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Soil moisture dynamics in the protected cultivation of potato mini-tubers *(Solanum tuberosum)*

Dinámica de la humedad del suelo en el cultivo protegido de minitubérculos de papa (Solanum tuberosum)

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ABSTRACT: The use of irrigation technologies in protected crops constitutes one of the main challenges for the efficient use of water. This study aims to evaluate irrigation uniformity parameters under grow house conditions with zeolite substrate, using micro-sprinkler and nebulizer methods for the cultivation of potato minitubers (*Solanum tuberosum*). The research was conducted at the Institute of Plant Biotechnology (IBP), located at the Marta Abreu Central University of Las Villas. The irrigation systems evaluated were the Hadar 7110 nebulizer and the Mamkad 16 micro-sprinkler. To determine the system parameters, a total of 21 collectors were installed in three rows, in a regular 2x2 m grid arrangement. The parameters evaluated were: uniformity coefficient, distribution uniformity, application coefficient of variation, and application efficiency. The spatial distribution of moisture and its variation during the cycle were also determined. The results showed that irrigation quality criteria were met in both cases, with the nebulizer performing as excellent and the micro-sprinkler performing as good. Better spatial moisture distribution was evident in irrigation with the nebulizer, associated with a smaller range of variation. As a result of uninterrupted irrigation, both sprinkler systems achieved substrate moisture levels above 50%. The most stable moisture level was reached in less time in the nebulizer system, and stable values were achieved throughout the remainder of the cycle.
Keywords: Substrate, Micro-Sprinkler, Efficiency, Irrigation.

RESUMEN: El uso de tecnologías de riego en cultivos protegidos constituye uno de los principales retos para el empleo eficiente del agua. El presente trabajo se propone como objetivo evaluar los parámetros de uniformidad del riego en condiciones de casa de cultivo con sustrato de zeolita, empleando los métodos de microaspersión y nebulizador en el cultivo de minitubérculos de papa *(Solanum tuberosum)*. La investigación se llevó a cabo en las instalaciones del Instituto de Biotecnología de Las Plantas (IBP), ubicado en la Universidad Central ¨Marta Abreu¨ de Las Villas. Los sistemas de riego evaluados fueron el nebulizador modelo Hadar 7110 y el microaspersor Mamkad 16. Para determinar los parámetros de los sistemas se instalaron un total de 21 colectores organizados en tres hileras, en arreglo regular de cuadriculas de 2x2 m. Los parámetros evaluados fueron: coeficiente de uniformidad, uniformidad de distribución, coeficiente de variación de aplicación y eficiencia de aplicación; se determinó además la distribución espacial de la humedad y la variación durante el ciclo. Los resultados mostraron que en ambos casos se cumplen con los criterios de calidad del riego, catalogándose de excelente el desempeño del nebulizador y bueno el del microaspersor. Se evidencia una mejor distribución espacial de la humedad en el riego con nebulizador, asociada a un menor rango de variación. Como consecuencia del riego ininterrumpido en ambos sistemas de aspersión se alcanzan valores de humedad del sustrato superiores al 50%. La humedad más estable se alcanza en menor tiempo en el sistema de nebulizadores lográndose valores estables durante el resto del ciclo.
Palabras clave: sustrato, microaspersión, eficiencia, riego.

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INTRODUCTION

Mini-tuber potato cultivation is currently a specialized method for producing high-quality, pathogen-free seeds. The process is carried out under controlled conditions in grow houses with lighting, temperature, and relative humidity within specific ranges (Veitía-Rodríguez et al., 2016). Among the most commonly used substrates are peat, perlite, vermiculite, manure, and zeolite. Their main requirements are inert behavior and good drainage. However, minituber production using in vitro-propagated plants presents several challenges, such as achieving high uniformity of population growth and increasing tuber yield and quality. Technological limitations include the application of fertigation schemes with commercial formulations and the variation in agrometeorological factors that affect irrigation quality (García-Segura et al., 2021; Cioloca *et al.*, 2024; López *et al.*, 2025).

