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Design of Portable Rainfall Simulator Prototype

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ABSTRACT

A rainfall simulator is laboratory equipment used to simulate rainfall and replicate the characteristics of natural rain with parameters such as rain intensity, raindrop diameter, rain kinetic energy, rain uniformity coefficient (CU), and rain distribution uniformity (DU). Therefore, this study aims to design a rainfall simulator for rain simulation with good performance. Portable rainfall simulator performance tests include functional tests and performance tests. Functional tests to ensure that the portable rainfall simulator is easy to assemble, lightweight, and functions well. Meanwhile, performance tests are carried out by analyzing rain intensity, raindrop diameter, kinetic energy, uniformity coefficient (CU), and rain distribution uniformity (DU). The results of the study indicate that the rainfall simulator functions well, is easy to assemble, and is lightweight so that it can be applied to various field conditions. Meanwhile, the rainfall simulator performance test shows good performance, with a significant linear relationship existing between pump pressure, rain intensity, raindrop diameter, and kinetic energy. Likewise, the results of the rainfall simulator performance evaluation produce good output with an average of CU and DU greater than 80%. Thus, the portable rainfall simulator functions well and can be used for rainfall simulation.

1. INTRODUCTION

Rainfall simulations at various intensities can be performed with a rainfall simulator. This can be done by adjusting the water flow rate to the nozzle according to needs. This rainfall simulator will produce rainfall event data with characteristics similar to natural rainfall (Sousa-Júnior *et al.*, 2017). Generally, rainfall simulators are divided into two categories: those with unpressurized nozzles and those with pressurized nozzles. Unpressurized rainfall simulators typically have their nozzles positioned at a height of 10 to 12 m to produce raindrops with a velocity similar to natural rainfall. Meanwhile, rainfall simulators with pressurized nozzles can produce the desired rainfall velocity with a lower nozzle position (Mhaske *et al.*, 2019).

Previous research (de Sousa Costa *et al*., 2023) has designed rainfall simulators with various shapes and structures, but the construction of rainfall simulators is relatively expensive and impractical, making them difficult to transport to the field for educational and research activities. Therefore, a rainfall simulator design with a lightweight structure, easy to carry and assemble in the field, but with good performance in representing natural rainfall patterns, is chosen. To produce a rainfall simulator that is lightweight, easy to carry and assemble, and has good performance, the rainfall simulator materials, including the iron frame, discharge pipe, and nozzle, are selected from lightweight materials, yet produce natural rainfall patterns. The water discharge pipe to the nozzle is selected with a small diameter and light weight, so that water requirements during rainfall simulation in the field are more efficient (Ngezahayo *et al*., 2021) stated that using a small pipe diameter will minimize the amount of water used for rainfall simulations.

Rainfall simulator performance evaluation can be considered excellent if the rainfall intensity uniformity level is greater than 70 (Ridwan *et al*., 2022). Similarly, raindrop diameters between 2.0 and 2.5 mm and rainfall intensities ranging between 86.0 and 220.0 mm/hour are expected outcomes (Mendes *et al*., 2021). Rainfall simulator performance is highly dependent on its construction and operating principles. The most important criterion in evaluating rainfall simulator performance is the match between simulated and natural rainfall characteristics.

The objective of this research is to design a lightweight, portable, and assembled rainfall simulator that can be used for educational and research activities in the field with excellent performance. Furthermore, a smaller and lighter portable rainfall simulator could expand its application in various field conditions. The expected benefit of this research is the availability of rainfall simulator equipment that can support educational and research activities in various field conditions, thereby improving the quality of educational and research activities.

2. MATERIALS AND METHODS

2.1. Materials and Assembly

The materials used were PVC pipe, square iron pipe, and a micro-sprinkler nozzle. This research consists of several stages, including the design and assembly of a portable rainfall simulator, functional testing, and performance testing. The detailed research stages can be seen in Figure 1.

The design phase includes preparing equipment and materials, then assembling the necessary components so that they are neat, work optimally, and are easy to use (Abbas *et al*., 2020). Several stages in tool design include literature studies, tool design calculations, and equipment testing (Ifan *et al*., 2024). In this regard, the portable rainfall simulator design process begins with identifying the tool's operating system, establishing parameters used in tool performance testing, and sketching. The next stage is assembling the portable rainfall simulator.

