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Soil Moisture Uniformity under Low-Pressure Sprinkler Irrigation System

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ABSTRACT

The use of a sprinkler irrigation system is becoming more popular to reduce water consumption and increase irrigation efficiency. Irrigation uniformity plays an important role in the performance of the sprinkler irrigation system. The use of low operating pressure instead of high operating pressure system offer many benefits including energy and water saving. An experimental study was performed using two systems; a square 12x12 m system and a rectangular 10x12 m system to investigate irrigation uniformity based on soil moisture content of the sprinkler irrigation system under low operating pressure. In addition, irrigation uniformity was compared based on water application and soil moisture content. In this study, different low operating pressures (62, 82, 102 and 122 KPa) were selected. Different nozzle diameters (4, 5, 6 and 7 mm) and different riser heights (0.5, 0.75, and 1.0 m) were also used. The soil moisture content uniformities of 10 min after irrigation are more dependent on the initial soil moisture content uniformity than any other design factor. It is also less influenced by water application uniformity.

Keywords:
Sprinkler irrigation system, Irrigation uniformity, Soil moisture uniformity

1. Introduction

Sprinkler irrigation is generally defined as a method of irrigation that applies water to the soil in the form of spray resulting from the flow of water under pressure through nozzles or orifices. Usually, the pressure is obtained by pumping, although it can be obtained by gravity if the water source is high enough above the irrigation area. Sprinkler irrigation is one of the most effective methods of irrigation due to its advantages including the adaptation with many types of soil, crop and topography, as well as low labor requirements [1]. Sprinkler irrigation systems are characterized by more favorable working conditions compared to surface irrigation systems because the discharge, the duration and the frequency of water application can be controlled [2]. Sprinkler irrigation systems produced 18% more yield and reduces consumption of water by 35% compared to surface irrigation systems [3]. Sprinkler irrigation is suitable for all types of soils such as sandy, gravelly and loamy soils, and also for most crops. However, it is not recommended for crops having high water need such as rice, jute and plantation such as coffee and tea. It is particularly suitable for production of crop having continuous and quick growth, high yielding crops and valuable crops [4].

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The main objective of irrigation system for agricultural use is the application of water to soil in order to meet crop demands and to supply adequate moisture for crop growth. In order to use water with an economical and sustainable way, water has to be utilized in such a manner to protect and conserve the available water resources. In irrigated agriculture, this will be obtained through effective management of water consumption. Therefore, irrigation systems will have to apply water in the most efficient possible way to prevent losses and wastage of water. In addition, water should be applied uniformly so that every portion of the irrigated field receives the same amount of water [5]. However, the approach to apply water in a completely uniform manner is practically impossible. In order to achieve that, an irrigation system should apply water evenly and uniformly as possible. Irrigation uniformity is defined as the variation in irrigation depth over an irrigated area. The uniformity of sprinkler irrigation depends on a number of factors, such as operating pressure, nozzle size, riser height and spacing layout [6, 7].

In order to reduce pumping cost, irrigators have gone from using high-pressure impact sprinkler to using low-pressure impact sprinkler [8]. In 1960s, sprinkler irrigation systems had standard high-pressure impact sprinklers greater than 50 psi (344.7 KPa). These sprinkler packages provided good application uniformity when the system nozzles were properly sized and the pressure variation along the lateral was within recommended limits. However, losses from wind drift and evaporation under dry or windy conditions often encountered in arid and semi-arid environments were excessive. The sprinkler irrigation industry addressed this problem by developing low-pressure impact sprinkler of 25 to 40 psi (172.3- 275.7 kPa). These effectively reduced wind drift and evaporation losses, but flow rate variation caused by undulating topography continued to be a significant problem. In mid-1970s, the sprinkler irrigation industry responded by developing a low-pressure impact sprinkler of 30 psi (206.8 kPa). The main disadvantage of the developed system was low application uniformities if it was not designed correctly. However, with a proper design and installation, uniform irrigation is possible [9]. Figure 1 shows the effect of pressure on the water distribution uniformity.

