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Artigo Científico

Portable rainfall simulator: evaluation and suitability of plot geometry to improve rainfall uniformity

Simulador de chuva portátil: avaliação e adequação da geometria da parcela para melhorar a uniformidade da chuva

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ABSTRACT

Rainfall simulators are an important tool in many areas of geosciences. The authors of most of the studies published with rainfall simulators try to get the most uniform distribution of precipitation as possible. However, since this is very difficult, indexes are used to assess the greater or lesser uniformity of precipitation in the plot area under study. One of the most used indexes is the Christiansen uniformity coefficient. In this work, changes in the geometry of the wetted area of the plot were analyzed to improve the uniformity of precipitation. This was evaluated through the intensity of precipitation and Christiansen uniformity coefficient in the wet area. The tests were carried out using two models of spray nozzles and different operating pressures. The initial plot geometry was 0.7 x 1.0 m (0.7 m²). The Christiansen uniformity coefficient results were classified as low, while the best performance in terms of precipitation uniformity was obtained at a pressure of 48.3 kPa. Non-uniform precipitation was observable near the outer limits of the plot. Based on the best Christiansen uniformity coefficient results, it was proposed to reduce the effective area of the experimental plot from 0.70 to 0.56 m², leading to a precipitation intensity of 114.07 and 149.20 mm·h^{-1}, and a Christiansen uniformity coefficient of 81.6 and 83.8%, with the two models of spray nozzles. The results showed that adjusting the geometry of the plot can lead, in a simple and fast way, to a better uniformity of artificial rainfall.

Keywords: simulated rainfall; Christiansen uniformity coefficient; spraying nozzles; rainfall uniformity' plot geometry.

RESUMO

Os simuladores de chuva são uma importante ferramenta para várias áreas das geociências. Os autores da maioria dos estudos publicados com simuladores de chuva tentam conseguir uma distribuição da precipitação o mais uniforme possível. Contudo, sendo tal muito difícil, são utilizados índices que visam aferir a maior ou menor uniformidade da precipitação na área da parcela em estudo. Um dos mais utilizados é o coeficiente de uniformidade de Christiansen. Neste trabalho, foram analisadas possíveis alterações da geometria da área molhada da parcela para melhorar a uniformidade da precipitação. Isso foi avaliado através da intensidade da precipitação e do coeficiente de uniformidade de Christiansen na área molhada da parcela. Os testes foram realizados utilizando dois modelos de bicos pulverizadores e diferentes pressões de operação. A geometria inicial da parcela era de 0,7 x 1,0 m (0,70 m²). Os resultados do coeficiente de uniformidade de Christiansen foram classificados como baixos, enquanto o melhor desempenho em termos de uniformidade de precipitação foi obtido a uma pressão de 48,3 kPa. A precipitação com menor uniformidade foi observável próximo dos limites externos da parcela. Com base nos melhores resultados do coeficiente de uniformidade de Christiansen, propôs-se reduzir a área útil da parcela experimental de 0,70 para 0,56 m², levando a uma intensidade de precipitação de 114.07 e 149.20 mm·h^{-1} e a um coeficiente de uniformidade de Christiansen de 81,6 e 83,8% para os dois modelos de bicos pulverizadores. Os resultados mostraram que proceder com ajustes na geometria da parcela pode conduzir, de forma simples e rápida, a uma maior uniformidade da precipitação artificial.

Palavras-chave: chuva simulada; coeficiente de uniformidade de Christiansen; pontas pulverizadoras; uniformidade da precipitação; geometria da parcela.

INTRODUCTION

The rainfall simulator is an important instrument, successfully applied in research to study several hydrological processes, such as soil erosion (YU *et al.*, 2021), infiltration (MENDES *et al.*, 2021), surface runoff (HAN *et al.*, 2021), urban drainage (ISIDORO; SILVEIRA; LIMA, 2022), and on hydrological modelling (MORAES *et al.*, 2019). Rainfall simulators allow rainfall characteristics to be controlled, seeking a similar effect to natural rainfall on a soil parcel (ZHAO; HUANG; WU, 2015). This type of equipment makes possible producing data

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without the need to wait for natural rainfall events, which happens sporadically (CONFESSOR; RODRIGUES, 2018).