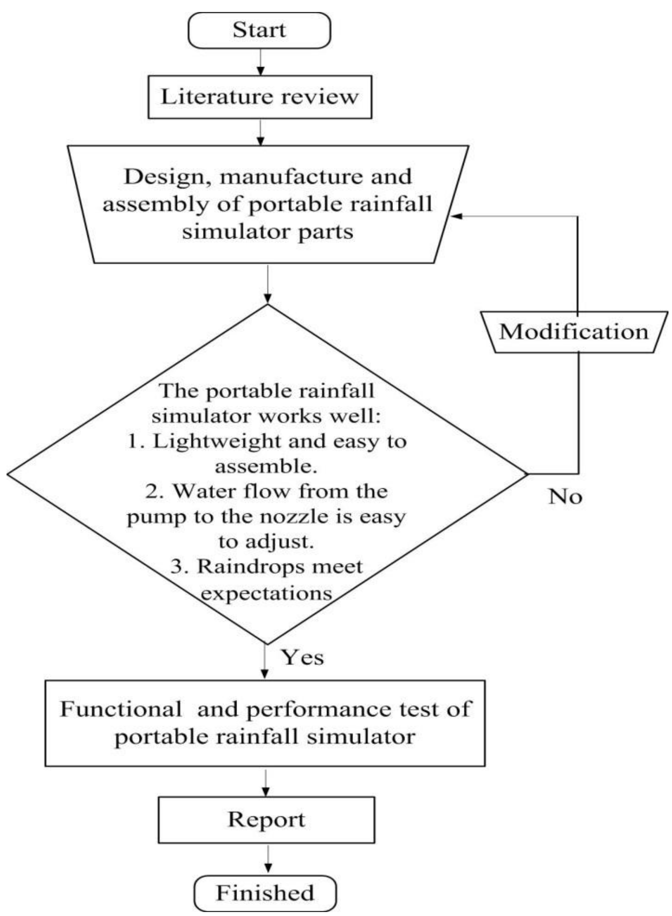

Figure 1. Research stages

Design analysis is a crucial stage to ensure the tool's design objectives meet expectations. Design analysis consists of functional and structural analyses conducted to determine the component requirements of the design (Suhardi & Marhaenanto, 2022). Functional analysis is conducted by observing the function of each component (Yusuf *et al.*, 2017). Functional analysis is useful in calculating component requirements. The main components of this portable rainfall simulator are a 0.55 kW water pump, a 150-L water tank, a nozzle, and a pump pressure gauge (de Sousa Costa *et al.*, 2023). The water pump functions to distribute water from the water tank to the nozzle, which then emits water as raindrops (Rončević *et al.*, 2022).

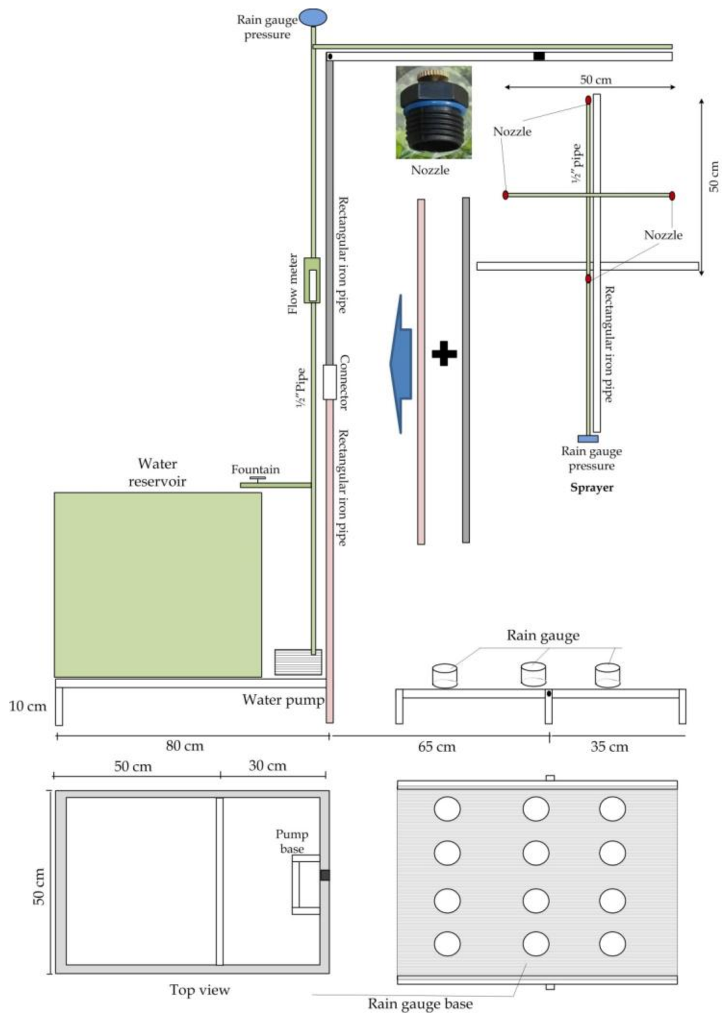

Figure 2. Structure and frame of portable rainfall simulator

Structural analysis arm to ensure the structure of a design can function according to requirements (Suhardi, 2020). The analysis of the rainfall simulator structure includes: (a) pump capacity to properly flow water to the sprayer; (b) a frame shape capable of supporting the sprayer's structural load; and (c) ease of assembly and ease of transporting the rainfall simulator frame to the field, as shown in Figure 2. The rainfall simulator structure is designed for ease of assembly and disassembly after equipment operation. The rainfall simulator frame is made of rectangular iron pipe with rectangular pole supports measuring 50×80 cm, which also function as supports for the water tank. The support poles were made in two 1-m lengths to facilitate connection. Likewise, the sprayer frame is designed to be easily disassembled and installed on the support poles. The selection of materials with these specifications is based on the consideration that the materials and supporting equipment for the rainfall simulator are relatively inexpensive and readily available on the market, as well as easy to assemble.

