrigation with multiple-outlet pipes simulates pressure, sectional flow rate, velocity, and head losses from the volume collected at each outlet. It was calibrated and validated in a low-pressure micro-irrigation system. The model is based on conservation of energy, applied through a balance between the lateral inlet and all outlets, using the Bernoulli equation to relate energy and flow velocity (Marín, 2021).

The inlet flow rate of the lateral was determined by summing the flow rates discharged by each emitter using the following equation:

$$Q_0 = \sum_{i=1}^N q_i \quad (1)$$

where Q_0 is the total lateral flow rate ($\text{m}^3 \text{s}^{-1}$), q_i is the flow rate discharged by each emitter ($\text{m}^3 \text{s}^{-1}$), N is the total number of lateral outlets, and i is the index representing the number of evaluated emitters ($i = 1, 2, \dots, N$).

As water moves through each pipe section, the total lateral flow rate decreases because of the combined effects of energy loss and the discharge of flow rate q_i at each outlet, as expressed by the following equation:

$$Q_i = Q_{i-1} - q_i \quad (2)$$

where Q_i is the flow rate through each section ($\text{m}^3 \text{s}^{-1}$), Q_{i-1} is the flow rate through the preceding section ($\text{m}^3 \text{s}^{-1}$), q_i is the flow rate discharged by each emitter ($\text{m}^3 \text{s}^{-1}$), and i is the index representing the number of evaluated emitters ($i = 1, 2, \dots, N$).

From the first lateral outlet onward, the diameter remains constant, but the flow rate varies because the pipe has multiple outlets. Therefore, velocity must be considered when analysing each section. In all cases, fluid velocity was calculated using the economic-velocity method according to Ladino et al. (2020), through the following equation:

$$v_i = \frac{4 \cdot Q_i}{\pi \cdot D^2} \quad (3)$$

where v_i is the flow velocity in each section (m s^{-1}), Q_i is the flow rate through each section ($\text{m}^3 \text{s}^{-1}$), and D is the lateral diameter (m).

Pressure head at each outlet was calculated by establishing an energy balance between the pressure-measurement point (0) and the different outlet points along the lateral (i), using the Bernoulli equation (Girola et al. 2020), as follows:

$$\frac{P_0}{\gamma} + \frac{v_0^2}{2g} + Z_0 = \frac{P_i}{\gamma} + \frac{v_i^2}{2g} + Z_i + \sum_0^i hf_T \quad (4)$$

$$\sum_0^i hf_T = 1.10hf_i \quad (5)$$

where P_0 is the pressure measured by the pressure gauge at the lateral inlet ($\text{kg m}^{-1} \text{s}^{-2}$), P_i is the pressure at each lateral outlet ($\text{kg m}^{-1} \text{s}^{-2}$), v_0 is the flow velocity at the lateral inlet (m s^{-1}), Z_0 is the lateral elevation at the pressure-measurement point (reference level) (m), v_i is the flow velocity in each section (m s^{-1}), Z_i is the lateral elevation at each outlet (m), $\sum hf_T$ is the sum of total friction and local head losses between the two points analysed (m), hf_i is the friction head loss in each section (m), γ is the specific weight of water ($\text{kg m}^{-2} \text{s}^{-2}$), and g is the acceleration due to gravity (m s^{-2}). Local losses were assumed to equal 10% of friction losses.

To calculate the pressure head at each lateral outlet, the pressure term in Eq. (3.4) was isolated to obtain the following expression:

$$\frac{P_i}{\gamma} = \frac{P_0}{\gamma} + \frac{v_0^2}{2g} + Z_0 - \frac{v_i^2}{2g} - Z_i - \sum_0^i hf_T \quad (6)$$

Rearranging the previous equation gives:

$$\frac{P_i}{\gamma} = \frac{P_0}{\gamma} + \left(\frac{v_0^2}{2g} - \frac{v_i^2}{2g} \right) + (Z_0 - Z_i) - \sum_0^i hf_T \quad (7)$$

Substitution of Eq. (3.4) into Eq. (3.8) gives an equation expressed only as a function of flow rate.

