Non-negligible factors in low-pressure sprinkler irrigation: droplet impact angle and shear stress (Postprint)

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Abstract

Droplet shear stress is considered a more accurate indicator than kinetic energy for reflecting soil erosion in sprinkler irrigation, and the effect of droplet impact angle on shear stress cannot be ignored. In this study, the radial distributions of droplet impact angles, velocities, and shear stresses were investigated using a two-dimensional video disdrometer with three types of low-pressure sprinklers (Nelson D3000, R3000, and Komet KPT) under two operating pressures (103 and 138 kPa) and three nozzle diameters (3.97, 5.95, and 7.94 mm). Furthermore, the relationships among these droplet characteristic parameters were analyzed, and their influencing factors were comprehensively evaluated. For various sprinkler types, operating pressures, and nozzle diameters, smaller impact angles and larger velocities occurred closer to the sprinkler, resulting in relatively low droplet shear stresses. As distance from the sprinkler increased, the droplet impact angle decreased while velocity increased, contributing to a significant increase in shear stress that reached its peak value at the end of the jet. Therefore, the jet end was most prone to soil erosion in the radial direction, and soil erosion in sprinkler irrigation cannot be attributed solely to droplet kinetic energy but must also consider shear stress analysis. Comparing radial distributions of average droplet shear stress among the three sprinkler types, D3000 exhibited the largest values (26.94–3313.51 N/m^2), followed by R3000 (33.34–2650.80 N/m^2) and KPT (16.15–2485.69 N/m^2). From the perspective of minimizing soil erosion risk, the KPT sprinkler was more suitable for low-pressure sprinkler irrigation than D3000 and R3000. In addition to selecting appropriate sprinkler types to reduce droplet shear stress, suitable sprinkler spacing could also provide acceptable results because distance from the sprinkler exhibited a highly significant ($P<0.01$) effect on shear stress. These results provide a new reference for des

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Preamble

Non-negligible factors in low-pressure sprinkler irrigation: droplet impact angle and shear stress

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Abstract: Droplet shear stress is considered a more accurate indicator than kinetic energy for reflecting soil erosion in sprinkler irrigation, and the effect of droplet impact angle on shear stress cannot be ignored. In this study, the radial distributions of droplet impact angles, velocities, and shear stresses were investigated using a two-dimensional video disdrometer with three types of low-pressure sprinklers (Nelson D3000, R3000, and Komet KPT) under two operating pressures (103 and 138 kPa) and three nozzle diameters (3.97, 5.95, and 7.94 mm). Furthermore, the relationships among these droplet characteristic parameters were analyzed, and their influencing factors were comprehensively evaluated. For various sprinkler types, operating pressures, and nozzle diameters, smaller impact angles and larger velocities occurred closer to the sprinkler, resulting in relatively low droplet shear stresses. As distance from the sprinkler increased, the droplet impact angle decreased while velocity increased, contributing to a significant increase in shear stress that reached its peak value at the end of the jet. Therefore, the jet end was most prone to soil erosion in the radial direction, and soil erosion in sprinkler irrigation cannot be attributed solely to droplet kinetic energy but must also consider shear stress analysis. Comparing radial distributions of average droplet shear stress among the three sprinkler types, D3000 exhibited the largest values (26.94–3313.51 N/m^2), followed by R3000 (33.34–2650.80 N/m^2) and KPT (16.15–2485.69 N/m^2). From the perspective of minimizing soil erosion risk, the KPT sprinkler was more suitable for low-pressure sprinkler irrigation than D3000 and R3000. In addition to selecting appropriate sprinkler types to reduce droplet shear stress, suitable sprinkler spacing could also provide acceptable results because distance from the sprinkler exhibited a highly significant ($P<0.01$) effect on shear stress. These results provide a new reference for designing low-pressure sprinkler irrigation systems.

Keywords: center pivot irrigation system; water droplet; universal model; soil erosion; water-saving irrigation

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1 Introduction

The lack of rainfall in arid and semi-arid areas inevitably makes sprinkler irrigation one of the significant alternatives and important methods for supplementing water to crops in these regions (Stambouli et al., 2013; Etikala et al., 2021). However, soil surface sealing or crusting often occurs during sprinkler irrigation. This not only reduces the soil infiltration rate but also leads to surface runoff, resulting in loss of soil, water, and fertilizer in farmland (Silva, 2006; de Jong et al., 2011). Previous studies have shown that soil surface sealing is primarily caused by the detachment of soil particles (Lu et al., 2016; Vaezi et al., 2017) and is commonly attributed to droplet kinetic energy (Yan et al., 2011; King and Bjorneberg, 2012a; Al-Kayssi and Mustafa, 2016). Nevertheless, some researchers have observed that mechanistically, the detachment of soil particles from aggregates is closely related to the shear stress generated by droplet impact on the ground rather than droplet kinetic energy (Huang et al., 1982; Chang and Hills, 1993a; Ghadiri and Payne, 2010). Therefore, further systematic explorations of droplet shear stress are still required and highly demanded for effective development of sprinkler irrigation systems.

To date, several studies have focused on droplet shear stress distribution and droplet impact on the ground. For example, Huang et al. (1982) used a marker-and-cell numerical technique to simulate raindrop impact on a rigid surface and found that impact pressure distribution was non-uniform, with maximum pressure occurring at the contact circumference and rebound velocity on the rigid surface being twice the impact velocity. Ferreira et al. (1985) used the principle of energy balance and a modified solution algorithm-volume of fluid (SOLA-VOF) numerical simulation scheme to investigate raindrop impact in a deep pool. They found that fragmentation of most soil aggregates appeared in crater formation due to impact pressure and shear stress at the pool bottom. Moreover, Ghadiri and Payne (1986) used water-hammer theory to evaluate compressive stress from falling raindrops and shear stress caused by flow impact, finding that shear stress was several times higher than compressive stress. The droplets in these studies were primarily raindrops. However, raindrops generally impact the ground vertically, which is fundamentally different from droplets impacting the ground at oblique angles in sprinkler irrigation. Consequently, to determine shear stress distribution characteristics when sprinkler droplets impact the ground, Chang and Hills (1993b) employed full three-dimensional (3D) Navier-Stokes equations and finite difference procedures to propose a numerical model and used it to simulate pressure and shear stress distributions of sprinkler droplets on the soil surface. Results indicated that compared with vertical droplet impact, oblique droplet impact decreased impact force magnitude while increasing shear stress. Chang and Hills (1993a) also conducted laboratory experiments to study the effect of droplet impact angles on soil infiltration under sprinkler irrigation, finding that average steady infiltration rates for all soil types gradually increased in the order of impact angles of 60°, 45°, and 90°. These findings indicated that sprinkler droplet impact angle significantly influenced shear stress distribution and soil infiltration. However, only three droplet impact angles were considered in their research, which was insufficient to reflect the multi-angle impact of droplets on the ground in actual sprinkler irrigation.