The working procedure of this rainfall simulator is described as follows: (a) the water pump was turned on to flow water from the water tank to the nozzle through a ½ inch pipe; (b) the water flow was adjusted using the flow control valve located above the pump to regulate the rainfall level. The flow was adjusted in such a way as to produce different rainfall according to needs; (c) took a reading of the pump pressure on a digital pressure gauge installed on the sprayer frame intake. The pump pressure reading was taken for each different rainfall measurement. The specification of the rainfall simulator is described in Table 1.

Table 1. Portable rainfall simulator specifications

Material	Specification	Note
Framework	The legs, pole, and sprayer frame are made from 40 × 40 mm rectangular iron pipe. A 1/2-inch pipe is used to channel water to the nozzle.	A 40 × 40 mm rectangular iron pipe is relatively inexpensive, and its structure is sturdy and lightweight enough for a rainfall simulator frame. A ½-inch pipe can produce greater water flow rates than larger diameter pipes. Using a ½-inch pipe is expected to produce better rainfall uniformity.
Water pump	Output (W): 125 Input (kW): 0.29 Maximum suction power (m): 9 Maximum total head (m): 33 Maximum capacity (L/min): 33 Suction pipe (inch): 1 Pull pipe (inch): 1	A 125W water pump is sufficient to produce uniform rain as desired.
Water reservoir	Capacity: 250 liters	The 250 liter water reservoir capacity is sufficient to hold water during the rainfall measurement simulation process.
Pressure gauge	Digital pressure gauge Weight : 200 gram Bar: 0-40 Drat: 1/8" Battery 2 Pcs X AAA	Digital pressure gauges are very sensitive and easy to read water pressure

2.2. Functional Test

The functional test of the portable rainfall simulator includes (a) a test of the water pump and water flow regulator. The functional test is declared good if the water flow to the nozzle can be adjusted according to needs. The water flow is regulated by closing and opening the water tap above the pump as needed; and (b) a test of the nozzle function is declared good if the nozzle can emit water droplets well, resulting in good raindrop uniformity.

2.3. Performance Test

Rainfall simulator performance testing was conducted by finding a linear relationship between pump pressure, rainfall intensity, raindrop diameter, and raindrop kinetic energy. The average of rainfall intensity can be calculated using equation 1. Meanwhile, the raindrop diameter can be calculated using equation 2 (Silveira *et al.*, 2017).

$$I = \frac{V_{pi}}{A.t} \tag{1}$$

$$Dm = 2.23\ (I)^{0.182} \tag{2}$$

where I is the rainfall intensity (mm/h), V_{pi} is the volume of rainwater collected in the rain gauge (mm^3), A is the surface area of the rain gauge (mm^2), and t is the duration of rainfall (h), and Dm is the raindrop diameter (mm).

Raindrop diameter was measured using an optical instrument that emits a laser beam. When raindrops pass through the laser beam, the laser beam is partially blocked. Meanwhile, a sensor on the other side detects changes in light intensity and measures the raindrop diameter based on the amount of light blocked by the raindrop. Another method for measuring raindrop diameter is to place a container filled with fine flour during a rainstorm. Small clumps of flour will form as raindrops fall on the flour. The diameter of these clumps was then used to determine the diameter of the raindrop.

Rainfall kinetic energy (E_k) is a function of the size of the raindrops and the rain velocity used as rain simulation parameters. The kinetic energy (E_k) of rainfall can be calculated using Equation (3) (Sitepu *et al*., 2017). The raindrop velocity (V) is based on the diameter of the raindrop, which is found by a modified version of Newton's equation (Chouksey *et al*., 2017) as presented in Equation (4).

$$E_k = 29.8 - \frac{127.5}{I} \tag{3}$$

$$V = (17.20 - 0.84d) \times (Dm) \times 0.5 \tag{4}$$

where E_k is the kinetic energy (J), and V is the raindrop velocity (m/sec).