$$\frac{P_i}{\gamma} = \frac{P_0}{\gamma} + \left[\frac{\left(\frac{4 \cdot Q_{i-1}}{\pi \cdot D_0^2} \right)^2}{2g} - \frac{\left(\frac{4 \cdot Q_i}{\pi \cdot D_i^2} \right)^2}{2g} \right] + (Z_0 - Z_i) - \sum_0^i hf_T \quad (8)$$

Expanding the squared terms in parentheses gives the following simplified equation:

$$\frac{P_i}{\gamma} = \frac{P_0}{\gamma} + \left(\frac{8Q_0^2}{\pi^2 \cdot D^4 \cdot g} - \frac{8Q_i^2}{\pi^2 \cdot D^4 \cdot g} \right) + (Z_0 - Z_i) - \sum_0^i hf_T \quad (9)$$

Because the irrigation lateral has a constant diameter, a constant K was calculated as follows:

$$K = \frac{8}{\pi^2 \cdot D^4 \cdot g} \quad (10)$$

Including this coefficient in Eq. (3.8) gives the following expression:

$$\frac{P_i}{\gamma} = \frac{P_0}{\gamma} + K(Q_0^2 - Q_i^2) + (Z_0 - Z_i) - \sum_0^i hf_T \quad (11)$$

The previous expression is the general equation for estimating pressure at all outlets of a lateral pipe in pressurised irrigation systems with multiple outlets. This analytical formulation was developed section by section from the pipe inlet to its end. Applying the equation requires knowledge of the head loss in each section between outlets, which was determined using the Darcy–Weisbach equation (Rojas and Orsag, 2017).

$$hf_i = f_i \cdot \frac{E}{D} \cdot \frac{v_i^2}{2g} \quad (12)$$

where hf_i is the friction head loss in each section (m), f_i is the friction factor in each lateral section (dimensionless), E is the outlet spacing (m), D is the lateral-pipe diameter (m), v_i is the flow velocity in each section (m s^{-1}), and i is the section index ($i = 1, 2, \dots, N$).

Substitution of Eq. (3.4) into Eq. (3.13) gives the following equation as a function of the flow rate through each lateral section:

$$h_{f_i} = f_i \cdot \frac{E \cdot 8 \cdot Q_i^2}{\pi^2 \cdot D^5 \cdot g} \quad (13)$$

The friction factor for turbulent flow was calculated using the Swamee–Jain equation (Silva et al. 2017).

$$f_i = \frac{0.25}{\left[\log \left(\frac{\varepsilon/D}{3.7} + \frac{5.74}{NR_i^{0.9}} \right) \right]^2} \quad (14)$$

For laminar flow, the friction factor was estimated using the Poiseuille equation (Moreno 2019).

$$f_i = \frac{64}{NR_i} \quad (15)$$

The Reynolds number as a function of velocity, diameter, and kinematic viscosity is written as follows:

$$NR_i = \frac{v_i \cdot D}{\nu} \quad (16)$$

Expressing velocity as a function of flow rate using the continuity equation gives:

$$NR_i = \frac{4Q_i \cdot D}{\pi \cdot 2g \cdot \nu} \quad (17)$$

where ε is the absolute roughness (m), D is the lateral-pipe diameter (m), and NR_i is the Reynolds number in each section (dimensionless).

Mathematical models are important for estimating pressure at all outlets of a lateral pipe in an irrigation system because they simulate flow-rate variation in the pipes and pressure at the nodes, which is useful for the hydraulic design of multiple-outlet pipes (Morelos 2017).

Agro-productive impact of the theoretical–experimental model

To determine the agro-productive impact of the theoretical–experimental model, a field experiment was conducted in the micro-irrigation system of the 14 July organoponic farm as a case study, because the variables involved could be measured frequently. The evaluated crops were lettuce cv. BSS-13, Chinese Swiss chard, bean cv. Escambray 8-5, and cucumber cv. HXS during 2021, 2022, and 2023. The experiment used a strip design with two treatments and three replications (Fig. 5).