Based on this result, Hui et al. (2021a) considered a ball-driven sprinkler as the research object and used a two-dimensional video disdrometer (2DVD) to investigate radial distributions of droplet impact angles corresponding to three operating pressures and two nozzle diameters. Furthermore, relationships between droplet impact angles and shear stresses under different working conditions were established. The study provided a new method for accurately predicting soil erosion under sprinkler irrigation. However, the structure of the ball-driven sprinkler was relatively unique, and conclusions drawn from the study might not provide guiding significance for farmland irrigation.

As one of the common high-efficiency water-saving irrigation devices in farmland, the center pivot irrigation system has been rapidly applied in China in recent years due to its advantages including high irrigation efficiency, wide coverage of irrigated area, high automation, and low labor costs (Yan et al., 2020; Baiamonte et al., 2021; Hui et al., 2022a). By the end of 2019, more than 18$×10^{3}$ sets of center pivot and linear-move irrigation systems were used in China, with an irrigation area of nearly 6$×10^{5}$ hm^{2}, accounting for about 14.2% of the total sprinkler irrigation area (Hui et al., 2022b). With the global objective of peaking carbon emissions and achieving carbon neutrality, it is imperative to realize low-pressure and energy-saving sprinkler irrigation. According to previous studies, low-pressure sprinkler irrigation could significantly reduce energy consumption while ensuring yield and water use efficiency (Robles et al., 2017). Recently, the use of center pivot systems has led to gradual replacement of medium- and high-pressure sprinklers with low-pressure sprinklers to minimize energy requirements. Low-pressure sprinklers are commonly classified into three types: fixed spray plate sprinkler (FSPS), rotating spray plate sprinkler (RSPS), and oscillating spray plate sprinkler (OSPS) (Manke et al., 2019; Hui et al., 2021b). The different structures and operating modes of these three sprinkler types result in significant performance differences. Among them, FSPS cost is lower than RSPS; however, this type attains high instantaneous application rates and poor application uniformity (Silva, 2007; Yan et al., 2011). In contrast, RSPS has higher energy consumption despite its wide spraying range and relatively uniform water distribution (Faci et al., 2001; Chen et al., 2020; Hui et al., 2022a). Nonetheless, the strong wind resistance characteristics of OSPS make it highly competitive in the sprinkler marketplace (Manke et al., 2019). Numerous studies have focused on water application rate, droplet diameter, kinetic energy, and other indicators of low-pressure sprinklers (Yan et al., 2010; Sayyadi et al., 2014; Robles et al., 2019; Hui et al., 2022b). However, droplet impact angle and shear stress have rarely been investigated, which is not conducive to further revealing the soil erosion mechanism under low-pressure sprinkler irrigation.

The main objectives of this study are: (1) to investigate the radial distribution of droplet impact angles under three types of low-pressure sprinkler with two operating pressures and three nozzle diameters; (2) to evaluate relationships among distance from sprinkler, droplet impact angle, and shear stress, as well as relationships among droplet impact angle, velocity, and shear stress; (3) to establish mathematical models among the above-mentioned indicators; and (4) to further determine effects of various factors on droplet impact angle, velocity, and shear stress.

2.1 Experimental Setup

A droplet distribution test of a single sprinkler was conducted to comprehensively investigate droplet impact angles and shear stresses of low-pressure sprinklers in center pivot irrigation systems. The three tested sprinkler types were: Nelson D3000 (Nelson Irrigation Corp., Walla Walla, USA), a fixed spray plate sprinkler equipped with a 36-grooved blue plate; Nelson R3000, a rotating spray plate sprinkler equipped with a 10-grooved brown plate; and Komet KPT (Komet Irrigation Corp., Lienz, Austria), an oscillating spray plate sprinkler with a 10-grooved black plate, as shown in Figure 1 [Figure 1: see original paper]. In each test, the sprinkler could be matched with a corresponding pressure regulator to obtain the required stable operating pressure. Moreover, all three sprinkler types used in this study were installed upside down. Therefore, the upper part of the pressure regulator was closely connected with the elbow of a height-adjustable riser. The riser was cast from steel, which exhibited high strength and no shaking during sprinkler irrigation.

Furthermore, a manual valve and a pressure gauge with 0.4% accuracy (MIK-Y190, Asmik Sensors Technology Co., Ltd., Hangzhou, China) were installed on the riser for real-time monitoring and adjustment of operating pressure. Water required for sprinkler irrigation was obtained from a stainless-steel water tank and pressurized before being sent to the sprinkler inlet using a centrifugal pump (IS80-50-250, Foshan Pump Factory Co., Ltd., Foshan, China). Meanwhile, an electromagnetic flowmeter with 0.5% accuracy (E-mag E, Kaifeng Instrument Co., Ltd., Kaifeng, China) was used to measure the flow rate in the pipeline.