A rainfall simulator must be able to reproduce important characteristics of natural rainfall. The evaluation of rainfall simulators is essential to suggest improvements in the equipment, and these results are fundamental for future research. Despite rainfall simulators have been used with success for many decades, it must be emphasized that recent advances in research with these simulators can be committed to the improvement of the equipment. Alves Sobrinho, Ferreira and Pruski (2002) developed a portable rainfall simulator, called InfiAsper, capable of adequately reproduce rainfall intensities up to 100 mm·h^{-1}, with similar characteristics to a natural rainfall, and with a Christiansen uniformity coefficient (CUC) ranging from 82 to 87% in an experimental plot of 0.7 m². Alves Sobrinho, Gómez-Macpherson and Gómez (2008) proposed improvements to the InfiAsper rainfall simulator, where the main changes were the replacement of mechanical and analogical controls for electronics, addition of a lighter adjustable rotating disc, and integration of a surface flow module. Isidoro and de Lima (2015) developed a hydraulic system to stabilize pressure when using spraying nozzles in rainfall simulators. More recently, Macedo *et al.* (2021) studied the InfiAsper rainfall simulator and made improvements with the implementation of an automatic rainfall intensity control system. This system regulates the rotation of the disk and allows the simulation of different rainfall patterns with CUC higher than 75%.

Some limitations of rainfall simulation are usually restricted to the experimental plot and the impossibility to completely replicate natural rainfall characteristics. The novelty of this study is to propose adjustments in the geometry of the experimental parcel to obtain higher rainfall uniformity. Thus, CUC value can be established according to the variation of the experimental plot size. The experimental plot size with an acceptable CUC value can be used in different studies and applications. In general, rainfall simulators with smaller experimental plots have higher CUC values (KIM *et al.*, 2018). Sousa Júnior, Mendes and Siqueira (2017) and Mendes *et al.* (2021) showed that CUC above 70% is sufficient for a 3.0 m² plot area. Spohr *et al.* (2015) and Tossell *et al.* (1987) considered 80% as the minimum CUC for simulators with 1.2 and 1.0 m² of plot effective areas. Iserloh *et al.* (2013) also argued that a well-distributed rainfall, i.e., with CUC above 80%, is essential for experiments with portable rainfall simulators.

The spatial uniformity of simulated rainfall depends on several factors, such as rainfall intensity, size of the experimental plot effective area, nozzle orifice diameter, and operating pressure (ISERLOH *et al.*, 2021). Therefore, this work aimed to: evaluate a portable rainfall simulator regarding the intensity and uniformity of the artificial rainfall produced with different operating pressures and spraying nozzles; and search for a higher rainfall uniformity (quantified by CUC) through adjustments of the plot geometry.

MATERIALS AND METHODS

The evaluation of rainfall uniformity using the portable rainfall simulator took place from May to December 2021. The experiments were carried out at the Irrigation Laboratory of the Department of Water Resources in the Federal University of Lavras (MG), Brazil (latitude 21º13'41.4" S, longitude 44º59'28.6"W, and altitude 845 m). During the tests, air temperature and relative humidity averages inside of the laboratory were of 22.6°C and 63%, respectively. Water quality in the reservoir coupled to the simulator was also monitored. Average values are summarized: pH (7.5), temperature (22.3°C), electrical conductivity (105.1 µS·cm^{-1}), and total dissolved solids (52.3 ppm). In situ, monitoring was made with a thermos-hygrometer model HT-600 (INSTRUTHERM) and by a pH/EC/TDS meter model HI98129 (Hanna). The water viscosity is 0.95 mPa·s and the surface tension is 7.24 N·m^{-1} (AZEVEDO NETTO; FERNÁNDEZ Y FERNÁNDEZ, 2018).

Rainfall simulator description

The original structure of the rainfall simulator is similar to the one developed by Alves Sobrinho, Gómez-Macpherson and Gómez (2008). The equipment is pressurized and follows the same dynamics of water application in a plot of 0.7 m². This rainfall simulator model is capable of generating a droplet distribution that comprises small and large sizes, with non-zero initial velocity, and impact velocity over the plot similar to the natural terminal velocity of a raindrop. This equipment (Figure 1) is composed by a set of independent parts, i.e., support structure, calibration and collection system, electrical network, pumping system, and water application components.