2.4. Rainfall Simulator Performance Evaluation

The performance evaluation of the portable rainfall simulator was carried out by calculating the rainfall uniformity coefficient (CU) and rainfall distribution uniformity (DU). A minimum DU value of 75% indicates a uniform distribution of rainfall produced by the sprayer (Nugroho *et al*., 2018). Meanwhile, a rainfall uniformity coefficient (CU) greater than 90% indicates excellent rainfall simulator performance (da Silva *et al*., 2023). A CU value classified as good is 80-90%, medium is 70-80%, and poor is 60-70% (Darimani *et al*., 2021). Distribution uniformity (%) is written in the following equation 5 (Elhussiny *et al*., 2023).

$$\text{DU} = \frac{\frac{1}{4}\text{lowest value of rainfall}}{\text{average value of rainfall}} \times 100\% \tag{5}$$

The uniformity test for rainfall distribution can be performed by placing 12 rain gauges at a distance of 20 cm × 35 cm. The size of the rainfall plot area is 70 cm × 60 cm. The determination of the dimensions of the rainfall plot area is based on the consideration that the distance between the outermost nozzles of 50 cm, at a certain pump pressure, results in a greater rainfall distribution. Therefore, the placement of rain gauges with this distance is expected to cover the rain distribution area resulting from the nozzles, thus providing a good and representative rainfall distribution at various pump pressures. Meanwhile, the uniformity coefficient of rainfall distribution in the rainfall simulator can be calculated using equation 6 (Bortolini & Martello, 2013; Mohammadi *et al*., 2022):

$$\text{CU} = 100\left[1 - \frac{\sum|x - \bar{x}|}{n\bar{x}}\right] \tag{6}$$

where CU is the uniformity coefficient (%), x is the rainwater catchment volume, n is the number of measurement data, and $\bar{x}$ is the average rainwater catchment volume of the measurement.

3. RESULTS AND DISCUSSION

3.1. Design and Assembly

The design stages of a rainfall simulator include preparing equipment and materials, assembling the necessary components, and ensuring optimal performance of use. Susanto & Pratiwi, (2021) state that equipment design needs to take into account the properties and characteristics of each component to result in equipment resistant to damage. In this regard, the design process for a portable rainfall simulator begins with identifying the device's operating system, establishing parameters for performance testing, and creating a sketch. The next stage is assembling the portable rainfall simulator.

Design analysis is a crucial step to ensure the device's design objectives meet expectations. Design analysis consists of functional and structural analyses, which are conducted to determine the component requirements for the design. Functional analysis is conducted by observing the function of each component. Functional analysis is useful in calculating component requirements. The main components of this portable rainfall simulator are a water pump, a water tank, a nozzle, and a pump pressure gauge. The water pump distributes water from the water tank to the nozzle to result in raindrops. The water tank serves as a water reservoir, and the pump pressure gauge measures the pump pressure to produce the raindrops.

Meanwhile, structural analysis serves to ensure that the structure of a design can function according to requirements. Structural analysis includes: (a) pump capacity to flow water to the nozzle; (b) the ability of the rainfall simulator frame to properly support the load of the sprayer frame structure; and (c) ease of assembly of the structure and ease of transporting the portable rainfall simulator frame structure to the field. Therefore, the portable rainfall simulator structure uses a Shimizu 125 BIT pump weighing 6.5 kg, the sprayer frame uses ½ inch pipe, and the rainfall simulator frame is made of rectangular iron pipe designed in several parts for easy transportation and assembly. These parts are designed to be easily assembled and disassembled with sock-shaped connections. The assembly of this portable rainfall simulator can be done by a single operator. Assembly is carried out by installing the pump and water reservoir. Assembly is continued by installing the support pole on the water reservoir base with a sock-shaped connection. The next stage is assembling the sprayer frame by inserting the sock on the sprayer frame into the sock connection of the support pole. The assembly process of this portable rainfall simulator is relatively quick and easy.

3.2. Function Test

The portable rain gauge function test was conducted by checking the pump, digital pressure gauge, and nozzle to produce rainfall. The function test was conducted at various pressures, resulting in different rainfall droplets, as shown in Figure 3a.