The acquisition of droplet characteristic parameters was achieved by the 2DVD (Joanneum Research Corp., Graz, Austria), which is regarded as the most advanced equipment globally for measuring precipitation particles. This equipment mainly consists of a measurement device, a laptop, and a power supply unit (Fig. 2a [Figure 2: see original paper]), and can monitor the size, shape, aggregation state, falling velocity, and direction of individual precipitation events (such as rain, snow, and hail). Moreover, 2DVD has been used in many fields, including meteorology and environment, telecommunications and wave propagation, and other industrial applications (Kruger and Krajewski, 2002; Huang et al., 2010). During the sprinkler droplet test, two perpendicularly disposed chargecoupled device cameras (cameras A and B) inside the 2DVD instrument could scan droplets passing through the measurement area (100 mm$\times$100 mm; Fig. 2b) and record the vertical and horizontal velocity components of each droplet (Ge et al., 2020). The test accuracy for droplet diameter of 2DVD could reach 0.19 mm. In addition to the above-mentioned devices, a tape measure (DL9830, Deli group, Ningbo, China), stopwatch (PC2810, Shenzhen Timestar Electronic Co., Ltd., Shenzhen, China), and wet and dry bulb thermometers (DL9013, Deli group, Ningbo, China) were also used in the test.

2.2 Experimental Design

An indoor sprinkler irrigation experiment was conducted at the Research Center of Fluid Machinery Engineering and Technology, Jiangsu University, Zhenjiang, China. The experiment was carried out under no-wind conditions with an air temperature of 10°C and relative humidity of 60%. The droplet distribution test design considered various factors including sprinkler type (D3000, R3000, and KPT), nozzle diameter (3.97 mm, 5.95 mm, and 7.94 mm), and operating pressure (103 and 138 kPa). A total of 18 trials were conducted. Specific working parameters and corresponding flow rates of sprinklers are listed in Table 1 . Due to different manufacturers of KPT, D3000, and R3000, certain differences in flow rate between KPT and the other two sprinkler types were observed. However, their maximum difference under the same nozzle diameter and operating pressure did not exceed 0.07 m^3/h, indicating that test accuracy could still be guaranteed.

Droplet distribution was analyzed using individual sprinkler irrigation. Before testing, we adjusted the sprinkler to a height of 1.2 m above the 2DVD instrument cameras to maintain similarity to sprinkler mounting height used in center pivot irrigation systems (Hui et al., 2022a). The water supply system was then turned on, and 2DVD was used to collect information regarding droplet velocity under stabilized pressure and flow rate conditions. Measuring points for water droplets were arranged at 1 m intervals in the radial direction within the radius of throw, and the number of effective droplets obtained at each measuring point was kept at about one thousand (Fig. 1). After collecting droplet data from all measuring points, the 3σ criterion (Pauta criterion for checking erroneous data) was used to check and eliminate errors caused by droplet splashing (Jiang et al., 2021).

2.3 Calculations

The resultant velocity of droplet (hereinafter referred to as droplet velocity) is calculated using the vertical and horizontal velocities recorded by 2DVD and expressed as Equation 1.

$$V = \sqrt{V_v^2 + V_h^2}$$

where V is the resultant velocity of the droplet (m/s); V_v is the vertical velocity of the droplet (m/s); and V_h is the horizontal velocity of the droplet (m/s).

The impact angle of droplet represents the angle between the direction of droplet impacting the ground and the soil surface, calculated by Equation 2.

$$\theta = \arctan\left(\frac{V_v}{V_h}\right) \times \frac{180}{\pi}$$

where θ is the impact angle of the droplet (°).

Equation 3 is used for calculating droplet shear stress (horizontal stress generated by droplet impact on the ground) (Ghadiri and Payne, 1986).

$$S_s = 0.5\rho V^2$$

where S_s is the shear stress of droplet (N/m^2); and ρ is the mass density of droplet (kg/m^3).

2.4 Data Analysis

Regression analysis was performed using Origin 8.5 software (OriginLab, Northampton, MA, USA), and Matlab R2010a software (MathWorks, Natick, MA, USA) was applied to develop relationships among droplet impact angle, distance from sprinkler, droplet velocity, and shear stress, as well as the relationship between droplet shear stress and distance from sprinkler. Coefficient of determination (R^2) was used to assess fitting accuracies of these relationships, while mean absolute error (MAE) and root mean square error (RMSE) between simulated and measured values were used to verify relationship accuracy. Meanwhile, coefficient of variation (CV) was used to evaluate the degree of dispersion of droplet impact angles under different distances from sprinkler. Higher CV indicates more discrete distribution of droplet impact angles. Moreover, effects of sprinkler type, operating pressure, nozzle diameter, and distance from sprinkler on droplet impact angle, velocity, and shear stress were subjected to multivariate analysis of variance (MANOVA). Mean values were separated using Fisher's protected least significant difference (LSD) at 0.05 level using SPSS 20.0 software (IBM Corp., Armonk, NY, USA).

3.1 Radial Distribution of Droplet Impact Angles

Figures 3 and 4 show radial distributions of droplet impact angles for the three sprinkler types with three nozzle diameters and two operating pressures. Irrespective of working conditions, relative frequencies of droplet impact angles within the 70°–90° range averaged 95.8% within 3 m distance from sprinkler. With increasing distance from sprinkler, the number of droplets with impact angles of 70°–90° gradually decreased, while droplets with impact angles less than 70° increased correspondingly. When distance from sprinkler reached 5 m, average relative frequency of droplets with impact angles of 70°–90° varied under different treatments, attaining only 49.9% on average, which was 46.2% lower than that at 3 m distance. Figures 3 and 4 clearly demonstrate that these reduced 70°–90° droplets shifted to the 60°–70° range, making average relative frequency of droplets in this impact angle range reach 48.5% under different treatments. In summary, changing distance from sprinkler could effectively alter distribution of droplet impact angles. In other words, throw radius of low-pressure sprinkler potentially affected droplet impact angle.