Furthermore, the use of zeolite as a substrate in grow houses improves the conditions for microtuber growth. Zeolite is a naturally occurring microporous aluminosilicate mineral with excellent physical properties and a distinctive crystal structure. Its use lowers pH and improves cation exchange capacity. Its use is associated with high adsorption efficiency due to its high internal surface area. The high number and distribution of pores in zeolite significantly increases adsorption potential, making it very useful in agricultural and soil amendment applications. As a result, soils amended with zeolite retain more water and nutrients, reducing irrigation frequency and improving plant growth (Sánchez *et al.*, 2006; Urbina-Sánchez et al., 2011; Franco *et al.*, 2024).

Under protected conditions, irrigation management in potato cultivation is vital to achieving expected yields. Maximum water demand should be concentrated during the tuberization and thickening phases, ensuring the required quantity and quality. To achieve efficient irrigation, it is necessary to apply water in the appropriate amount, according to the substrate conditions, and at the right time, ensuring sufficient moisture content and even distribution throughout the plot. To properly moisten the soil, it is essential to understand how water moves, how it is stored, how it is absorbed by plants, and what losses occur (García-Segura et al., 2021).

Micro-sprinkler and misting systems offer opportunities to increase irrigation efficiency in grow rooms; however, their use under imprecise patterns can have negative impacts. Their advantages include increased relative humidity and the resulting reduction in temperature, thus avoiding heat stress, and uniform foliage distribution and cleanliness. However, they pose a greater risk of fungal diseases, excessive water use, and the resulting leaching of nutrients (Colombi *et al.*, 2023). The present work aims to evaluate the parameters of irrigation uniformity under conditions of cultivation house with zeolite substrate, using the methods of micro-sprinkler and nebulizer in the cultivation of potato minitubers *(Solanum tuberosum)*.

MATERIALS AND METHODS

The research was carried out under the conditions of a Granma-1 model grow house at the Plant Biotechnology Institute located at the Central University of Las Villas, in the city of Santa Clara, Villa Clara, Cuba. The substrate used for minituber production was 100% clinoptilolite-type zeolite, with a particle size range of 1.0-4.0 mm, apparent density da = 0.76 g/cm3, field capacity cc = 38.3%, pmp 16.5%, and porosity p = 63.7% (Urbina-Sánchez et al., 2011).

The Hadar 7110 fogger and the Mamkad 16 micro-sprinkler were used to evaluate the irrigation systems. The foggers were arranged overhead with 3x3 m spacing, a 1.4 mm nozzle, a delivery flow rate of 103 L/h, a working pressure of 1.5-3.0 bar, a rainfall of 11.4 mm/h, and a delivery efficiency of 90%. The micro-sprinklers were installed 5x5 m apart with a delivery flow rate of 252 L/h, a working pressure of 2.5 bar, a rainfall of 10.2 mm/h, and a delivery efficiency of 92%. The systems were installed using high-strength 16 mm polyethylene pipes. Water was supplied by a motor pump with a flow rate of 200 L/min and a pressure of 2.5 bar.

The potato minitubers grown were of the Yara variety, propagated using biotechnological methods, with a yield potential exceeding 32 t/ha, and more than 90% classified as marketable. This variety exhibits good leaf development, an average height of 0.55 m, a dark green color, a vegetative period of 80 to 85 days, and a water demand of 650 mm with a weekly dose of 50 mm distributed evenly according to its development stage.