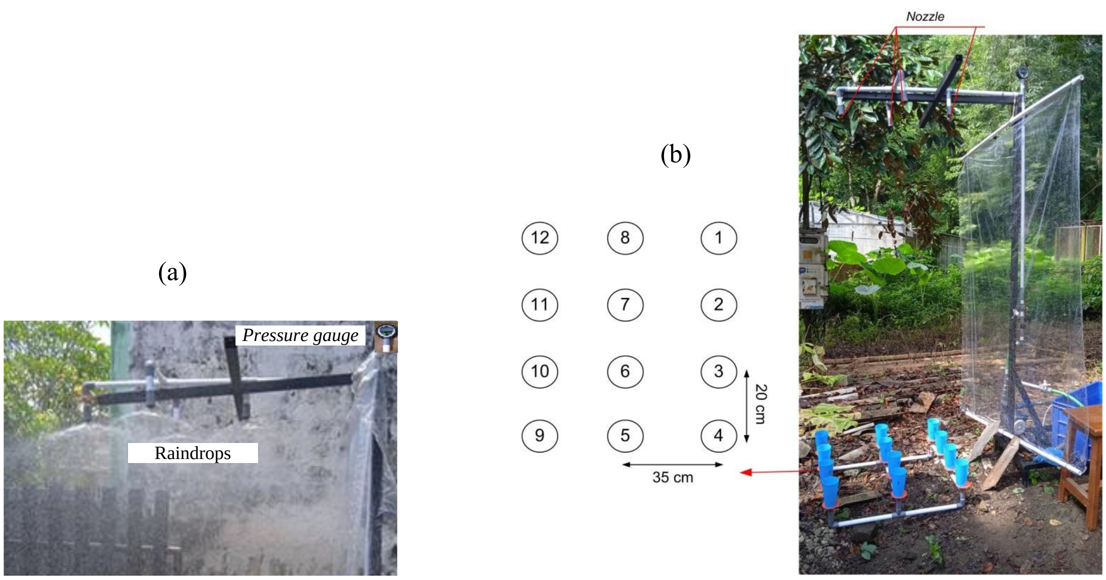

Figure 3. (a) Functional test of rainfall simulator, (b) Layout and numbering of rain gauges during rainfall intensity measurement

3.3. Performance Test

3.3.1. Rainfall Intensity

Rainfall intensity measurements of a portable rainfall simulator were made using 12 rain gauges, which were arranged at a distance of 20 cm × 35 cm (Figure 3b). Rainfall data measurements were performed at different pump pressures: 20,000 Pa, 21,000 Pa, 22,000 Pa, 24,000 Pa, and 26,000 Pa. This pump pressure was regulated by adjusting the overflow valve. When the overflow valve is opened to a certain size, the water flow to the nozzle decreases. Nozzle performance will decrease over time due to the quality of well water or tap water containing fine sediment. Water flow facilities through narrow gaps, such as nozzles, drip irrigation, and the like, are quickly clogged by sediment and corrosion. This needs to be considered to avoid the simulator jamming in a short time. Increasing the water flow rate of the pump to the nozzle affects the increase in pump pressure at the nozzle, and vice versa. Next, rainfall data from each rain gauge is analyzed to obtain rainfall intensity using equation 1. The relationship between pump pressure and rainfall intensity is used as a parameter to convert pump pressure data during rainfall measurement into rainfall intensity, as shown in Figure 4.

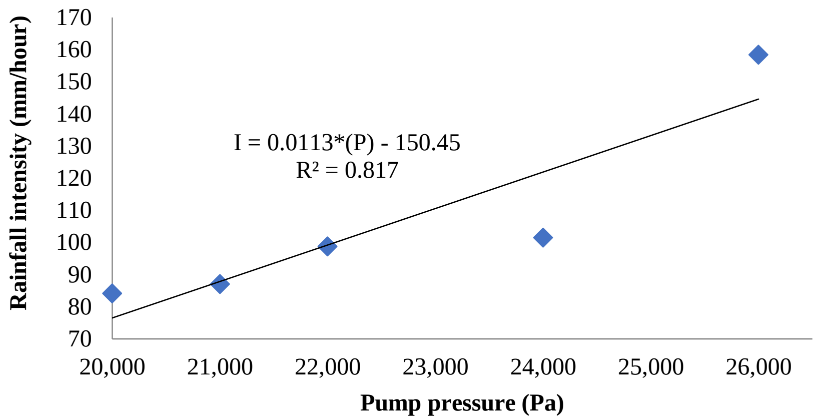

Figure 4. Relationship between pump pressure (Pa) and average rainfall intensity (mm/h)