With continuous increase in distance from sprinkler, distribution range of droplet impact angles spread further. When distance increased to the jet end, relative frequency of droplet impact angles within the 50°–60° range increased dramatically, while those within 60°–70° and 70°–90° ranges decreased accordingly. Average relative frequencies of these three impact angle ranges (50°–60°, 60°–70°, and 70°–90°) at jet end were 23.7%, 53.2%, and 23.1%, respectively. From the perspective of overall distribution, the number of droplets with medium impact angles (60°–70°) still dominated, although the number with small impact angles (50°–60°) increased. Consequently, relative frequency distribution of droplet impact angles at jet end took the form of a logarithmic distribution. Furthermore, Table 2 shows radial CVs of droplet impact angles for three low-pressure sprinkler types. Notably, the greater the distance from sprinkler, the more discrete the distribution of droplet impact angle. Considering D3000-138 kPa-7.94 mm (sprinkler type-operating pressure-nozzle diameter) as an example, its CVs at 2, 5, and 8 m from sprinkler were 10.21%, 17.94%, and 31.19%, respectively. Therefore, the jet end might be the most vigorous area for droplet breakup and collision, thus leading to very dispersed distribution of droplet impact angle.

3.2 Relationship Between Droplet Impact Angle and Distance from Sprinkler

To clarify the relationship between droplet impact angle and distance from sprinkler, radial distribution of average droplet impact angles under three sprinkler types with three nozzle diameters and two operating pressures was systematically analyzed, as shown in Figure 5 [Figure 5: see original paper]. Overall, increasing distance from sprinkler caused average droplet impact angle to decrease, reaching its minimum at jet end. Average droplet impact angles of D3000, R3000, and KPT sprinklers along the spray direction were distributed within ranges of 62.12°–87.26°, 60.08°–86.30°, and 61.61°–87.60°, respectively, for three nozzle diameters and two operating pressures.

Figure 5 shows similar radial distributions of average droplet impact angles for three nozzle diameters or two operating pressures with the same sprinkler type. For instance, at the same distance from sprinkler, maximum differences of average droplet impact angles among three nozzle diameters and two operating pressures for D3000 remained around 2.23° and 3.27°, respectively. These values changed to 2.84° and 3.51° for R3000, and to 2.72° and 4.11° for KPT. As a result, irrespective of low-pressure sprinkler type, maximum differences of average droplet impact angles under different irrigation treatments existed within 2°–5°, which was only 2.66%–6.66% of average droplet impact angle (75.06°) for the three sprinkler types. Taken together, nozzle diameter and operating pressure had little effect on distribution of droplet impact angle and could be ignored in irrigation system design.

Furthermore, a certain exponential relationship was observed between average droplet impact angle and distance from sprinkler through regression analysis. The specific exponential equations under three sprinkler types, three nozzle diameters, and two operating pressures could be expressed by $\theta = e^{\beta l^{\alpha}}$, as depicted in Table 3 . Apparently, R^2 values of different treatments exceeded 0.900 except for D3000-103 kPa-3.97 mm treatment that exhibited a slightly lower R^2 (0.866). High R^2 values suggested that exponential relationships of these correlations reached an excellent level. Based on these results, it could be inferred that exponential relationship between average droplet impact angle and distance from sprinkler was universal for low-pressure sprinklers used in center pivot irrigation systems. This was also confirmed by results showing that droplet impact angle exhibited weak correlation with operating pressure and nozzle diameter. The following universal correlation (Eq. 4) was derived by reintegrating data regarding average droplet impact angles and distances from sprinkler under different treatments. Comparative analysis between simulated average impact angles and measured values found that correlation accuracy was excellent, with MAE and RMSE values of 2.061° and 2.587°, respectively (Fig. 6 [Figure 6: see original paper]).

$$\theta = 90.066e^{-0.0449l}, \quad R^2 = 0.882$$

where θ is the average droplet impact angle (°); and l is the distance from sprinkler (m).

3.3 Relationship Between Droplet Impact Angle and Velocity

Figures 7 and 8 illustrate relationships between radial droplet impact angles and velocities for three sprinkler types with three nozzle diameters and two operating pressures. Overall, droplet impact angle initially increased then decreased with increasing velocity. In addition to strong correlation between droplet velocity and impact angle, distance from sprinkler was also highly correlated with droplet velocity and impact angle. At 1 m distance from sprinkler, droplet velocity distribution ranges for the three low-pressure sprinklers (D3000, R3000, and KPT) were 0.56–4.74, 0.62–5.91, and 0.62–5.39 m/s, respectively. Correspondingly, droplet impact angle ranges were 60.75°–90.00°, 53.53°–90.00°, and 65.38°–90.00°, respectively (as shown in Table 4). Among the three sprinkler types, R3000 had the widest distribution range near sprinkler for both droplet velocity and impact angle. With increasing distance from sprinkler, distribution range of droplet velocities expanded slightly while that of impact angles shrank. When distance increased to 3 m, maximum droplet velocities and minimum impact angles of D3000, R3000, and KPT were higher by 0.33, 0.56, and 0.32 m/s, and lower by 2.82°, 6.20°, and 2.82°, respectively, than those at 1 m. Therefore, within 3 m distance from sprinkler, a positive correlation was observed among distance from sprinkler, droplet velocity, and impact angle. The longer the distance from sprinkler, the greater the droplet velocity and impact angle. On the other hand, it demonstrated that with increasing velocity, droplet impact angle of R3000 increased faster than those of D3000 and KPT.

With increasing distance from sprinkler, distribution ranges of droplet velocities and impact angles for each sprinkler began to expand rapidly. When distance from sprinkler was 5 m, maximum droplet velocities of the three sprinkler types increased by 1.27 m/s on average compared with those at 3 m distance. In particular, average reduction of their minimum impact angles reached 10.80°, a decrease of more than 16%. With increasing velocity, variation trend of droplet impact angle changed from gradual increase to continuous fall at 3–5 m from sprinkler. When distance exceeded 5 m, further increase in distance from sprinkler still brought continuous increase in droplet velocity and successive decrease in impact angle. However, results in Table 4 clearly showed that droplet velocity and impact angle distribution ranges of several measuring points (6, 7, and 8 m) near jet end were very close to each other, indicating stabilization of variation trends. Finally, droplet velocities of D3000, R3000, and KPT at 8 m were stable within ranges of 0.62–7.00, 0.62–8.76, and 0.62–7.46 m/s, respectively, whereas corresponding ranges for droplet impact angles were 50.03°–90.00°, 50.19°–90.00°, and 50.03°–90.00°, respectively. Overall, jet end produced the highest droplet velocity and smallest impact angle, resulting in the highest shear stress during the entire jet trajectory.