To determine the parameters of the irrigation systems, a total of 21 collectors were installed in three rows, in a regular 2x2 m grid arrangement, covering an area of 84 m², and the volume of water delivered by the system in

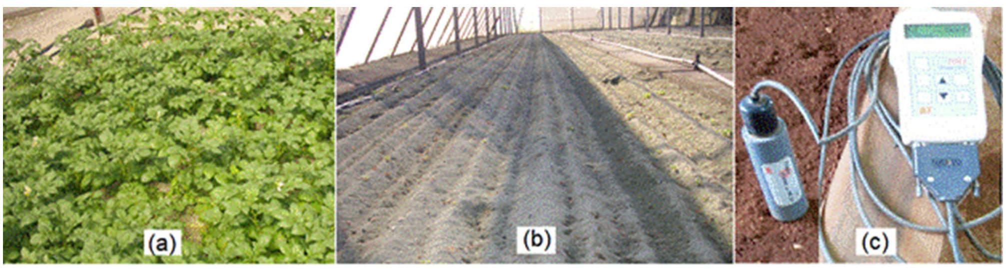

Figure 1. Potato crop (a), zeolite substrate (b) and soil moisture sensor (c).

one hour of irrigation was collected. Substrate moisture measurements were taken following the same sample pattern at 3-hour intervals, until the following 48 hours, at which point the irrigation cycle was repeated. For this purpose, the HH2 Delta T humidity sensor was used. Air temperature and relative humidity were also monitored using a MT306 model mini-weather station.

The irrigation uniformity coefficient (CU) was determined using the following equation (Christiansen, 1942).

$$CU = 100 \ \ 1\text{-}\frac{\sum_{i=1}^{n}|x|}{M\cdot n} \qquad (1)$$

Where:
n: Number of measurements;
M: Average of the collected water quantities, mm;
X: Absolute deviation.

To evaluate irrigation quality, CU ≥ 85% is considered: Excellent uniformity, 80% ≤ CU < 85%: Good, 70% ≤ CU < 80%: Fair, and CU < 70%: Poor.

To determine the uniformity of irrigation distribution (DU), sampling of the dripper flow (Gg) was carried out according to the procedure described by Merriam & Keller (1978), and the following equation was used:

$$DU = \frac{Q_{25}}{Qn}\cdot 100 \qquad (2)$$

Where:
DU: Distribution Uniformity Coefficient (%);
Q_{25}: Average value of the 25% of emitters with the lowest flow rate (ml);
Qn: Average value of all emitters (ml).

Accepted criteria for irrigation uniformity Keller & Bliesner (1990) They define irrigation uniformity as UD ≥ 85%: Excellent; 75% ≤ UD < 85%: Good; 60% ≤ UD < 75%: Acceptable; and UD < 60%: Poor.

The irrigation coefficient of variation was calculated using the following expression:

$$CV = \frac{\sigma}{M} \qquad (3)$$

Where:
σ: mean deviation;
M: average.

The total usable water was determined as:

$$AUT = cc - pmp\cdot d_a\cdot p_{raíz} \qquad (4)$$

Where:
cc: Field capacity (%);
pmp: Permanent wilting point (%);
da: Bulk density (kg/cm3);
p_{raiz}: Root depth (cm).

To present the spatial variation in irrigation distribution, the Kriging interpolation method adapted by Goovaerts (2008). To prepare the maps, records were taken 8 hours after irrigation and the data were tabulated in the Matlab-R2020a program.

RESULTS AND DISCUSSION

Irrigation Uniformity

The results of the evaluation of the different parameters of the micro-sprinkler and nebulizer systems are shown in Table 1. In both cases, irrigation uniformity (UI) is considered excellent according to the criteria proposed by Christiansen (1942), with values above 85%. This assessment is consistent with systems that have been properly designed and are also subject to systematic review and maintenance (Ajete-Gil *et al.*, 2011; Roque *et al.*, 2013). The difference between the CU of each case does not show a significant difference after applying the Fisher test, with p values > 0.05. The irrigation distribution uniformity reaches values that are considered excellent for the nebulizer and good for the micro-sprinkler based on the criteria of Keller & Bliesner (1990). The 2.6% improvement in DU in the nebulizer provides better water distribution throughout the area; however, the statistical analysis yields p values > 0.05, which is considered insignificant at a 95.0% confidence level. Meanwhile, the calculation of the application coefficient of variation (CV) shows better results in the nebulizer system, although the difference obtained is not significant between the two systems.