Irrigation uniformity is an important factor in the performance of a sprinkler irrigation system. With poor uniformity, sprinkler will not release water as far, droplet size will increase and pattern shapes of an individual sprinkler will change. This can increase the instantaneous application rate, thus causes potential runoff. Irrigation uniformity is the measure of even distribution of water over an irrigated area. When less amount of water is applied, it will produce dry areas, and when too much water is applied, the excessive amount of water will cause runoff. Therefore, that part of the field becomes under-irrigated, and another part becomes over-irrigated [6].

Irrigation uniformity is an important indicator for the evaluation on the performance of sprinkler irrigation systems. Hence, irrigation uniformity must be considered during design and installation of the system [10]. Irrigation amount affects crop yields, as excessive amount of irrigation water reduces yield, whereas inadequate amount of irrigation water causes crop stress and reduces crop production where in most cases, it leads to death of plants [11]. High irrigation uniformity is required to attain optimal irrigation efficiency [12]. Increased irrigation uniformity and reduced water application will lead to increase in water-use efficiency [13]. Coefficient of uniformity (CU) is a critical indicator in the evaluation of irrigation systems efficiency. Water application uniformity in the field is expressed with uniformity coefficient (CU), and this index is a basic parameter in the design and evaluation of irrigation systems. Increase of CU through irrigation system improvement or system upgrading requires investment. Economic analysis should be applied in this investment in order to increase yield through CU increase [14]. The performance of sprinkler irrigation system needs to be improved by doing some improvement in the irrigation uniformity [15].

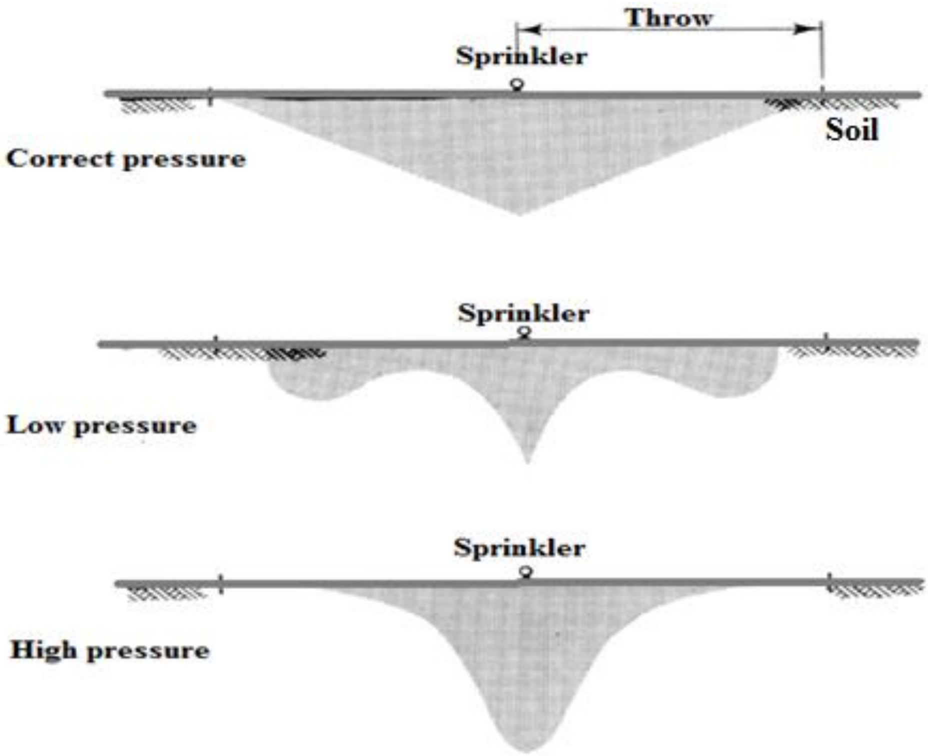

Fig. 1. The effect of pressure on water distribution uniformity

Irrigation uniformity can be calculated either based on water distributed on the soil surface by using catch-can method or based on water distributed in the soil by using soil moisture content method. The response of crop yield is more affected by the water uniformity in the root zone than the water uniformity on the soil surface. Therefore, soil water uniformity is more important than water application uniformity. To obtain the gross water depth required for satisfying crop water requirement, soil water uniformity must be considered instead of water application uniformity during individual irrigation events [16, 17]. The difference between soil moisture content calculated before and after irrigation represents the actual soil moisture content applied by sprinklers. Measuring soil moisture uniformity is one of the ways to properly determine irrigation timing and amount. It can help farmers save water, reduce energy cost, increase yield, and protect the environment. Excess irrigation will increase the cost of production and can have negative environmental effects such as runoff, water logging, and leaching of soil nutrients, and also other chemicals that can eventually contaminate water sources and reduce yield. Insufficient irrigation, on the other hand, can result in crop stress and reduced yield [17- 19].