Furthermore, regression analysis for relationships between radial droplet velocities and impact angles under different sprinkler types, nozzle diameters, and operating pressures was conducted (Figs. 7 and 8). The relationship between droplet velocity and impact angle could be expressed as: $V^2 = \gamma\theta^2 + \delta\theta + \varepsilon$, where γ, δ, and ε are fitting coefficients. Table 5 shows regression analysis results. Noticeably, R3000 sprinkler showed the worst fitting accuracy, with average R^2 value of only 0.407 under different working conditions. One possible explanation was that R3000 had an irregular plate structure, which affected distribution of droplet velocities and impact angles. In contrast, fitting accuracies of both D3000 and KPT sprinklers were acceptable, with average R^2 values of 0.648 and 0.748, respectively. These results signified that appropriate low-pressure sprinkler type played an important role in droplet distribution. Similarly, droplet velocity and impact angle data under three sprinkler types, three nozzle diameters, and two operating pressures were integrated. A universal correlation was deduced, represented by Equation 5. Comparative analysis of simulated and measured values clearly indicated that correlation accuracy was poor, with MAE and RMSE values as high as 7.876° and 9.627°, respectively

(Fig. 9 [Figure 9: see original paper]).

$$\theta = -0.021V^2 + 7.699V + 67.518, \quad R^2 = 0.452$$

where θ is the droplet impact angle (°); and V is the resultant velocity of the droplet (m/s).

3.4 Relationship Between Droplet Impact Angle and Shear Stress

Figures 10 and 11 show relationships between droplet impact angles and shear stresses for three sprinkler types with three nozzle diameters and two operating pressures. Apparently, larger droplet impact angle resulted in smaller shear stress. This was not surprising because larger droplet velocity tended to result in smaller impact angle due to increased shear stress (Figs. 7 and 8). Moreover, droplet shear stress was found to increase gradually with increasing distance from sprinkler, reaching maximum value at jet end, as supported by data presented in Table 6 . Considering distances of 2, 5, and 8 m from sprinkler as examples, droplet shear stresses of D3000 lay within ranges of 0.00–1740.05, 0.00–4317.32, and 0.00–9720.36 N/m^2, respectively. Correspondingly, they were within ranges of 0.00–4082.97, 0.00–6289.79, and 0.00–14,532.66 N/m^2 for R3000, and 0.00–1122.19, 0.00–8145.64, and 0.00–11,748.69 N/m^2 for KPT, respectively. It was evident that droplet shear stress range for R3000 near sprinkler (2 m) was much larger than those for the other two sprinklers, and its maximum droplet shear stress was 2.35 and 3.64 times those of D3000 and KPT sprinklers, respectively. This was mainly attributed to the fact that distribution ranges of droplet velocities and impact angles were wider for R3000 near sprinkler than for other two sprinklers.

However, when distance increased, distribution ranges of droplet shear stresses for the three sprinkler types began to expand gradually, among which KPT exhibited the fastest expansion, followed by D3000 and R3000. Therefore, when distance increased to the middle of jet (5 m), maximum droplet shear stresses for the three sprinkler types increased by 7023.45, 2577.27, and 2206.82 N/m^2, respectively, with droplet shear stress range of KPT exceeding that of R3000. Nevertheless, this trend did not remain the same with further increase in distance from sprinkler. When approaching jet end, R3000 showed sharp expansion in distribution range of droplet shear stress, while expansion of KPT became increasingly slow. Eventually, droplet shear stress range of R3000 exceeded that of KPT when reaching jet end (8 m). In contrast, droplet shear stress range of D3000 was still smaller than those of other two sprinklers, which was related to steady expansion of droplet shear stress range along radial direction.

Regression correlations between droplet impact angles and shear stresses for three sprinkler types with three nozzle diameters and two operating pressures are shown in Table 7 . Clearly, these regression correlations under different working conditions showed good fitting accuracies (average R^2 value of 0.906). Equation 6 is a universal correlation derived by integrating data of droplet impact angles and shear stresses under different low-pressure sprinkler treatments, with R^2 value of 0.862. Overall, although R^2 value was reduced compared with those obtained using individual regression correlations, it still showed high accuracy in predicting droplet shear stress. Figure 12 [Figure 12: see original paper] shows comparative analysis of simulated and measured values. Obviously, correlation accuracy was quite good, with MAE and RMSE values of 214.542 and 418.134 N/m^2, respectively.

$$S_s = 26.996\theta^2 - 1170.371\theta + 48765.045, \quad R^2 = 0.862$$

where S_s is the droplet shear stress (N/m^2); and θ is the droplet impact angle (°).

3.5 Relationship Between Droplet Shear Stress and Distance from Sprinkler

Figure 13 [Figure 13: see original paper] shows radial distribution of average droplet shear stresses for three sprinkler types with three nozzle diameters and two operating pressures. Average droplet shear stresses increased exponentially with increasing distance from sprinkler. Distribution ranges of average droplet shear stresses along spray direction were 26.94–3313.51, 33.34–2650.80, and 16.15–2485.69 N/m^2 for D3000, R3000, and KPT sprinklers, respectively. Droplet shear stress of D3000 was highest, followed by R3000 and KPT. Average droplet shear stresses near sprinkler were very close for different operating pressures and nozzle diameters for any low-pressure sprinkler type. For instance, maximum differences of average droplet shear stresses for D3000 were 30.48 and 35.59 N/m^2 at 1 and 2 m from sprinkler, respectively. Corresponding values for R3000 were 124.04 and 112.32 N/m^2, while for KPT they were 41.05 and 58.10 N/m^2, respectively. Although average droplet shear stress differences of R3000 at these two distances were larger than those of other sprinklers, the differences were only 7.66% and 6.93% of average value of maximum shear stresses (1619.87 N/m^2) under different working conditions from the entire jet trajectory.