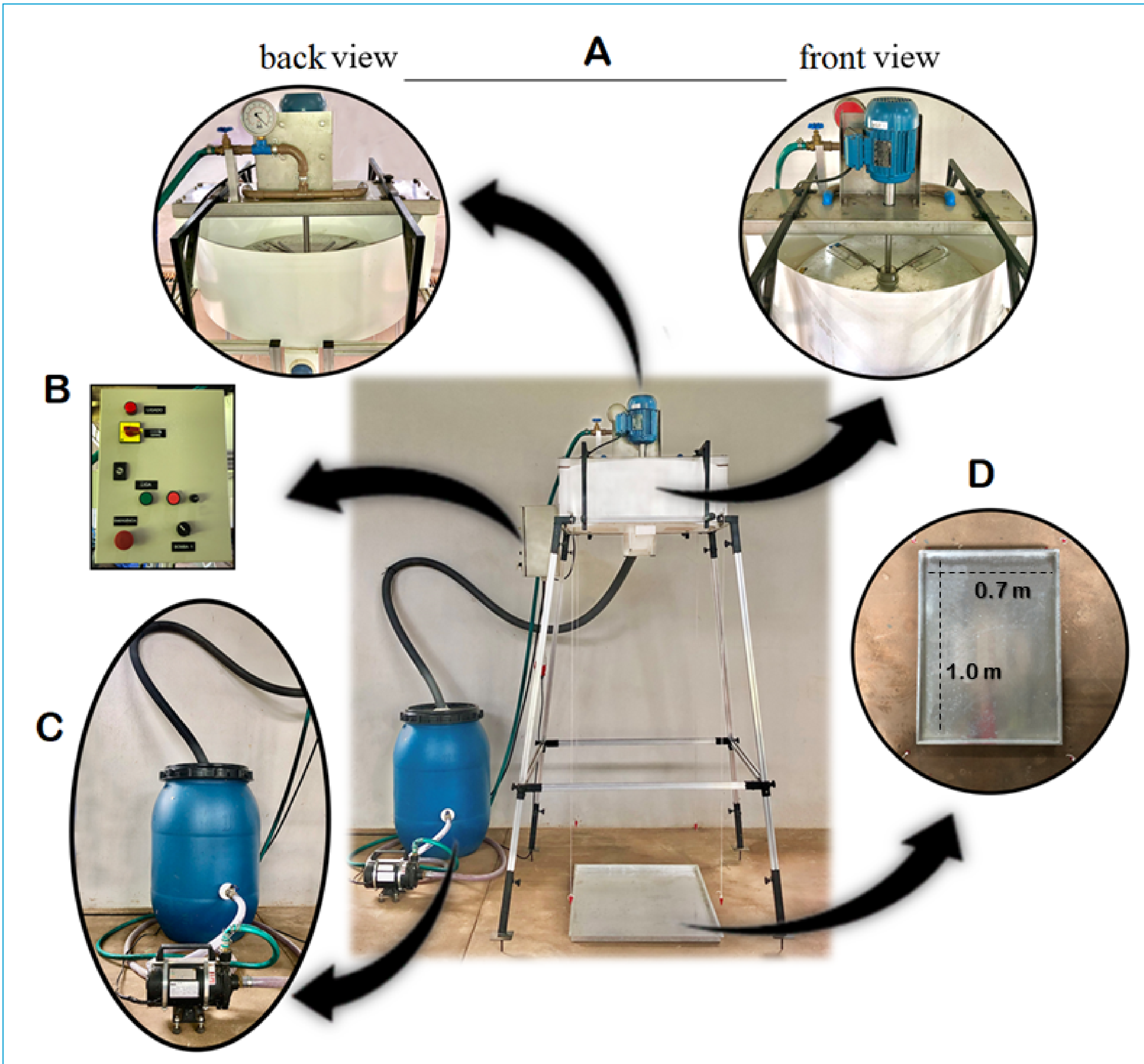
The support structure is assembled with steel tubes that can be adjusted by a telescopic system to level the equipment over the ground level and adjust the height of the nozzles up to 2.30 m over the experimental plot surface. The electrical system operates with 220 V and is controlled by a panel equipped with a variable frequency driver and circuit breakers that activate both a water pump (0.55 kW) and an electric motor (0.55 kW) that moves the rotating disk.

The water pumping system consists of a 150 L reservoir, a centrifugal water pump, gate valve, anti-vibration manometer, and a water application device with two nozzles. The water flows from the reservoir through hoses to the nozzles, where it is sprayed over a steel rotating disk containing four adjustable windows that regulates the rainfall intensity and maintains constant application of water.

The excess water over the rotating disk flows by gravity back to the reservoir through a drain tube. The nozzles flowrate can be regulated by a gate valve. Finally, the plot is a metal plate 0.7 m wide, 1 m long (0.7 m²) and 0.16 m tall, which must be centered below the rainfall application system. This set allows to adjust and calibrate the rainfall intensity.