A number of research have attempted to study the soil moisture uniformity of sprinkler irrigation system within the root zone and concerned on its effect on crop yields. Their studies also focused on the factors affecting the soil moisture uniformity.

Tarjuelo *et al*. [19] measured the increase in crop yields and the effect of soil water uniformity. An increase in soil water uniformity led to 4% increase in yield. The aim of residential irrigation is the maintenance of high quality landscapes, which is mainly to assure optimal soil moisture conditions for plant growth.

Ortiza *et al*. [20] studied the soil water uniformity coefficient (CUs) and accumulated water uniformity coefficient (CUa) for sugar beet yield using stationary plates (SPS) and moving plates

(MPS) at two heights (1 and 2.5 m). Soil water uniformity coefficient (CUs) was similar to the accumulated water uniformity coefficient (CUa). MPS at 1 m gave higher values of CUs, CUa and average yield. Another study was also done by Ortiza *et al*. [16], which analyzed the effect of CU based on water application uniformity on the CUs based on soil moisture content uniformity and CU based on crop yield uniformity for the center pivot system. They found that the final crop yield was more influenced by the amount of water available to the crop than the small differences in soil water uniformity.

Many researchers have used high operating pressure in the operation of sprinkler irrigation systems to achieve high irrigation uniformity. In a normal condition, high operating pressure requires a high-pressure pump associated with high energy cost. From this point of view, a low-pressure pump is considered to be the best option due to low pumping cost.

Based on previous studies, it is proved that the irrigation uniformity of sprinkler irrigation system is largely dependent on many design factors such as operating pressure, nozzle diameter, riser height and spacing layout. Most of the previous studies focused on one or a maximum of two design factors of sprinkler irrigation, and they neglected the role of all-important system design factors. They discussed these factors separately or two factors together. These factors have to be studied together as a combination of several factors.

Only few studies focused on the use of low operating pressure in the operation of sprinkler irrigation system because it is always associated with low irrigation uniformity. From their studies, they revealed that the most important factor affected the irrigation uniformity of sprinkler irrigation system is operating pressure. However, the operating pressure that was used in their works was high (more than 150 kPa). There is no study yet on the irrigation uniformity of sprinkler irrigation for low operating pressure under 20 psi (137.8 kPa).

This study was conducted to investigate the irrigation uniformity based on soil moisture content under low operating pressure and to study the effect of combined factors of operating pressure, nozzle diameter, riser height and spacing layout on the irrigation uniformity. In addition, the irrigation uniformity based on water application and the irrigation uniformity based on soil moisture content was also compared.

2. Methodology

2.1 Site and Soil Description

The study was conducted at Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Tronoh, Perak, Malaysia (4°25′16.5936″N latitude and 100° 59′26.5056″E longitude). The elevation of this area ranges from 45 to 350 m above the sea level. Figure 2 shows the location of the study area. The experiments were conducted for 5 months during November 2013-March 2014. The area is fully covered with turf grass. The climate is typically humid tropical and seasonal heavy rain, and February and March are the driest months, with the mean annual rainfall of 1,820.23 mm [21].

Fig. 2. Location of study area

Soil sample was taken and oven-dried for 24 h at 105°C. The sample was then crushed, and 200.2 g of the soil was taken to conduct the sieve analysis test. The results attained showed that the soil was a sandy loam. Several other studies concerned with the soil type also found that the soil type in Perak was mainly sandy [21, 22].