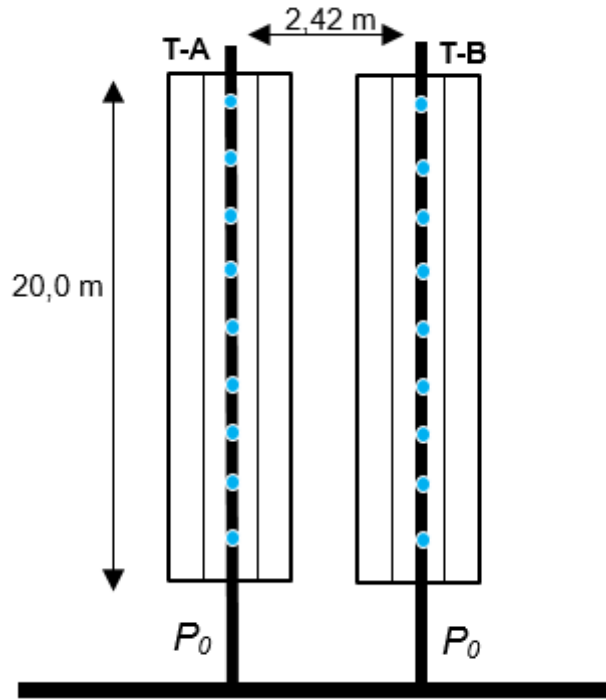


Fig. 5 Schematic representation of the experiment

For each treatment, the experimental unit consisted of a 19.62-m-long bed with nine micro-sprinklers spaced 2.40 m apart. It was subdivided into three replications (inlet, middle, and end), each receiving water from three emitters. Table 1 describes the experimental procedure and the variables evaluated for each treatment.

Irrigation-system uniformity was evaluated using the Christiansen uniformity coefficient, total flow-rate coefficient of variation, and flow-rate variation. The Christiansen uniformity coefficient (CU) for an isolated irrigation lateral in a pressurised irrigation system was determined using the equation of Merriam and Keller (1978), a modification of the equation originally developed by Christiansen for sprinkler irrigation.

Table 1 Treatments

Treatments	Description
T-A	Irrigation under normal operating conditions in the organoponic unit.
	Management actions included:
	• Initial diagnosis of the lateral line. • Volumetric discharge measurement of emitters. • Measurement of the initial lateral pressure (P_0).
	• Control of irrigation-system uniformity (Christiansen uniformity coefficient, total flow-rate coefficient of variation, and flow-rate variation).
	• Measurement of crop yield.
T-B	Irrigation using the TEM based on control of the variables P_i and q_i to improve system management in the organoponic unit.
	Management actions included:
	• Initial diagnosis of the lateral line. • Correction of failures. • Volumetric discharge measurement of emitters. • Measurement of the initial lateral pressure (P_0).
	• System maintenance (lateral-line drainage, replacement of damaged emitters, etc.).
	• Control of irrigation-system uniformity (Christiansen uniformity coefficient, total flow-rate coefficient of variation, and flow-rate variation).
	• Measurement of crop yield.

The total flow-rate coefficient of variation (CvT) was calculated using the equation proposed by Bralts and Kesner (1983), and flow-rate variation (Δq) was obtained using the equation reported by Loaiza (2021). This equation expresses

the difference between the flow rate of the emitter associated with the highest pressure and that of the emitter associated with the lowest pressure along the irrigation lateral. The equations used were as follows:

$$C_U = \left(1 - \frac{\sum |q_i - q_m|}{\sum q_i} \right) \cdot 100 \quad (19)$$

$$Cv_T = \left(\frac{\sigma_q}{q_m} \right) \cdot 100 \quad (20)$$

$$\Delta q = \left(\frac{q_{\max} - q_{\min}}{q_{\max}} \right) \cdot 100 \quad (21)$$

where C_U is the Christiansen uniformity coefficient (%), Cv_T is the total flow-rate coefficient of variation (%), Δq is flow-rate variation (%), q_i is the flow rate discharged by each emitter ($L s^{-1}$), q_m is the mean emitter flow rate ($L s^{-1}$), $q_{\max}$ is the maximum emitter flow rate ($L s^{-1}$), $q_{\min}$ is the minimum emitter flow rate ($L s^{-1}$), and σ_q is the standard deviation of the experimentally measured flow rates ($L s^{-1}$).