Intensity and uniformity of rainfall

The equipment was preliminarily tested to check the resulting rainfall intensity for different operating pressures. Two flat fan type spraying nozzles were used: two units of a Veejet 80100 model with the aperture diameter of 4.8 mm, and two units of a Veejet 80150 with the aperture diameter of 6.2 mm (Spraying Systems Company). These spraying nozzles have 12.7 mm of internal diameter and a wide spray pattern, with a nominal spray angle of approximately 80°. The nozzles have a limitation in the spray pattern from a radius of 1.0 m regarding the center of the fixed nozzle (MEYER; HARMON, 1979). The rainfall simulator was configured by adjusting the maximum opening of the four windows of the rotating disk, with a rotation velocity of 121 rpm. Rainfall was generated by applying water under the operating pressures of 27.6, 34.5, 41.4, and 48.3 kPa. Before the beginning of each test, the operating pressure was adjusted and then maintained during a 30 seconds rainfall event, to ensure a steady state flow. During this procedure, the collecting cups were protected from receiving rainfall water. Rainfall intensity was estimated from the ratio between the volume of water collected during the test event (five minutes of duration) and the size of the wetted effective area of plot.



Source: elaborated by the authors.

Figure 1 – Portable rainfall simulator: A) water applicator system, B) control panel, C) pumping system, and D) effective experimental plot.

The simulated rainfall uniformity was evaluated according to the CUC (CHRISTIANSEN, 1942). The rainfall tests were carried out with a duration of 10 minutes, and the water depths were obtained by weighing the collected water from the collecting cups, which were distributed uniformly throughout the wetted effective plot area (0.7 m^2). All the tests were replicated three times, to ensure statistical representativity. The CUC was calculated by Equation 1:

$$CUC = 100\left(1 - \frac{\sum_{i=1}^{n}|X_i - \overline{X}|}{n\overline{X}}\right) \quad (1)$$

In which:

CUC – Christiansen uniformity coefficient (%);

X_i – water depth in each cup (mm);

$\overline{X}$ – average water depth in the cups (mm);

n – number of cups.

Experimental design

The CUC was obtained by collecting the water depth for 10 minutes, using collecting cups with an area of 50.26 cm^2, uniformly distributed in the plot effective area. Twenty collecting cups were placed orthogonally (4 × 5) with spacing of 0.20 and 0.17 m (length and width), along the initial wetted area (0.7 m^2). The operating pressure was changed (27.6, 34.5, 41.4, and 48.3 kPa) to verify how it affected the artificial rainfall uniformity. A minimum limit value for CUC of 80% was set as a criterion to achieve a good performance of the equipment. The best CUC values will be selected at each operating pressure to aid in the validation of the equipment.

The strategy of reducing the wetted area of the experimental plot was used for further evaluation to improve the rainfall distribution. The rectangular wetted area was reduced to 0.56 m² (0.7 x 0.8 m). Then, tests to verify the artificial rainfall uniformity were carried out with 16 collecting cups (4 x 4 mesh) but keeping the same spacing (0.20 and 0.17 m). The validation of the rainfall simulator will be carried out with 0.56 m² wetted area, under the operating pressure that resulted in the best rainfall uniformity in the 0.7 m² wetted area.

RESULTS AND DISCUSSION

Performance evaluation of the rainfall simulator

Rainfall intensities, CUC averages, and standard deviations are shown in Table 1. These results were obtained to evaluate the performance of the rainfall simulator under different operating pressures.

The standard deviation for rainfall intensity and CUC were low, ranging from 0.24 to 0.78 mm·h⁻¹, and 0.11 to 0.79%, respectively. The environmental control (i.e., wind, temperature, relative humidity, etc.) was possible because the tests were conducted in an indoor laboratory. Other authors conducted studies with rainfall simulators in uncontrolled environments. Examples of this are the studies by Alves Sobrinho, Gómez-Macpherson and Gómez (2008) and Sporh *et al.* (2015), in which the artificial rainfall characteristics showed a higher variability with standard deviations of 1.2 to 2.4 mm·h⁻¹ for rainfall intensity and from 1.2 to 3.1 in CUC, in the first study, and with a variability of 6% for rainfall intensity in the second study.

The water flow rate of a nozzle (discharge) is proportional to the product of the nozzle orifice area to the square root of the operating pressure. Thus, a linear relationship is expected between the rainfall intensity and pressure square root, as observed in Figure 2. The high R^2 values obtained ensure the quality of the measurements carried out in the laboratory, as also shown in Table 1.

Regarding the CUC, all the tests resulted in values considered "poor" according to the criteria proposed by Little, Hills and Hanson (1993), i.e., between 70 and 79%. The uniformity test showed that the rainfall simulator performed better when equipped with a Veejet model 80150 spraying nozzle, compared to the 80100 model. This may be a result of the droplets diameter produced, since spraying nozzles with larger openings, as Veejet 80150, when compared with the 80100, produce larger droplets (MEYER; HARMON, 1979), and this may have influenced the rainfall uniformity over the effective plot area. In Alves Sobrinho, Gómez-Macpherson and Gómez (2008), a slightly higher CUC was obtained when the equipment was assembled with the Veejet 80100 spraying nozzles (1% higher in the overall average regarding the Veejet 80150 nozzle). However, this difference did not assure a better rainfall uniformity, as a higher standard deviation for Veejet 80150 can be observed when compared to the Veejet 80100 nozzle. These results may have been influenced by external factors such as temperature, relative humidity, wind, and electric power fluctuations, due to the tests being carried out in an uncontrolled environment.