The usable water content in the zeolite at an estimated root depth of 200 mm was 33.4 mm. Irrigation depth and its relationship to root density and root depth are critical to understanding how plants utilize available water (Veitía-Rodríguez et al., 2016). These factors determine the efficiency with which a crop can absorb water and nutrients, avoiding water stress (Franco *et al.*, 2024).

Tabla 1. Results of the evaluation of the different parameters of the micro-sprinkler and nebulizer systems

Paramerters	Simbol	Irrigation Nebulizer	Irrigation Micro-Sprinkler
Uniformity coefficient, %	CU	87.8	83,7
Distribution uniformity, %	DU	85,2	81,6
Application variation coefficient	CV	0.12	0.14
Total usable water, mm	AUT	33,4	33,4
Applied water, mm	AA	30.0	34.2
Application efficiency, %	EA	111.4	97.7

The applied water volumes achieved high irrigation application efficiency, which prevents losses due to runoff, evaporation, and deep percolation. For irrigation with mist sprayers, this value exceeds 100% as a result of applying a lower volume than the usable water in the substrate.

Spatial variation in water distribution

The spatial variation in water distribution in the zeolite is shown in Figure 2a. Micro-sprinkler irrigation is characterized by a zone with minimum values in the center and multiple zones with maximum values regularly distributed throughout the study area. This pattern coincides with the spatial distribution of the sprinklers, and the maximum humidity with the location of the overlapping zones. Irrigation with nebulizers, on the other hand, shows less discontinuity in humidity (Figure 2b), with a predominance of average values of 41%. Three zones with maximum values distributed in the center and on the periphery are observed, only two of them with values in the range of 44% humidity. Despite the variability found, substrate humidity uniformity coefficients above 80% are obtained for both cases, with low coefficients of variation in ranges suitable for tuber cultivation (Ruiz & Rodrigo, 2011).

The causes of distribution fluctuations in both cases include potential differences in the flow rate of the sprinklers used and the tendency for water to run off due to slight level deviations. Similar work in grow houses using drip systems shows that uniformity varies by up to 5% despite achieving adequate leveling. Similarly, sprinkler flow rates can vary slightly, which must be controlled by increasing the pressure in the pipe sections (Ajete Gil et al., 2011; Ruiz & Rodrigo, 2011).

Substrate moisture variations during the irrigation cycle

The variation in moisture content in the zeolite throughout the 48-hour cycle is shown in Figure 2. Measurements before irrigation began yielded moisture values above 35% in both cases. This initial value corresponds to the substrate's field capacity and corroborates its water retention capacity. The increase in moisture content occurs as a result of uninterrupted irrigation in the following three hours, reaching values above 50%. The intensity with which water is delivered exceeds the zeolite's field capacity, demonstrating a state of water saturation, which is greater in the case of the micro-sprinkler. This excess can be harmful due to increased susceptibility to fungal diseases and the occurrence of nutrient leaching (Colombi *et al.*, 2023).

The rapid decrease in humidity in both cases, which occurs within 24 hours of the cycle following irrigation, highlights that irrigation with nebulizers shows a faster adjustment to more stable humidity values. This is mainly due to the high infiltration capacity of zeolite, which favors the drainage of excess water along with the plant's evapotranspiration processes. Moisture loss through infiltration, runoff, and evapotranspiration has been studied in various studies, demonstrating its relationship with irrigation cycles. (Ruiz & Rodrigo, 2011; Colombi *et al.*, 2023).

