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The Spatial Variation Mechanism of Size, Velocity, and the Landing Angle of Throughfall Droplets under Maize Canopy

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Abstract: Larger diameter and velocity and smaller landing angle of sprinkler irrigation droplets are more likely to cause soil splash and erosion. However, the mechanism of crop canopy influence on the physical parameters of sprinkler droplets is unknown. In this study, with the landing angle of sprinkler irrigation droplets as the independent variable and maize plants (*Zea mays* L.) as the research object, an indoor sprinkler irrigation experiment was carried out. The effects of maize canopy and variation in sprinkler irrigation droplets landing angle on the value and spatial distribution pattern of size, the velocity, and the landing angle of throughfall droplets was analyzed. In addition, the spatial variation patterns of throughfall droplets size, velocities' distribution, and individual droplet's speed, kinetic energy were also explored. The results showed that maize canopy and the decreasing of the sprinkler irrigation droplet landing angle had a positive and obvious effect on reducing the size and velocity of penetrating rain droplets. However, the throughfall droplets' landing angles were only small variations. When the landing angle of sprinkler irrigation droplets was >45°, the spatial distribution of throughfall droplets size and velocity corresponded well with the canopy structure and leaf projection area of maize, i.e., the further away from the maize stalk, the larger the size and velocity of throughfall droplets. Nevertheless, if the landing angle of sprinkler irrigation droplets was <45°, the spatial distribution mentioned above was mainly affected by droplets landing angle. The spatial variation of throughfall droplets' size and velocities at different measurement points was attributed to the change of the larger droplets' volume proportion and the equivalent velocity. Although the maize leaves had a certain degree of perturbation effect on the velocities and kinetic energy of the larger kinetic energy droplets, the flight path of these drops did not alter significantly. The results of this research will be of practical value in guiding the development of a new sprayer and the optimum selection of sprinkler heads.

Keywords: sprinkler irrigation; maize canopy; droplets landing angle; distribution of drop size and velocity; kinetic energy

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1. Introduction

Sprinkler irrigation technology, as a high degree of mechanization and more modern irrigation mode, can significantly improve the utilization rate of water and fertilizer, irrigation efficiency, and crop yield and quality, and has been widely promoted and applied in the world [1]. Unlike natural rainfall, sprinkler droplets have different landing angles, in addition to specific drop size and velocity [1,2]. When the sprinkler droplets impact the soil surface, soil splash detachment is more likely to be caused [3]. At the same time, the soil agglomerate structure is disassembled, and the fine soil particles tend to fill the soil void, and the soil surface compactness increases. Consequently, soil surface crust formation and soil infiltration rate decrease, and runoff generation will begin to occur gradually [4–6]. Moreover, the above phenomenon becomes more serious as the sprinkler droplets' landing angle decreases [7–9].

Kinetic energy is an essential indicator of the degree to which droplets strike the soil surface, and the magnitude of kinetic energy is determined by the drop size and velocity [10]. In general, the ground is covered with crop canopy during sprinkler irrigation, and there is spatial variability in crop canopy structure [11]. Due to the crop canopy partitioning, sprinkler irrigation water is partitioned into three parts (interception, stemflow, and throughfall), and the penetrating raindrops are the only net sprinkler water retaining kinetic energy [12]. Many previous studies have confirmed that plant canopy could significantly alter (increase or decrease) the kinetic energy of throughfall droplets [13–16] and their spatial distribution patterns [12,17–19]. Therefore, compared to when there was no canopy, the size and velocity of the throughfall droplets under the plant canopy have changed considerably. Many researchers have conducted in-depth studies on the effects of plant canopy and physical characteristics of rainfall on the drops' size (D_{50}) and velocity of throughfall. The results of Nanko et al. [20] show that the D_{50} of throughfall droplets under the forest canopy is all greater than uncrowned, and there is a tendency for the D_{50} of penetrating raindrops to increase when the wind speed and rainfall intensity is lesser. Using maize canopy as a study object, Frasson and Krajewski [21] compare and analyze the variation pattern of droplets' size in the presence and absence of maize canopy. Their results also show that when the D_{50} is between 2.50 and 2.75 mm in the absence of canopy, the D_{50} of throughfall increases to 3.75 mm. However, the results of Zapata et al. [12] are significantly different from previous studies. Their results show that, compared to sprinkler irrigation droplets, the size of the droplets of throughfall is somewhat reduced due to the presence of the maize canopy. In addition, in forests with taller plants, the droplets' velocities of throughfall are significantly greater than that of natural rainfall because leaf dripping drops have sufficient fall height to reach their terminal velocities [22–24]. Moreover, the landing velocity of throughfall droplets is smaller due to their shorter fall height [24]. However, the results of Zapata et al. [12] show that, compared to uncrowned, the velocities of penetrating raindrops at different measurement points present a decreasing trend, and the degree of velocity abatement varies at different measurement points. A careful analysis of previous research methods reveals that most of the previous studies used fixed-point monitoring outdoors when measuring the droplets size and velocity of throughfall, and the effect of spatial variability of plant canopy structure on the size and velocity of throughfall droplets was considered less, which may also be the reason for the significant differences in the results of previous studies. Moreover, if there is spatial variability in the size and velocity of throughfall droplets under the crop canopy, it is not known what factors cause the spatial variability of drop size and velocity.