It was found that higher operating pressure led to better rainfall uniformities. Thus, CUC reached the highest values for 48.3 kPa of operating pressure, both for the Veejet 800100 and 80150 spraying nozzles. This confirms the findings of Montebeller *et al.* (2001), who attributed these findings to the larger wetted area, due to the pressure increase. Moreover, lower water pressures generate rainfall with coarser droplets with a smaller wetted area (CONFESSOR; RODRIGUES, 2018).

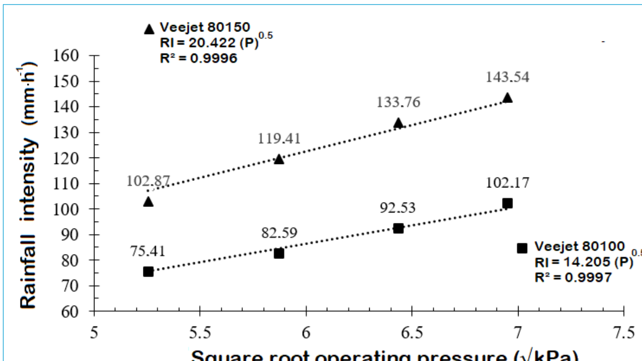
The spatial distribution of rainfall depth measured under the Veejet 80100 spraying nozzle, under different operating pressures, is shown in Figure 3. The values correspond to the average rainfall depth obtained in the collecting cups positioned over the effective plot area. Globally, rainfall depths varying between 5 and 30 mm were observed during a 10-minute application. It is clear a higher volume of water in the central region and a deficit at the edges of the experimental plot, under the different operating pressures, similarly to the observed by Spohr *et al.* (2015). Thus, the best CUC result (74.97%) was obtained with an operating pressure of 48.3 kPa and may be explained by the smaller droplets, well distributed over the effective plot area.

Figure 4 shows the rainfall spatial distribution over the wetted area when using the spraying nozzle model 80150, operating under different pressures. Similar results were observed when using the 80100 nozzle, i.e., higher depths of water in the center and a deficit at the edges of the experimental plot. However, the water depth peaks were higher than the ones produced by the Veejet 80100 under the same operating pressures. This result was similar to Macedo *et al.* (2021), where a higher rainfall concentrated in the center of the experimental plot was also observed. Meyer and Harmon (1979) evaluated the intensity distribution of the spray pattern of Veejet nozzles models 80100 and 80150. These authors found that the intensity distribution varied across the action range (0.9 m) of the nozzle pattern. Thus, the spray pattern of these nozzles is characterized by more water depth in the center of the sprayed area and less in the edges.

Table 1 – Average and standard deviation of rainfall intensity and Christiansen uniformity coefficient obtained with nozzles operating at different pressures over an effective plot of 0.7 m².