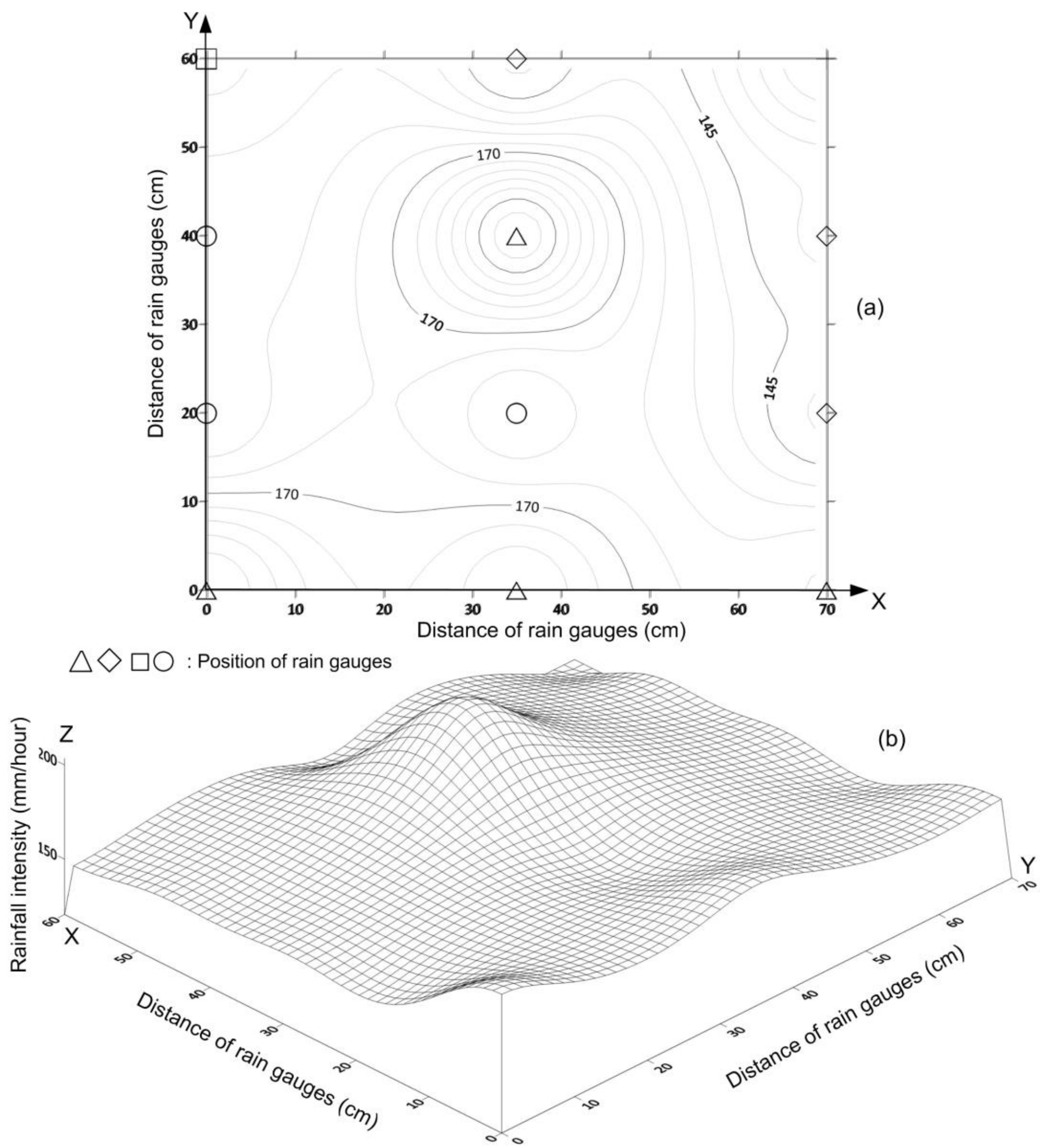

Figure 5. Rainfall intensity distribution (mm/h) at a pump pressure 26,000 Pa: (a) 2-dimensional top view; (b) 3-dimensional view

The higher the pump pressure, the higher the rainfall intensity. The linear relationship between rainfall intensity and the pump pressure is used as the basis for determining the rainfall intensity of the rainfall simulator during field simulations. The linear equation between pump pressure and rainfall intensity is $I = 0.0113*(P) - 150.45$ with R^2 of 0.817, where I is the rainfall intensity and P is the pump pressure. This indicates that pump pressure influences rainfall intensity by 81.7%. The rainfall intensity of this portable rainfall simulator shows good output, with a range of rainfall intensities from 84.23 mm/hour to 158.48 mm/hour. This is based on previous research (Mendes *et al*., 2021) which states that rainfall intensity ranging from 86.0 mm/hour to 220.0 mm/hour is the expected output in rainfall simulator design. Performance testing with three variations in pump pressure is expected to represent rainfall intensity measurements under light, moderate, and heavy rainfall conditions that occur in the field. This was also done by researchers (Bateni *et al*., 2018), who carried out rainfall simulator performance tests at 3 different variations of rainfall intensity.

An even distribution of rainfall intensity is also the desired outcome. The more even the distribution of rainfall intensity, the better the performance of the rainfall simulator, as shown in Figure 5. The distribution of rainfall intensity is quite even, with most rain gauges falling at rainfall intensities between 170 mm/h and 150 mm/h. However, the rain gauge at coordinates (35,40) (rain gauge number 7) has the highest rainfall intensity. This is because: (a) residual water from the nozzle falls into the rain gauge when the pump is turned off; and (b) the rain gauge is located at the intersection of the outer diameters of the rainfall from several nozzles.