As shown in Figure 3, the decrease in substrate moisture is smaller in the last 24 hours, with losses in the range of 4% at the end of the cycle and noticeable after 32 hours. It is noted that these values are within the field capacity range, and their variation does not constitute a risk of water stress for the plants. However, despite the decrease in moisture values in the last 8 hours, agroclimatic conditions are favorable, as there is a decrease in air temperature and an increase in relative humidity typical of nighttime hours. Evapotranspiration processes are slowed by the absence of solar radiation and stomatal closure; these have been studied for different conditions and crops. Minimum moisture content should not fall below 20% due to the risk of water stress in heavy soil conditions. However, previous studies suggest certain short periods of low moisture content to promote root growth (Roque *et al.*, 2013; Colombi *et al.*, 2023; López *et al.*, 2025).

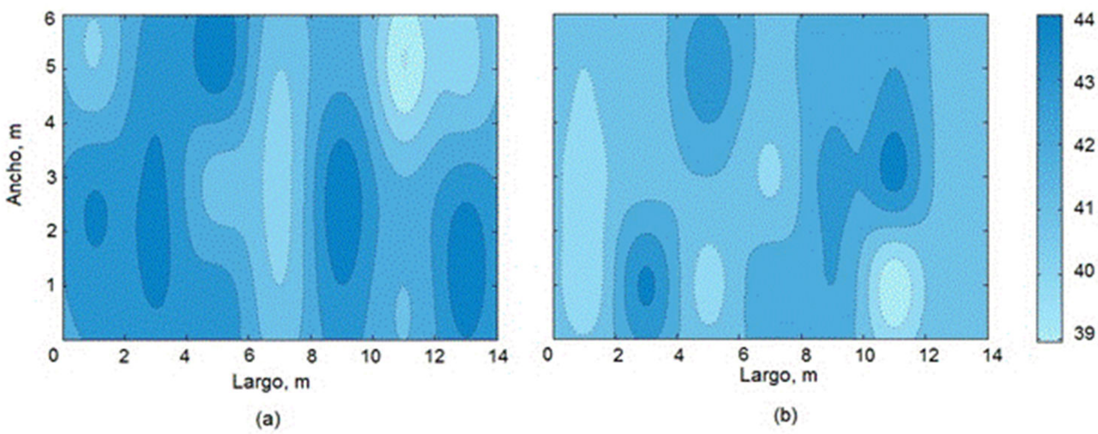

Figure 2. Spatial variation in zeolite moisture content with irrigation. a) irrigation with micro-sprinklers, b) irrigation with nebulizers.

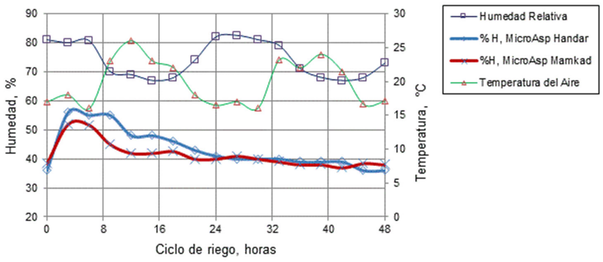

Figure 3. Variation of substrate moisture, temperature and relative humidity.

CONCLUSIONS

The irrigation parameters of the nebulizer system show better results than those of the micro-sprinkler in aspects such as uniformity coefficient, distribution uniformity, and distribution efficiency. In both cases, the irrigation quality criteria are met, with the CU and DU being rated as Excellent for the nebulizer, and the CU and DU being Good for the micro-sprinkler. Similarly, better spatial moisture distribution is evident in irrigation with the nebulizer, associated with a smaller range of variation. However, the substrate uniformity moisture coefficients exceeding 80% in in both cases. The increase in moisture in the zeolite during the three hours of uninterrupted irrigation in both systems reaches values greater than 50%, slightly exceeding the field capacity of the zeolite. During the following 24 hours, moisture decreases rapidly in both systems, and more stable moisture is achieved in a shorter time in the nebulizer system, achieving satisfactory values for the remainder of the cycle.

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