2.2 System Design

In this study, two different spacing layouts were designed; a square 12x12 m layout, 12 m between the sprinklers in the same lateral and 12 m between the laterals, and a rectangular 10x12 m layout, 10 m between the sprinklers in the same lateral and 12 m between the laterals [23-25]. Different low operating pressures were used (62, 82, 102 and 122 kPa). The operating pressure range used in this study was less than the recommended range (150-250 KPa) used in previous studies. Different nozzle diameters (4, 5, 6 and 7 mm) and different riser heights (0.5, 0.75 and 1.0 m) were used. The air pressure tank was provided with a pressure gauge. It was connected to a pump to control the operating pressure and avoid fluctuation during the experiments. The pressure gauge was used to measure the working pressure of the pump. A control valve was used to allow water to be delivered and cycled to different parts of the system. The valve worked manually and was used to control the operating pressure in the system at the required pressure range. Two control valves were used; one was connected to the pump and other one was connected to the main line. A measuring unit that represented the pressure gauge was used to measure the operating pressure of the system. Two pressure gauges were used, one was connected to the pump and the other one was put in the centre between the two laterals. Figure 3 shows the schematic diagram of the sprinkler irrigation system that was designed for this study.

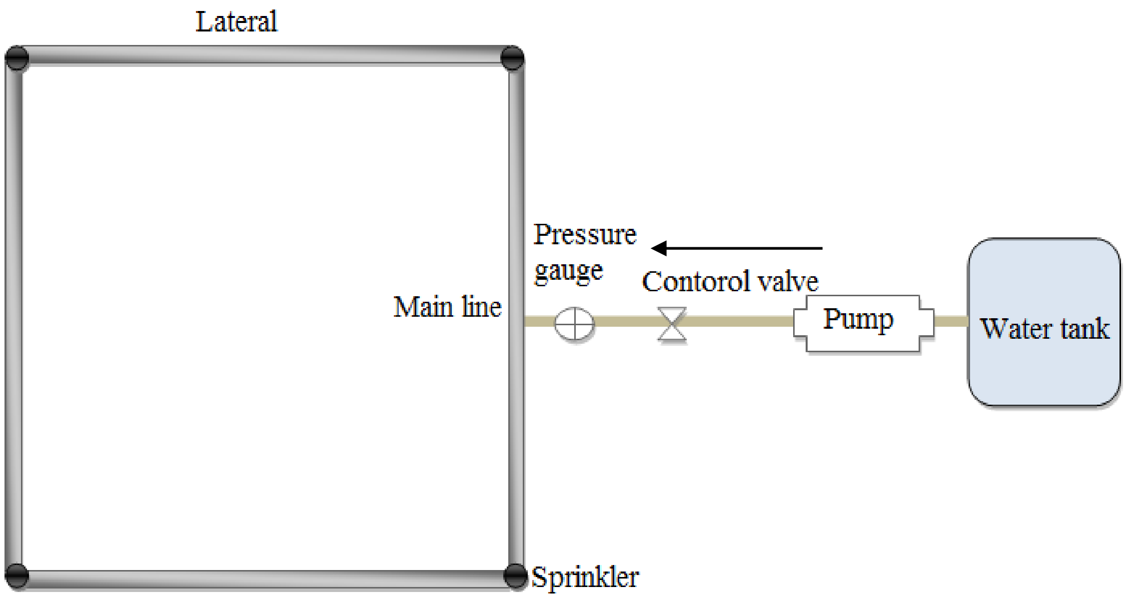

Fig. 3. Schematic diagram of the sprinkler irrigation system

2.3 Water Application Uniformity Test

Water application uniformity tests were conducted in an installation composed of four laterals of PVC pipeline with four sprinklers [25]. For the square spacing of 12x12 m, a square, two-meter grid was arranged among the four sprinklers, and 36 graduated catch-cans with 95 mm diameter and 108 mm height were used, and every catch-can was put at the centre of each grid [23-26]. For the rectangular spacing of 10x12 m, a rectangle, two-meter grid was also used and arranged among the four sprinklers, and 30 graduated catch-cans were used, and every catch-can was put at the centre of each grid [24-28]. Figure 4 shows the catch-cans arrangement for the block irrigation test. Then, the system was run for 1 h under calm wind condition to avoid the effect of wind in catch water volume measurements [28, 29]. After that, the water volume caught for each graduated catch-can was read and recorded to calculate the Christiansen's coefficient of uniformity of water application (CU) using Equation 1.

$$\mathrm{CU} = 1 - \frac{\sum_{i=1}^{n} |Xi - Xm|}{n \times Xm} \mathrm{x}100 \qquad (1)$$

where CU = Christensen's coefficient of uniformity of water application, X_i = the caught volume in catch-can i, X_m = the overall average caught volume, and n = the number of catch-cans.