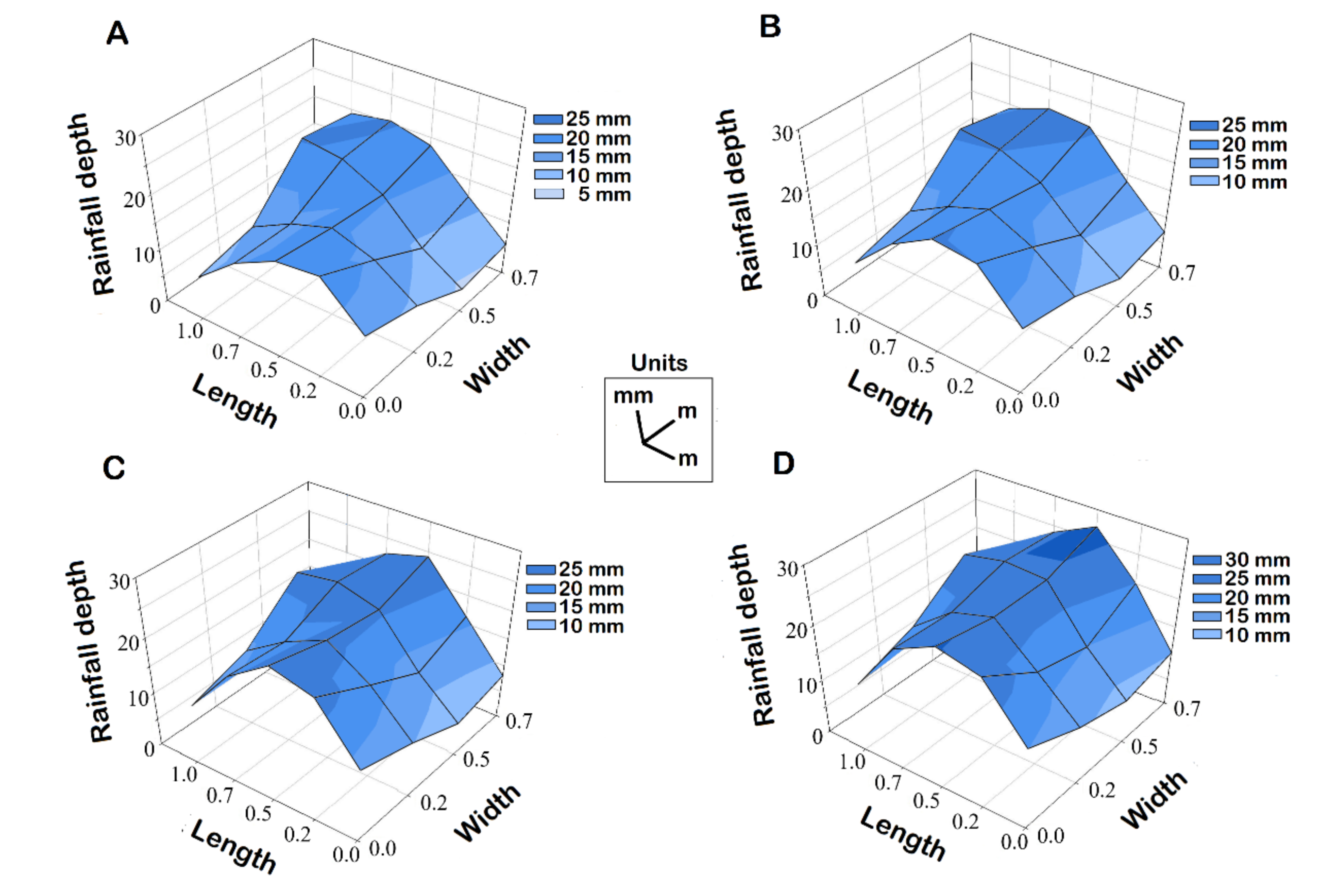
Pressure (kPa)	Nozzle (Veejet)			
	80100ᵃ / 80150ᵇ			
	Rainfall intensity (mm·h⁻¹)		Christiansen uniformity coefficient (%)	
27.6	75.41ᵃ ± 0.69	102.87ᵇ ± 0.78	70.14ᵃ ± 0.79	73.89ᵇ ± 0.54
34.5	82.59ᵃ ± 0.24	119.41ᵇ ± 0.40	72.27ᵃ ± 0.11	75.07ᵇ ± 0.39
41.4	92.53ᵃ ± 0.74	133.76ᵇ ± 0.35	72.87ᵃ ± 0.26	75.00ᵇ ± 0.34
48.3	102.17ᵃ ± 0.40	143.54ᵇ ± 0.51	74.97ᵃ ± 0.75	77.33ᵇ ± 0.63

Note: lowercase letters represent results from Veejet 80100 (a) and 80150 (b) nozzles.
Source: elaborated by the authors.



Note: RI: rainfall intensity; P: pressure; R²: determination of coefficient.
Source: elaborated by the authors.

Figure 2 – Relationship between rainfall intensity and square root of the operating pressure.



Source: elaborated by the authors.

Figure 3 – Spatial distribution of rainfall depth collected under the Veejet 80100 nozzle operating at different pressures: (A) 27.6 kPa, (B) 34.5 kPa, (C) 41.4 kPa, and (D) 48.3 kPa.

The evaluation of rainfall uniformity showed that the operating pressures of 34.5, 41.4, and 48.3 kPa led to CUC values higher than 75%, with the highest value (77.33%) obtained with the 80150 nozzle under the highest pressure (48.3 kPa). Macedo *et al.* (2021) stated that CUC higher than 75% indicate adequacy of the rainfall simulator to represent rainfall events. However, regarding the improvement of rainfall uniformity in small rainfall simulators, Spohr *et al.* (2015) concluded that CUC greater than 80% should be considered as an adequacy criterion.