3.3.2. Raindrop Diameter

The raindrop diameter is calculated using Equation (2). The Raindrop diameter increases with increasing rainfall intensity. Therefore, the higher the rainfall, the larger the raindrops that fall to the ground. The raindrop diameter is one indicator of rainfall simulator performance. The raindrop diameter produced by this portable rainfall simulator is 5.02 mm–5.60 mm (Figure 6). Therefore, this rainfall simulator is excellent for use in rainfall simulation activities. Researchers (Sinaga *et al*., 2023) stated that raindrops in the field, as measured using a spectro-pluviometer, ranged from 3.8 mm to 5.7 mm. Therefore, the raindrop diameter produced by the portable rainfall simulator is consistent with field conditions. Increasing pump pressure beyond a certain limit will result in larger raindrop diameters. However, when the pump pressure is increased beyond this limit, the raindrops become smaller and form fog. Therefore, rain simulation with this portable rainfall simulator is best used at a maximum pump pressure of 26,000 Pa.

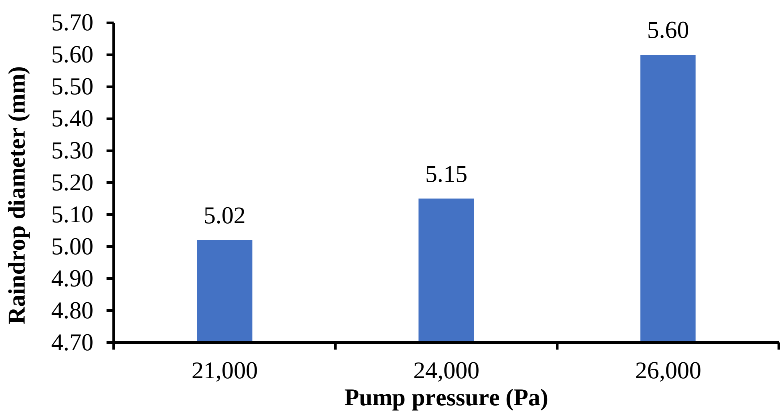

Figure 6. Average raindrop diameter of the rainfall simulator

3.3.3. Raindrop Velocity

The raindrop velocity is significantly influenced by rainfall intensity. This is consistent with previous research. (Mohammadi *et al*., 2022), which states that raindrop velocity increases with increasing rainfall intensity. The relationship between raindrop velocity and rainfall intensity at the same pump pressure is shown in Figure 7a. The linear relationship between rainfall intensity and rainfall velocity has the equation $I = 29.415*(V) - 870.71$ with R^2 of 0.996, where I is rainfall intensity (mm/hour) and V is rainfall velocity (m/sec). This indicates that 99.6% of rainfall intensity is influenced by rainfall velocity.

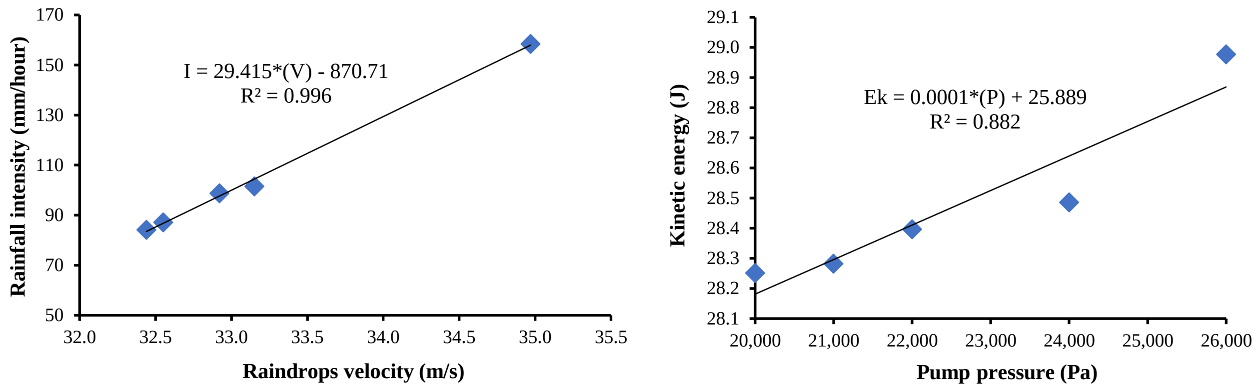

Figure 7. Linear relationship of: (a) rainfall intensity (mm/hour) and raindrop velocity (m/s); (b) rainfall kinetic energy (J) and pump pressure (Pa)

3.3.4. Rainfall Kinetic Energy

The rainfall kinetic energy is the kinetic energy of raindrops. High rain kinetic energy can damage soil aggregates and release soil particles, causing erosion. Similarly, in agriculture, high rain kinetic energy negatively impacts plant growth because it damages young plants. Previous research indicates that rainfall kinetic energy of 26.57 joules can cause erosion on a 20° slope (Sitepu *et al.*, 2017). Therefore, it can be stated that the kinetic energy produced by a portable rainfall simulator is sufficient to simulate natural rainfall. Rain kinetic energy is calculated using Equation (3). The linear relationship between rain kinetic energy and pump pressure is very useful for predicting rain kinetic energy when operating a rainfall simulator. Based on the results of pump pressure readings, the resulting rain kinetic energy can be predicted. The linear relationship between rain kinetic energy and pump pressure is shown in Figure 7b.