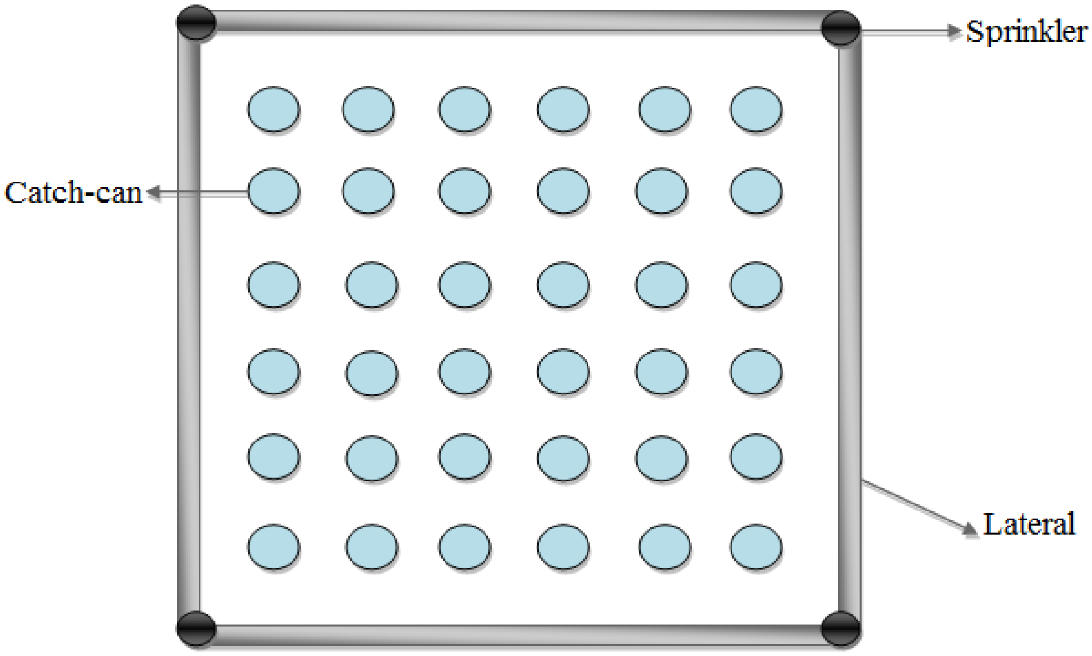

Fig. 4. Catch-cans arrangement for the block irrigation test

2.4 Soil Water Uniformity Test

This test was conducted to observe spatial variations of water in soil. In this test, the area between the laterals was divided into 9 equal grids. Sprinkler heads were located at the four sides of this area. Then, the location of soil sample was identified at the centre of each grid.

These samples were used to measure the soil moisture content at different locations in the field [16]. Figure 5 shows sampling locations of grid samples for soil moisture content measurements at the field site. The soil samples were taken at 5 cm depth of soil before irrigation and 10 min after irrigation, and covered with plastic cover to avoid evaporation loss. 5 cm represents the upper soil layer. After that, the soil samples were weighed, and oven-dried using thermostatically controlled oven for 24 h to find the volumetric soil moisture content of different samples at different locations. To convert soil moisture into volumetric soil moisture content, the weight fraction was multiplied by the bulk density γb and divided by the water density γ_w, which can be assumed to have a value of unity as shown in Eqs. 2 and 3.

$$\theta = \frac{w2 - w3}{w3 - w1} \times 100 \qquad (2)$$

$$\theta_{\text{volumetric}} = \frac{\gamma b\ \theta g}{\gamma w} \qquad (3)$$

where θ_g = soil moisture content based on weight (g/g), $\theta_{\text{volumetric}}$ = volumetric soil moisture content (cm^3/cm^3), w_1 = weight of container (g), w_2 = weight of container and wet soil (g), w_3 = weight of container and dry soil (g), and γ_b in this study for sandy loam soil was = 1.40056 g/cm^3, with γ_w approximately 1 g/cm^3.

Then, the Christiansen's coefficient uniformity of soil moisture content (CU_{mc}) was calculated using Equation 4.