Another unexpected result was that greater difference in average droplet shear stress was associated with larger distance from sprinkler. Maximum difference of average droplet shear stresses at jet end reached values of 1566.81, 1589.64, and 905.77 N/m^2 for D3000, R3000, and KPT, respectively. The main reason for such significant difference was that higher operating pressure could result in greater droplet shear stress at jet end. Furthermore, when operating pressure was kept constant, shear stress increased gradually with increasing nozzle diameter. Therefore, droplet shear stress under larger operating pressure and nozzle diameter was subtracted from corresponding value under smaller ones, yielding an extraordinarily appreciable difference.

Table 8 shows exponential regression correlations between average droplet shear stresses and distances from sprinkler for three sprinkler types with three nozzle diameters and two operating pressures. Obviously, fitting accuracy of these correlations (R^2 values exceeding 0.860) under different treatments was good, indicating close relationship between droplet shear stress and distance. This study reintegrated data of average droplet shear stress and distance from sprinkler under different working conditions, and universal correlation (Eq. 7) suitable for low-pressure sprinklers was successfully obtained. From comparative analysis of simulated average shear stresses and measured values (Fig. 14 [Figure 14: see original paper]), MAE and RMSE values were 370.246 and 718.291 $\mathrm{N/m^2}$, respectively. Thus, accuracy of the universal correlation was not good, although its goodness of fit was satisfactory.

$$S_s = 0.562e^{0.5823l}, \quad R^2 = 0.848$$

where S_s is the average droplet shear stress ($\mathrm{N/m^2}$); and l is the distance from sprinkler (m).

3.6 Effects of Various Factors on Droplet Impact Angle, Velocity, and Shear Stress

MANOVA results for effects of sprinkler type, operating pressure, nozzle diameter, and distance from sprinkler on three droplet parameters are shown in Table 9 . According to results, sprinkler type and distance from sprinkler exhibited highly significant effects ($P<0.01$) on droplet impact angle and velocity. Therefore, droplet shear stress was also significantly influenced ($P<0.05$) by these two factors. Furthermore, results clearly showed that effect of operating pressure on droplet impact angle and velocity achieved significant level ($P<0.05$), but it failed to significantly influence ($P>0.05$) droplet shear stress. These results demonstrated that both sprinkler type and distance from sprinkler were crucial for distribution of droplet shear stress. In contrast, impacts of other two factors (operating pressure and nozzle diameter) were not as significant as expected, although previous analysis reported that they showed certain impacts. Therefore, in design of low-pressure irrigation systems, appropriate sprinkler type should be determined. Meanwhile, sprinkler spacing should be carefully selected because it was found to be related to overlap of droplet shear stress at different distances from sprinkler and helped minimize risk of soil erosion.

4.1 Distribution Characteristics of Droplet Impact Angle and Shear Stress

This study systematically analyzed distributions of droplet impact angle and shear stress of low-pressure sprinklers along spray direction using 2DVD instrument. Radial distribution trends of droplet impact angle and shear stress for different low-pressure sprinklers generally remained consistent under various nozzle diameters and operating pressures. That is, larger impact angle and smaller shear stress were observed for droplets near sprinkler (Chang and Hills, 1993a; Hui et al., 2021a). This performance might be attributed to presence of many small-sized droplets not far from sprinkler. At distances of 1, 2, and 3 m from sprinkler, relative frequencies of droplet diameters within 0–1 mm were as high as 96.1% on average (Hui et al., 2022b). Smaller droplets show larger specific surface area (surface area per unit volume), which causes higher air frictional resistance ratio, thereby making horizontal velocity of droplet reduce quickly and approach zero (Chang and Hills, 1993a). Accordingly, horizontal distance traveled by small droplet is short, and its impact angle is almost perpendicular to horizontal plane, resulting in small shear stress (Hui et al., 2021a). With increasing distance from sprinkler, droplet impact angle and shear stress gradually decreased and increased, respectively, reaching minimum and maximum values at jet end. Hui et al. (2021a) obtained similar results for radial distribution of droplet impact angle and shear stress using a ball-driven sprinkler. These results revealed that jet end was always prone to surface runoff, consistent with results of maximum soil erosion position obtained from perspective of specific power (Silva, 2006; Yan et al., 2011; King and Bjorneberg, 2011; Hui et al., 2022b). Accordingly, specific power and droplet shear stress showed certain similarity in predicting soil erosion of sprinkler irrigation system. Nonetheless, significant differences existed between them in terms of formation mechanism, because shear stress considered direction of droplet impacting ground, while specific power incorporated factor of water application rate (Chang and Hills, 1993b; Ge et al., 2018). Therefore, both droplet characteristic parameters exhibited advantages in evaluating soil erosion of sprinkler irrigation system. However, it remains uncertain which parameter is better, thus requiring further studies.

4.2 Effect of Various Factors on Distribution of Droplet Shear Stress

Even though distributions of droplet shear stress under different treatments in radial direction were generally similar, some differences were observed. Overall, larger operating pressure or nozzle diameter resulted in greater shear stress. It was worth noticing that larger operating pressure and nozzle diameter could lead to bigger radius of throw (Carrión et al., 2001; Ge et al., 2020). Therefore, above-mentioned difference in droplet shear stress could also be partly attributed to difference in radius of throw. However, these differences were non-significant ($P>0.05$) according to MANOVA. These findings were in good agreement with results reported by Hui et al. (2021a), who found that although nozzle diameter had certain effect on maximum shear stress, overall effect was insignificant. In addition to droplet shear stress, kinetic energy and specific power of low-pressure sprinkler were also found to be insignificantly affected ($P>0.05$) by operating pressure and nozzle diameter (Hui et al., 2022b), but this result was not supported by Bautista-Capetillo et al. (2012) on a VYR35 sprinkler and Osman et al. (2015) on a double nozzle impact sprinkler. One possible explanation is that their studies were conducted based on medium-and high-pressure sprinklers such as impact sprinklers. These sprinklers are fundamentally different from spraying methods of low-pressure sprinklers. On the other hand, they selected larger distribution ranges of operating pressures and nozzle diameters in experiments, which could easily lead to significant differences in droplet characteristics. In this study, highly significant ($P<0.01$) differences in distributions of droplet shear stresses were found among different types of low-pressure sprinklers, due to their different nozzle structures and spraying characteristics, as previously reported by Faci et al. (2001) on distributions of droplet diameters for various low-pressure sprinkler types. Among them, average shear stress range of D3000 attained the largest value, followed by R3000 and KPT. It was suggested that FSPS was prone to generating significant droplet shear stress. Therefore, direct spraying on bare ground should be avoided in field irrigation to prevent severe soil erosion. In contrast, it was recommended to promote application of OSPS in irrigation engineering due to its smallest shear stress among the three low-pressure sprinkler types, which was in line with results reported by Hui et al. (2022b) for optimization of center pivot irrigation system from perspective of droplet kinetic energy.