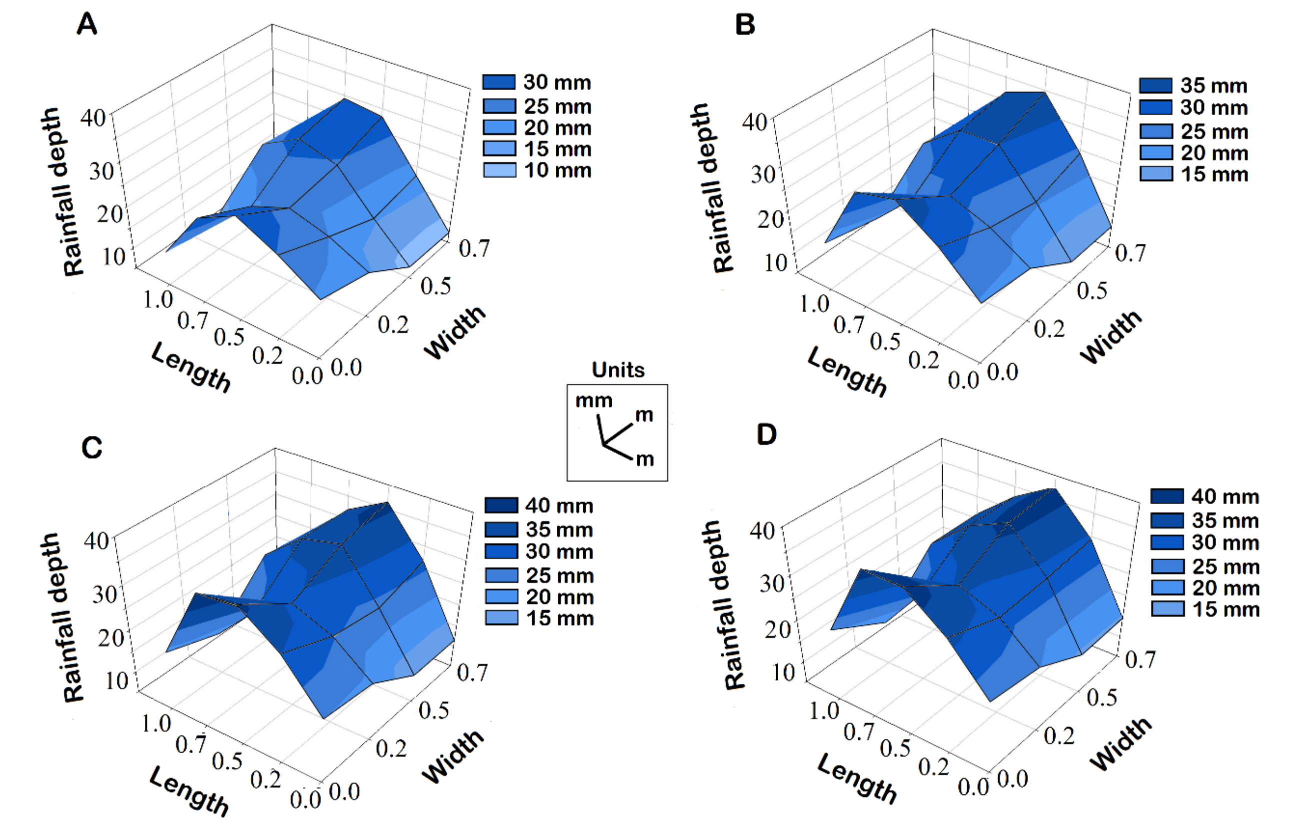
Adequacy of the geometry of the rainfall simulator experimental effective plot

The asymmetry observed in the spray pattern produced by the nozzles, especially at the edges of the 0.7 m² plot, influenced the performance of the simulator related to the spatial uniformity of rainfall. There is no minimum plot-size rainfall simulation well-specified in the literature. Mhaske, Pathak and Basak (2019) state that most small-scale portable rainfall simulators (as in this study) have an effective plot around 0.5 to 1.0 m². Smith (1976) reports that experiments where the plot area is smaller than 0.5 m² are subject to biased results. Therefore, this is an important argument that was considered in this research. The effective area was reduced by 0.1 m at both sides of the plot. Thus, the proposed new plot has a rectangular shape with a total area of 0.56 m². Considering this new plot area, rainfall intensity and CUC were re-evaluated under a pressure of 48.3 kPa. The rainfall spatial distributions obtained with the Veejet 80100 and 80150 nozzles are presented in Figure 5.