Figure 8 shows that the linear relationship between rainfall kinetic energy and pump pressure is very good, so that the rainfall kinetic energy can be predicted by the equation $E_k = 0.0001^* (P) + 25.889$ with R^2 of 0.882, where *Ek* is the rainfall kinetic energy (joules) and *P* is the pump pressure (Pa). This shows that 88.2% of the rainfall kinetic energy is greatly influenced by the pump pressure. Connecting kinetic energy and pump pressure is a practical and important step in applied research. Based on this relationship between *Ek* and *P*, we can determine the minimum rainfall kinetic energy threshold required to initiate erosion on a particular soil type by adjusting the pump pressure.

3.4. Performance Evaluation

The performance evaluation of the portable rainfall simulator includes: (a) testing the uniformity of rainfall distribution (DU); and (b) calculating the uniformity coefficient (CU). The uniformity of rainfall distribution (DU) is calculated using Equation (5). The coefficient of diversity (CU) is calculated using Equation (6). The uniformity and coefficient of diversity tests are shown in Figure 8. The uniformity of rainfall distribution shows good performance with

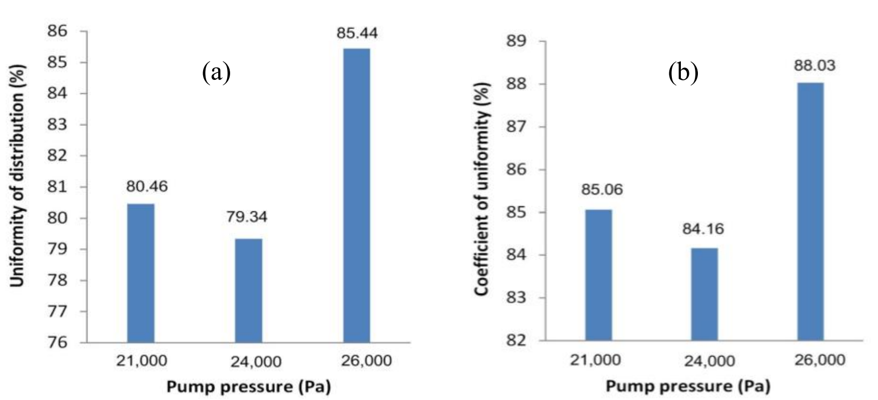

Figure 8. Performance of portable rainfall simulator: (a) uniformity of rainfall distribution, (b) rainfall uniformity coefficient.

DU values ranging from 79.34% to 85.44%. Likewise, the uniformity coefficient (CU) generally shows good performance as the level of uniformity of rainfall increases. This is supported by the opinion of previous researchers (Chandana *et al.*, 2021), who stated that a high CU value indicates uniform rainfall produced by the nozzle. This opinion is also supported by previous research, which stated that rainfall simulator simulations with an average CU value of 73% can be used to support educational activities (Jaqueth *et al.*, 2023). The performance of this portable rainfall simulator is better than the results of previous researchers, who showed a uniformity coefficient value of 81.6% - 83.8% (de Sousa Costa *et al*., 2023).

4. CONCLUSION

This portable rainfall simulator functions well and is easy to assemble by a single operator. Assembly begins with the installation of the pump and water reservoir. Next, two support poles equipped with sock joints are installed. The final stage is assembling the sprayer frame by inserting the sprayer frame into the sock joints of the support poles. The assembly of this rainfall simulator can be done relatively quickly.

The rainfall simulator also performed well, with rainfall intensities of 87.13 mm/hour to 158.48 mm/hour and raindrop diameters of 5.03 mm to 5.61 mm. The performance evaluation of the portable rainfall simulator also showed good output, with average DU of 80.46% to 85.44% and CU of 85.06% to 88.16%. This portable rainfall simulator also has several advantages: (a) it is easy to assemble, lightweight, and inexpensive; and (b) it has a better uniformity coefficient than previous rainfall simulators. Based on the research results that have been presented, it is recommended to conduct further research by developing a microcontroller-based control system that is integrated with pressure sensors and rainfall sensors to reduce dependence on manual calibration.

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AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Suh	✓	✓			✓			✓	✓		✓			✓
BM							✓			✓				
DWS				✓										

C: Conceptualization	Fo: Formal Analysis	O: Writing - Original Draft	Fu: Funding Acquisition
M: Methodology	I: Investigation	E: Writing - Review & Editing	P: Project Administration
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

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