4.3 Limitation and Suggestion

This research can provide new possibility for accurate prediction and prevention of soil erosion in sprinkler irrigation systems and shows important reference value for transformation of low-pressure sprinkler irrigation systems. However, some limitations exist.

In this study, correlations among various indicators such as droplet impact angle, velocity, shear stress, and distance from sprinkler were developed. We observed weak correlations between droplet impact angle and velocity (MAE and RMSE of 7.876° and 9.627°, respectively) and between average droplet shear stress and distance from sprinkler (MAE and RMSE of 370.246 and 718.291 N/m^2, respectively). The reason might be that accuracy of correlations was affected by data errors due to droplet splashing, although significant portion of error was processed by statistical tests based on 3σ criterion (Jiang et al., 2021). Therefore, it is critical to further standardize droplet testing process to minimize experimental error in future studies. Moreover, it should be noted that universal correlations developed in this study were based only on three low-pressure sprinkler types: D3000, R3000, and KPT. Actually, many types of low-pressure sprinklers from different manufacturers exist, which exhibit differences in droplet distribution (King and Bjorneberg, 2012b). Therefore, it is necessary to supplement droplet data from more sprinklers to improve universalities of developed correlations. In addition, droplet distribution test of single sprinkler in this study was conducted under indoor conditions, while actual sprinkler irrigation systems are usually used in field. Accordingly, future research should consider effects of meteorological factors including wind velocity, direction, temperature, humidity, and solar radiation on distributions of droplet impact angle and shear stress. More importantly, it is necessary to further compare effects of specific power and droplet shear stress on soil infiltration under same sprinkler irrigation condition to reveal which of these two droplet characteristic parameters has greater impact on soil erosion. Furthermore, a center pivot irrigation system is composed of multiple sprinklers. Spraying method of multiple sprinklers is more complicated than that of single sprinkler. Some droplets between adjacent sprinklers may collide with each other during movement (Ge et al., 2015). This phenomenon can lead to unpredictable changes in droplet diameter, velocity, and shear stress. Therefore, it is highly desirable to conduct future research regarding droplet characteristics and their impacts on crop growth under center pivot irrigation system with multiple sprinklers.

5 Conclusions

Lower droplet shear stresses under different sprinkler types, operating pressures, and nozzle diameters generally occurred near sprinkler. However, with increasing distance from sprinkler, shear stress continuously increased and reached peak value at jet end, indicating that highest risk of soil erosion occurred at jet end, and soil erosion in sprinkler irrigation system cannot be simply attributed to droplet kinetic energy but must also consider shear stress. Moreover, sprinkler type and distance from sprinkler were found to play key roles in radial distribution of droplet shear stress. Although operating pressure showed significant effect on distribution of shear stress, its overall effect was non-significant. Therefore, when designing low-pressure irrigation systems, compared with adjusting nozzle diameter and operating pressure, it was more important to reasonably select sprinkler type and sprinkler spacing to reduce soil erosion. In this study, we found that D3000 exhibited the largest radial average shear stress range among three low-pressure sprinkler types, followed by R3000 and KPT. To minimize soil erosion by reducing droplet shear stress, KPT sprinkler was undoubtedly more suitable than D3000 and R3000 sprinklers for promotion in center pivot irrigation systems.

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References

Al-Kayssi A W, Mustafa S H. 2016. Modeling gypsifereous soil infiltration rate under different sprinkler application rates and successive irrigation events. *Agricultural Water Management*, 163: 66–74.

Baiamonte G, Provenzano G, Iovino M, et al. 2021. Hydraulic design of the center-pivot irrigation system for gradually decreasing sprinkler spacing. *Journal of Irrigation and Drainage Engineering*, 147(7): 04021027, doi: 10.1061/(ASCE)IR.1943-4774.0001568.

Bautista-Capetillo C, Zavala M, Playán E. 2012. Kinetic energy in sprinkler irrigation: different sources of drop diameter and velocity. *Irrigation Science*, 30(1): 29–41.

Carrión P, Tarjuelo J, Montero J. 2001. SIRIAS: a simulation model for sprinkler irrigation. *Irrigation Science*, 20(2): 73–84.

Chang W J, Hills D J. 1993a. Sprinkler droplet effects on infiltration. II: laboratory study. *Journal of Irrigation and Drainage Engineering*, 119(1): 157–169.

Chang W J, Hills D J. 1993b. Sprinkler droplet effects on infiltration. I: impact simulation. *Journal of Irrigation and Drainage Engineering*, 119(1): 142–156.

Chen R, Li H, Wang J, et al. 2020. Effects of pressure and nozzle size on the spray characteristics of low-pressure rotating sprinklers. *Water*, 12(10): 2904, doi: 10.3390/w12102904.

De Jong S M, Addink E A, Van Beek L P H, et al. 2011. Physical characterization, spectral response and remotely sensed mapping of Mediterranean soil surface crusts. *CATENA*, 86(1): 24–35.

Etikala B, Adimalla N, Madhav S, et al. 2021. Salinity problems in groundwater and management strategies in arid and semi-arid regions. *Groundwater Geochemistry: Pollution and Remediation Methods*, 42–56.

Faci J M, Salvador R, Playán E, et al. 2001. Comparison of fixed and rotating spray plate sprinklers. *Journal of Irrigation and Drainage Engineering*, 127(4): 224–233.