The Christiansen uniformity coefficient was classified according to Fernández et al. (2010) as minimum acceptable (75%), medium quality (85%), and high quality (>90%). Irrigation uniformity based on the total flow-rate coefficient of variation was classified as unacceptable (>0.40), low (0.30–0.40), acceptable (0.20–0.30), very good (0.10–0.20), or excellent (0.00–0.10). Flow-rate variation should be 10% according to international standards and was evaluated as uniform irrigation when this threshold was met (Loaiza 2021).

Irrigation was scheduled according to crop water requirements and the irrigation rates established by the Alejandro de Humboldt Institute for Fundamental Research in Tropical Agriculture (INIFAT): $5.0 L m^{-2}$ for lettuce and $8.0 L m^{-2}$ for Swiss chard, bean, and cucumber (INIFAT 2000). The irrigation rates and gross volume, as well as irrigation time and applied water volume, were determined using the following equations:

$$M_b = \frac{M_r}{\eta} \quad (2.5)$$

$$V_b = M_b \cdot A_{Tc} \quad (2.6)$$

$$A_{Tc} = A_c \cdot N_c \quad (2.7)$$

$$A_c = B_c \cdot L_c \quad (2.8)$$

$$T_r = \frac{V_b}{V_a} \quad (2.9)$$

$$V_a = \frac{q_e \cdot N_e \cdot N_c}{60} \quad (2.10)$$

where M_b is the gross irrigation rate ($L m^{-2}$), M_r is the irrigation rate according to soil type ($L m^{-2}$), η is irrigation-system efficiency (dimensionless), V_b is the gross irrigation volume ($L d^{-1}$), A_{Tc} is the total bed area (m^2), A_c is bed area (m^2), N_c is the number of beds, B_c is bed width (m), L_c is bed length (m), T_r is irrigation time (min), V_a is the applied water volume ($L min^{-1}$), and q_e is emitter flow rate ($L h^{-1}$).

RESULTS AND DISCUSSION

Analysis of the agro-productive impact of the theoretical–experimental model

Table 2 shows irrigation uniformity in the micro-irrigation system of the 14 July organoponic farm for the two treatments, based on the Christiansen uniformity coefficient (CU), total emitter flow-rate coefficient of variation (CvT), and flow-rate variation (Δq). Under treatment T-A, the Christiansen uniformity coefficient was 87.76% (medium-quality

uniformity) and the total emitter coefficient of variation was 0.17% (very good uniformity). Under treatment T-B, which used the theoretical–experimental model, the corresponding values were 93.30% (high-quality uniformity) and 0.09% (excellent uniformity).

Table 2 Comparison of treatments T-A and T-B according to irrigation-uniformity criteria and crop yield

Evaluation criterion	T-A	T-B
Christiansen uniformity coefficient (CU, %)	87.76	93.30
Total flow-rate coefficient of variation (CvT, %)	0.17	0.09
Flow-rate variation (Δq , %)	34.09	9.13
Crop yield (R. t ha ⁻¹)		
• Lettuce	9.2	11.3
• Swiss chard	25.4	32.2
• Bean	13.9	16.3
• Cucumber	19.4	25.2

Flow-rate variation was 34.09% (poor uniformity) under T-A and 9.13% (good uniformity) under T-B. The irrigation strategy based on the TEM, with control of P_i and q_i , increased the Christiansen uniformity coefficient by 5.54 percentage points and reduced the total emitter coefficient of variation by 0.08 percentage points and flow-rate variation by 24.96 percentage points. All three criteria therefore indicated improved system performance.

The Christiansen uniformity coefficient measures the homogeneity of water application and should exceed the established minimum value (Loaiza 2021; Laserna et al. 2016), whereas the total emitter coefficient of variation quantifies variability in emitter discharge (Basso et al. 2008). Both indicators are important for evaluating irrigation efficiency and uniformity.