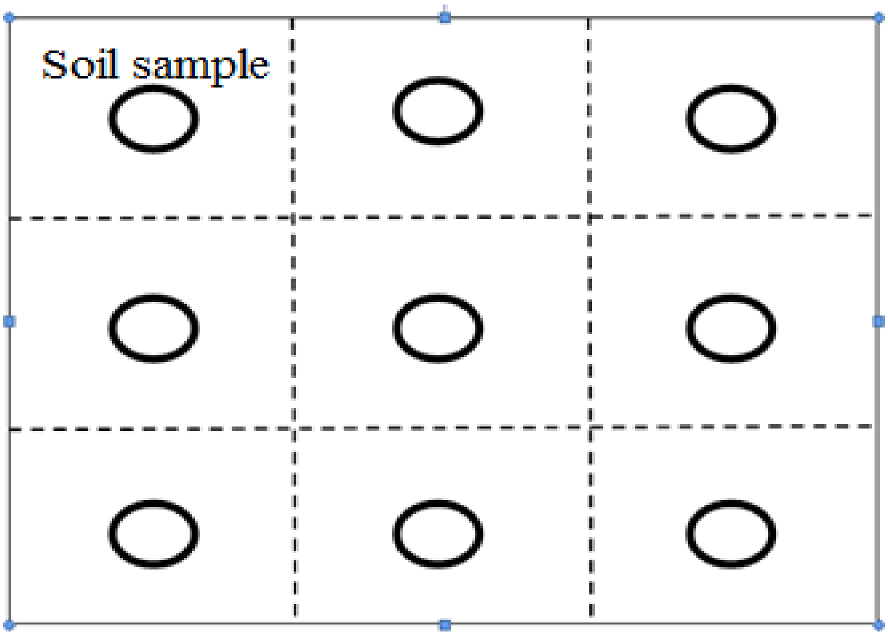

Fig. 5. Sampling locations of grid samples for soil moisture content measurements at the field site

$$CU_{mc} = \left[\frac{1-\sum_{i=1}^{n}|\theta i-\theta m|}{n\times\theta m}\right] x100 \quad (4)$$

3. Results and Discussion

3.1 Christiansen's Coefficient of Uniformity of Soil Moisture Content for 0-5 cm Depth

As shown in Figures 6-8, the Christiansen's coefficient of uniformity of soil moisture content of 10 min after irrigation increased as the Christiansen's coefficient of uniformity of soil moisture content before irrigation increased. The Christiansen's coefficient of uniformity of moisture content of 10 min after irrigation ranged between 65-96% for most of the combinations. There was a small and significant difference between the Christiansen's coefficient of uniformity of moisture content before irrigation and 10 min after irrigation. This is because the soil moisture content before irrigation ranged between 62-85%, which was influenced by the soil moisture content after irrigation. This result agreed with the result by Kieffer and Connor [30]. They found that the uniformity of the soil moisture content test before and after irrigation was very similar. There were more fluctuations on the values of Christiansen's coefficient of uniformity of soil moisture content before irrigation, while the values of Christiansen's coefficient of uniformity of soil moisture content of 10 min after irrigation were more stable due to the effect of water application in the soil.