Ferreira A G, Larock B E, Singer M J. 1985. Computer simulation of water drop impact in a 9.6-mm deep pool. *Soil Science Society of America Journal*, 49(6): 1502–1507.

Ge M, Wu P, Zhu D, et al. 2015. Effect of jets interaction on spray characteristics between adjacent sprinklers. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 31(9): 100–106. (in Chinese)

Ge M, Wu P, Zhu D, et al. 2018. Analysis of kinetic energy distribution of big gun sprinkler applied to continuous moving horse-drawn traveler. *Agricultural Water Management*, 201: 118–132.

Ge M, Wu P, Zhu D, et al. 2020. Comparisons of spray characteristics between vertical impact and turbine drive sprinklers – A case study of the 50PYC and HY50 big gun-type sprinklers. *Agricultural Water Management*, 228: 105847, doi: 10.1016/j.agwat.2017.12.009.

Ghadiri H, Payne D. 1986. The risk of leaving the soil surface unprotected against falling rain. *Soil & Tillage Research*, 8: 1–8.

Ghadiri H, Payne D. 2010. The formation and characteristics of splash following raindrop impact on soil. *European Journal of Soil Science*, 39(4): 563–575.

Huang C, Bradford J M, Cushman J H. 1982. A numerical study of raindrop impact phenomena: the rigid case. *Soil Science Society of America Journal*, 46(1): 14–19.

Huang G, Bringi V N, Cifelli R, et al. 2010. A methodology to derive radar reflectivity-liquid equivalent snow rate relations using C-band radar and a 2D video disdrometer. *Journal of Atmospheric & Oceanic Technology*, 27(4): 637–651.

Hui X, Lin X, Zhao Y, et al. 2022a. Assessing water distribution characteristics of a variable-rate irrigation system. *Agricultural Water Management*, 260: 107276, doi: 10.1016/j.agwat.2021.107276.

Hui X, Zheng Y, Meng F, et al. 2022b. Comprehensively evaluating and modelling droplet diameters and kinetic energies of low-pressure sprinklers. *Irrigation and Drainage*, 71(4): 829–854.

Hui X, Zheng Y, Yan H. 2021b. Water distributions of low-pressure sprinklers as affected by the maize canopy under a centre pivot irrigation system. *Agricultural Water Management*, 245: 106646, doi: 10.1016/j.agwat.2020.106646.

Jiang Y, Liu J, Li H, et al. 2021. Droplet distribution characteristics of impact sprinklers with circular and noncircular nozzles: Effect of nozzle aspect ratios and equivalent diameters. *Biosystems Engineering*, 212: 200–214.

King B A, Bjorneberg D L. 2011. Evaluation of potential runoff and erosion of four center pivot irrigation sprinklers. *Applied Engineering in Agriculture*, 27(1): 75–85.

King B A, Bjorneberg D L. 2012a. Transient soil surface sealing and infiltration model for bare soil under droplet impact. *Transactions of the ASABE*, 55(3): 937–945.

King B A, Bjorneberg D L. 2012b. Droplet kinetic energy of moving spray-plate center-pivot irrigation sprinklers. *Transactions of the ASABE*, 55(2): 505–512.

Kruger A, Krajewski W F. 2002. Two-dimensional video disdrometer: A description. *Journal of Atmospheric & Oceanic Technology*, 19(5): 602–617.

Lu J, Zheng F, Li G, et al. 2016. The effects of raindrop impact and runoff detachment on hillslope soil erosion and soil aggregate loss in the Mollisol region of Northeast China. *Soil and Tillage Research*, 161: 79–85.

Manke E B, Norenberg B G, Faria L C, et al. 2019. Wind drift and evaporation losses of a mechanical lateral-move irrigation system: oscillating plate versus fixed spray plate sprinklers. *Agricultural Water Management*, 225: 105759, doi: 10.1016/j.agwat.2019.105759.

Osman M, Hassan S B, Yusof K. 2015. Effect of combination factors of operating pressure, nozzle diameter and riser height on sprinkler irrigation uniformity. *Applied Mechanics & Materials*, 695: 380–383.

Robles O, Playán E, Cavero J, et al. 2017. Assessing low-pressure solid-set sprinkler irrigation in maize. *Agricultural Water Management*, 191: 37–49.

Robles O, Zapata N, Burguete J, et al. 2019. Characterization and simulation of a low-pressure rotator spray plate sprinkler used in center pivot irrigation systems. *Water*, 11(8): 1684, doi: 10.3390/w11081684.

Sayyadi H, Nazemi A H, Sadraddini A A, et al. 2014. Characterising droplets and precipitation profiles of a fixed spray-plate sprinkler. *Biosystems Engineering*, 119: 13–24.

Silva L L. 2006. The effect of spray head sprinklers with different deflector plates on irrigation uniformity, runoff and sediment yield in a Mediterranean soil. *Agricultural Water Management*, 85(3): 243–252.

Silva L L. 2007. Fitting infiltration equations to centre-pivot irrigation data in a Mediterranean soil. *Agricultural Water Management*, 94(1–3): 83–92.

Stambouli T, Martínez-Cob A, Faci J M, et al. 2013. Sprinkler evaporation losses in alfalfa during solid-set sprinkler irrigation in semiarid areas. *Irrigation Science*, 31(5): 1075–1089.

Vaezi A R, Ahmadi M, Cerdà A. 2017. Contribution of raindrop impact to the change of soil physical properties and water erosion under semi-arid rainfalls. *Science of the Total Environment*, 583: 382–392.

Yan H, Jin H, Qian Y. 2010. Characterizing center pivot irrigation with fixed spray plate sprinklers. *Science China Technological Sciences*, 53(5): 1398–1405.

Yan H, Bai G, He J, et al. 2011. Influence of droplet kinetic energy flux density from fixed spray-plate sprinklers on soil infiltration, runoff and sediment yield. *Biosystems Engineering*, 110(2): 213–221.

Yan H, Hui X, Li M, et al. 2020. Development in sprinkler irrigation technology in China. *Irrigation and Drainage*, 69(52): 5–17.

Note: Figure translations are in progress. See original paper for figures.