The results show an average rainfall intensity of 114.07 (± 0.16) mm·h^{-1} and 149.20 (± 0.72) mm·h^{-1}, respectively for the 80100 and 80150 nozzles. These values are higher when compared to the results obtained in the experimental area of 0.70 m². A higher rainfall intensity was observed with the optimization of the effective plot. CUC results were also higher, with an average of 81.66 and 83.84% for the 80100 and 80150 nozzles, respectively. It becomes clear that the simulator shows a better performance with the smaller experimental plot area, as rainfall uniformity efficiency increased by approximately 9 and 8%, respectively for Veejet 80100 and 80150 nozzles.

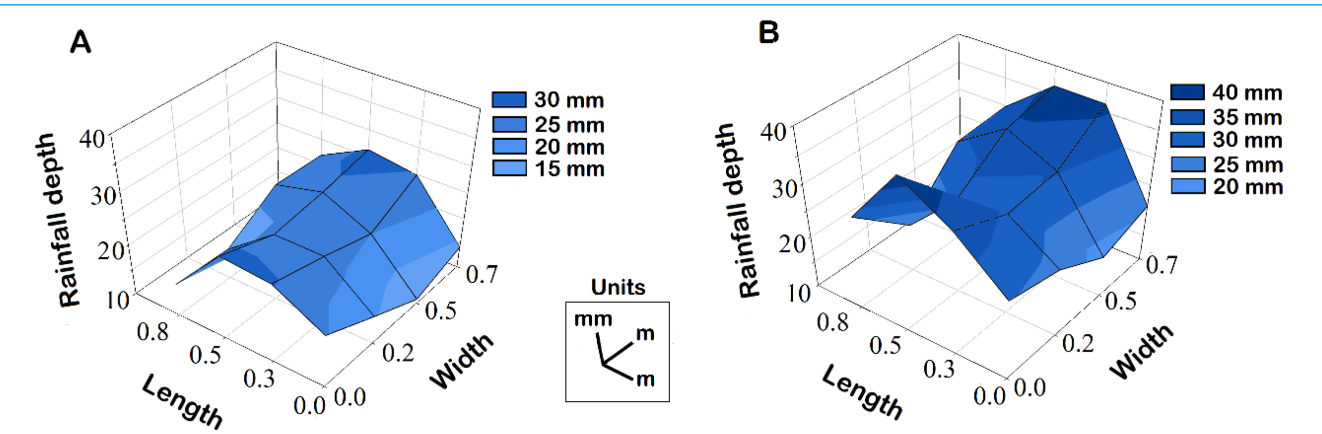
CONCLUSIONS

An evaluation of rainfall intensity and uniformity produced by a portable rainfall simulator equipped with Veejet 80100 and 80150 spray nozzles was carried out. The rainfall intensity ranged from 75.41 to 102.17 mm·h^{-1}, and from 102.87 to 143.54 mm·h^{-1}, for the 80100 and 80150 models, respectively. For an effective plot of 0.7 m², generally, CUC increased, ranging from 70.14 to 77.33%, with increasing operating pressure. The CUC results were classified as reasonable and the best performance of the equipment regarding



Source: elaborated by the authors.

Figure 4 – Spatial distribution of rainfall depth collected under the Veejet 80150 nozzle operating at different pressures: (A) 27.6 kPa, (B) 34.5 kPa, (C) 41.4 kPa, and (D) 48.3 kPa.



Source: elaborated by the authors.

Figure 5 – Spatial distribution of rainfall depth collected under the Veejet 80100 (A) and 80150 (B) nozzles operating at a 48.3 kPa pressure.

rainfall uniformity was obtained at an operating pressure of 48.3 kPa. Aiming to achieve a more uniform spatial distribution of rainfall (i.e., higher CUC), the effective plot area was reduced from 0.70 to 0.56 m^2. The tests with a plot area of 0.56 m^2 under an operating pressure of 48.3 kPa resulted in rainfall intensities of 114.07 and 149.20 mm·h^{-1}, with a CUC of 81.66 and 83.84%, respectively, using the Veejet 80100 and 80150 nozzles. The rainfall simulator presented a satisfactory performance and meets the validation criteria established in the literature. These results show that it is important to consider both the operating pressure and the plot wetted area, when using rainfall simulators, as a proper selection of these variables can lead to a more uniform spatial distribution of the artificial rainfall.

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AUTHORS' CONTRIBUTIONS

Costa, A.R.S.: Conceptualization, Data curation, Writing – original draft. Alvarenga, L.A.: Conceptualization, Data curation, Writing – review & editing. Thebaldi, M.S.: Conceptualization, Data curation, Writing – review & editing. Melo, P.A.: Conceptualization, Data curation, Writing – review & editing. Colombo, A.: Conceptualization, Data curation, Writing – review & editing. Isidoro, J.M.G.P. Conceptualization, Writing – review & editing.

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