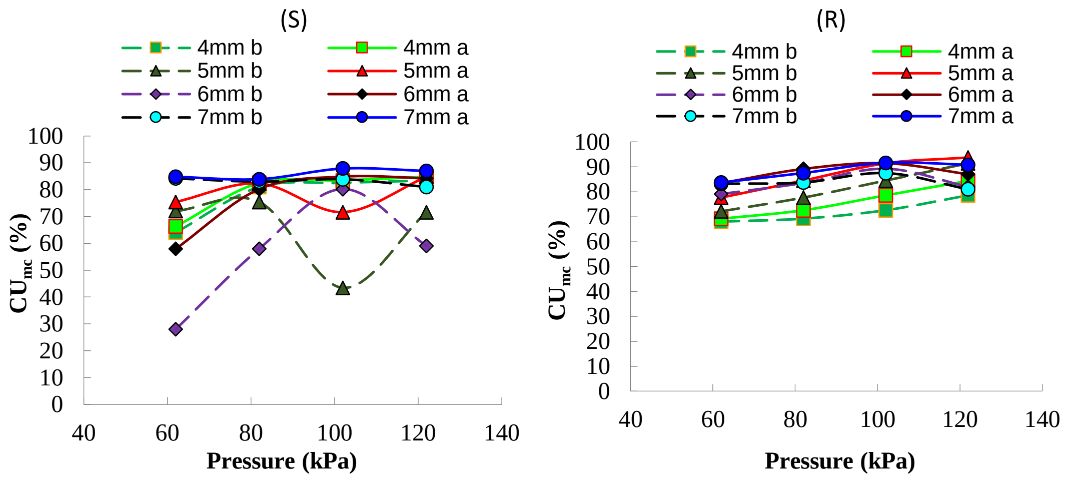

Fig. 6. Christiansen's coefficient of uniformity of soil moisture content (CU_{mc}) at 0-5 cm depth before (b) and 10 min after (a) irrigation for different nozzle diameters (mm) and pressures (KPa) at 0.5 m riser for (S) a square system of 12x12 m and (R) a rectangular system of 10x12 m

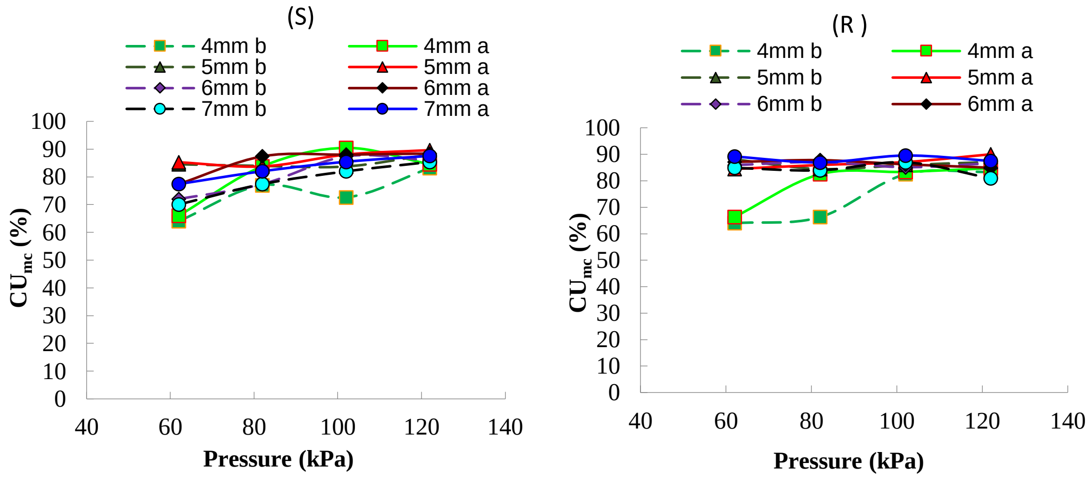

Fig. 7. Christiansen's coefficient of uniformity of soil moisture content (CU_{mc}) at 0-5 cm depth before (b) and 10 min after (a) irrigation for different nozzle diameters (mm) and pressures (KPa) at 0.75 m riser for (S) a square system of 12x12 m (R) and a rectangular system of 10x12 m