Technical maturity was reached after an average of 45 days, according to observations of crop growth and development (Fig. 6). All indicators were satisfactory, with cucumber showing the strongest performance (Fig. 7).



Fig. 6 Vegetative status of lettuce, Swiss chard, bean, and cucumber

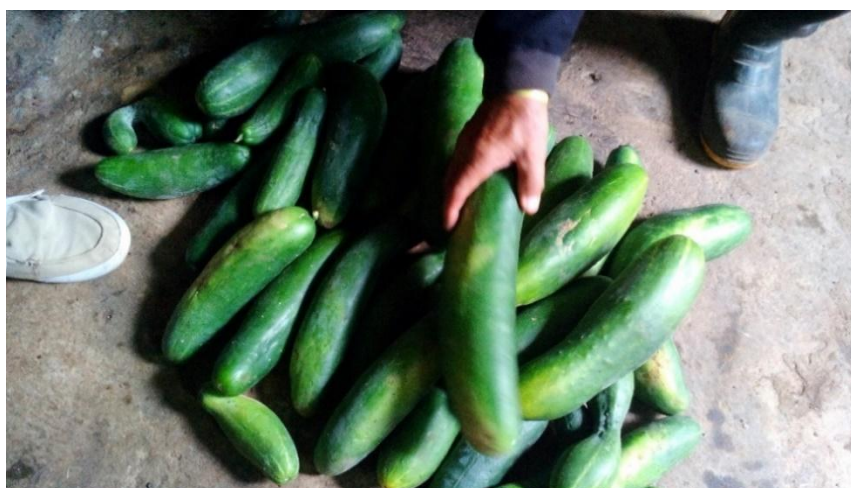


Fig. 7 Maturity stage of harvested cucumber

Table 2 also presents crop yield and production during the evaluated planting season. The results were appropriate for each crop, and application of the theoretical–experimental model (T-B) increased yields by 19% for lettuce, 21% for Swiss chard, 15% for bean, and 23% for cucumber.

Analysis of daily precipitation during 2021–2023 showed a mean annual rainfall of 1473.3 mm, of which 80.5 mm was effective precipitation during October–December, the optimal planting period for lettuce, Swiss chard, bean, and cucumber according to INIFAT (2000). This rainfall contributed to crop growth, development, and maturation; the effective volume was quantified as 1642.4 L per bed.

Table 3 presents daily precipitation depths in 2022 and the number of rainfall events exceeding 5.0 mm ($NdLL > 5.0$ mm) and 8.0 mm ($NdLL > 8.0$ mm), according to crop water requirements and the INIFAT (2000) irrigation rates.

Table 3 Daily precipitation depths in 2022 (mm)

Día	Ene	Feb	Mar	Abr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dic
1									14,5			
2						35,0			32,0			
3		2,5		0,1		23,0				2,5		
4				1,8								
5						51,0						
6	25,8				4,8			4,6	61,0	50,0		
7	3,8				7,8				4,2	8,5		
8					8,4							
9	19,0										3,7	
10	6,0				21,4					6,3		39,5
11	5,3				19,6			21,5		6,5		
12					42,6	20,3		10,0	15,0			
13					1,0							
14						47,0			4,0			17,0
15	0,2				8,0	12,7						
16	1,7			1,3								
17					1,0				18,5			
18					12,5	3,0			12,3	16,5		
19				34,8	15,6							
20				7,0	56,0							
21					4,0							

22				36,5		27,3		1,6
23		26,0	8,3	6,2		23,5		
24			24,5		6,0			
25		2,7	0,1				19,8	
26	13,0	0	160,2			11,0		
27	4,5	24,5					77,5	
28		9,6	13,9					
29		1,0		5,0	70,4			
30				2,0	9,4			
31						18,0		
<i>N_{dLL}</i> > 5,0 mm	6	5	14	9	3	4	9	7
<i>N_{dLL}</i> > 8,0 mm	3	4	13	7	2	3	9	5

Table 4 presents the projected number of irrigation events according to crop water demand (*N_{rp}*), the water volume supplied to the bed (*V_{ac}*), the total water volume that should be supplied by irrigation (*V_{Ta}*), and the irrigation-water volume saved (*V_{saved}*) because of rainfall, quantified as 41,055.0 L.

Table 4 Water volumes supplied to the bed by irrigation and daily rainfall

Crop	<i>N_{rp}</i>	<i>V_{ac}</i> (L)	<i>V_{Ta}</i> (L)	<i>V_{saved}</i> (%)
Lettuce	41	256.3	262 656.3	15.6
Swiss chard	10	100.0	25 000.0	100.0
Bean	26	260.0	169 000.0	24.3
Cucumber	44	440.0	484 000.0	8.5

Using rainfall reduced the number of irrigation events for lettuce, Swiss chard, bean, and cucumber by 21.9%, 90.0%, 34.6%, and 20.5%, respectively, with water savings of 15.6%, 100.0%, 24.3%, and 8.5%. For Swiss chard, rainfall almost completely covered crop water requirements and also reduced pumping-energy consumption.

Rainwater capture and use should be improved through alternative rain gauges and use of the existing roof and cistern, which may also support soil biological activity (Miranda et al. 2022; Calzadilla et al. 2020; Hugues 2019; Brown et al. 2016; Calli et al. 2016; Cely 2015; Brown et al. 2009; Montes 2008).

Irrigation scheduling should account for crop and soil characteristics, crop water demand, system efficiency, and rainfall contribution to avoid waste and optimise water use (Bayabil et al. 2020; Sánchez and Mata 2006; Bayabil et al. 2023).

Reducing the applied water volume decreases pumping time and energy consumption, producing economic benefits (Santos et al. 2009).

Declarations and Responsibilities

Use of Artificial Intelligence Tools: During the preparation of the manuscript, artificial intelligence tools were used to assist with translation into English and language editing.

Consent for Publication: Not applicable, since the figures and tables do not contain personal data or identifiable images of individuals.

Ethical Approval: The study did not involve human participants, animals, or protected plant species. Therefore, ethical approval was not applicable.

Consent to Participate: Not applicable, since the study did not involve human participants.

Ethical Approval: The study did not involve human participants, animals, or protected plant species. Therefore, ethical approval was not applicable.

Data Availability: All data used in this study were generated directly by the authors through their own research and field measurements carried out within the framework of the project. These data form an integral part of the doctoral thesis of Rider Riveras Hernández, which is kept in the authors' files. Although they are not publicly available in a repository, they can be obtained from the corresponding author upon reasonable request for academic or research purposes.

Author Contributions: Rider Riveras Hernández, Oscar Brown Manrique, and Maiquel Lopez Silva participated in the conceptualization, development, and review of the research. R. Rider contributed to the methodology, analysis of the results, and drafting of the manuscript. B. Brown contributed to the field measurements, provided information required for the study, and participated in the drafting and critical review of the manuscript. M. Maiquel contributed relevant information and data and participated in the review of the manuscript. All authors reviewed and approved the final version.

Competing Interests: The authors declare that they have no financial or non-financial competing interests directly or indirectly related to this work.

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CONCLUSIONS

The results obtained indicate that the theoretical–experimental model improved the hydraulic performance and crop productivity of the evaluated microirrigation system. Its application increased the Christiansen uniformity coefficient from 87.76% to 93.30%, reduced the total flow-rate variation coefficient from 0.17% to 0.09%, and decreased flow-rate variation from 34.09% to 9.13%. These improvements were associated with yield increases of 19% for lettuce, 21% for Swiss chard, 15% for green beans, and 23% for cucumber. In addition, the use of rainfall reduced irrigation demand and saved water, particularly for Swiss chard, with a further reduction in pumping time and energy consumption. Under the conditions studied, the model constitutes a useful tool for supporting hydraulic diagnosis, irrigation scheduling, and efficient water use in low-pressure microirrigation systems.

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