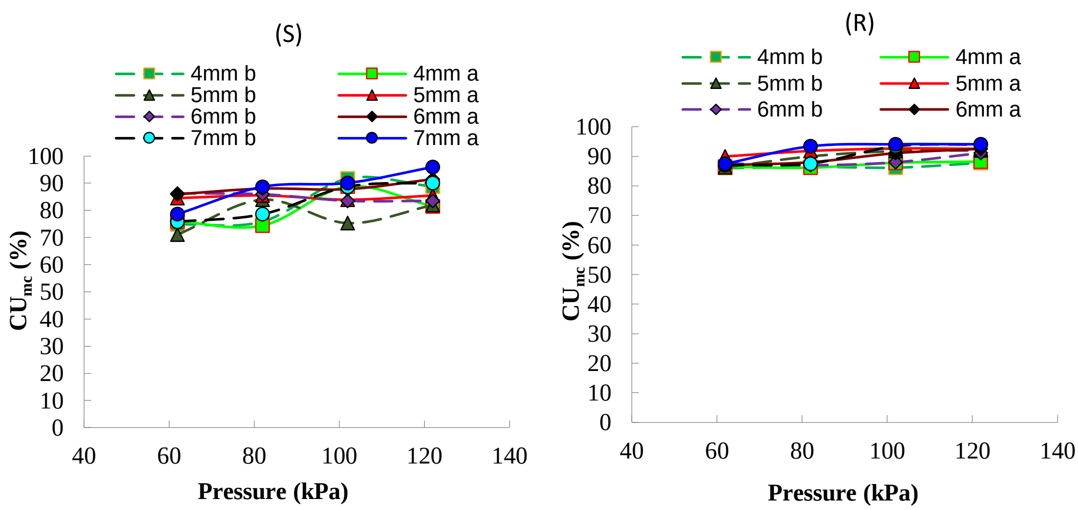

Fig. 8. Christiansen's coefficient of uniformity of soil moisture content (CU_{mc}) at 0-5 cm depth before (b) and 10 min after (a) irrigation event for different nozzle diameters (mm) and pressures (KPa) at 1.0 m riser for (S) a square system of 12x12 m and (R) a rectangular system of 10x12 m

It was also noticed that CU_{mc} was very high with 7 mm nozzle compared to other nozzles. The reason is that in this work, the experiments of 7 mm nozzle were done later than other experiments, hence it was more influenced by the accumulation of moisture in soil from previous experiments, thus showed high CU_{mc}.

It was also observed that nozzle 5 and 6 mm at 0.5 m height for the square system showed greater differences between the Christiansen's coefficient of uniformity of moisture content before and 10 min after irrigation. During the experiments, it was raining during the 10 min of irrigation. The rainfall affected the soil moisture content after irrigation, which caused high difference between soil moisture content before and after irrigation. The CU_{mc} after irrigation was high for all combinations of operating pressure, nozzle diameter, riser height and spacing layout. There was no significant effect of operating pressure, nozzle diameter, riser height and spacing layout on CU_{mc}. CU_{mc} was more dependent on the initial soil moisture content than any other design factor.

3.2 The relation between CU_{mc} of 10 min after Irrigation and CU

It is very important to determine the relation between the Christiansen's coefficient of water application (CU) and the Christiansen's coefficient of uniformity of soil moisture content (CU_{mc}) of 10 min after irrigation. As shown in Figure 9, it was clear that CU_{mc} ranged between 65-96%, while CU ranged between 4.2-95.4%, CU_{mc} was high regardless CU was high or low. CU_{mc} was less influenced by CU. This is in agreement with Sahoo et al. [26], who demonstrated that the CU for soil moisture was greater than 90% even though sprinkler uniformities varied from 57% to 89%. The uniformity of soil moisture content after irrigation was more influenced by the uniformity of soil moisture content before irrigation than the uniformity of water application on the surface.

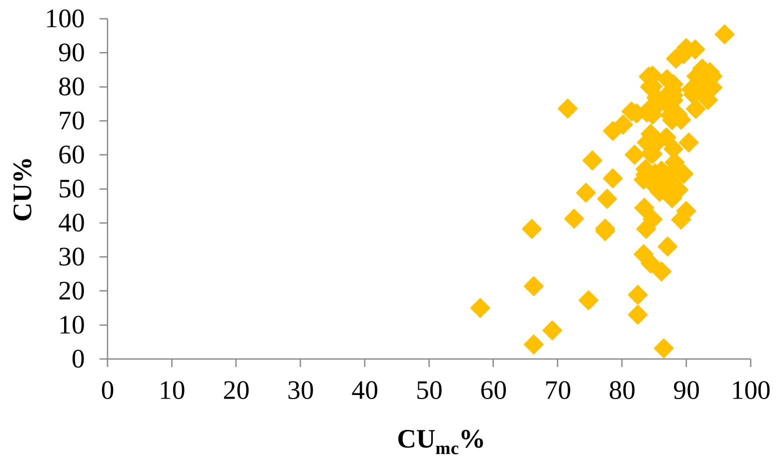

Fig. 9. The relation between CU_{mc} of 10 minutes after irrigation and CU

4. Conclusion

It can be concluded that the soil moisture content uniformity of 10 min after irrigation is more dependent on the initial soil moisture content uniformity than any other design factor. There was no significant effect of operating pressure, nozzle diameter, riser height and spacing layout on CU_{mc}. Moreover, soil moisture content uniformity was less influenced by water application uniformity.

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