Since there is a certain angle between the nozzle of the sprinkler head and the horizontal plane, and the spray range needs to be considered, it is inevitable that sprinkler droplets have a specific landing angle. If the droplets landing angle is slight, the amount of kinetic energy of droplets in the horizontal direction and the tangential impact strength of the soil surface struck by droplets tend to increase [7,25]. The increase in droplet shear stress directly leads to the increase of soil particle detachment and transfer rate, and erosion force [25]. To clarify the effect of the droplets landing angle on soil splash and erosion, some researchers have conducted more studies with droplets impact angle as the independent variable and with bare ground soils [7–9]. Their results show that the smaller droplet impact angle accelerates the transport rate of soil particles, the significant splash effect carries soil particles farther away from the droplet impact site, and the coexistence of surface runoff and spattering effect makes the soil erosion more obvious. It is often assumed that the crop canopy can alter droplets' flight path when the kinetic energy of sprinkler droplets is affected by the crown, resulting in a significant increasing trend or near-vertical of landing angles of throughfall droplets. However, it remains to be explored whether this is the case as described above.

As an indispensable food crop in people's daily lives, maize has become one of the top three food crops globally, and the area under cultivation is still expanding. In addition, sprinkler irrigation technology plays an irreplaceable role in maize cultivation [26].

Therefore, in this paper, sprinkler irrigation experiments were conducted indoors under windless conditions with maize plants as the study object and the droplets landing angle as the dependent variable. A two-dimensional video disdrometer (2DVD) was used to collect the droplets' size and velocity at different measurement points among the micro-scale spatial range of the maize plants (the basic unit that constitutes the field environment), and the droplets landing angles of throughfall were calculated. The main objective of this study is to investigate the influence of maize canopy and the variation of sprinkler droplets landing angle on the values and spatial distribution of size, velocity, and the landing angle of throughfall droplets in the micro-scale spatial space range, and to clarify the main control factor that causes the spatial variation of physical parameters of throughfall droplets.

2. Materials and Methods

2.1. Experimental Device

2.1.1. Droplet Landing Angle Control Facility

When a sprinkler head works well in farmland, the droplets descend slowly as a single water curtain. A droplet landing angle control device was created in our research (Figure 1a). The device's working principle is that the power supply provides power for the pump and the mobile trolley, and the working pressure of needles could be controlled by adjusting the speed of the inverter pump. The actual work pressure of needles can be displayed by a pressure gauge. The pump pumps water from the reservoir, and the water flows through the water delivery hose and reaches needles. Figure 1b presents the conventional working condition of the device. A single aluminum water delivery pipe, on which some needles are fixed, is installed on a height-adjustable and vertical bracket. The bracket is placed on a mobile cart, and the cart's movement speed is adjustable. Automatic steering is installed separately at both ends of the cart, and the water curtain could work well in a cycle above the crop canopy. Table 1 shows the main structural parameters of the device and the nozzle diameter.

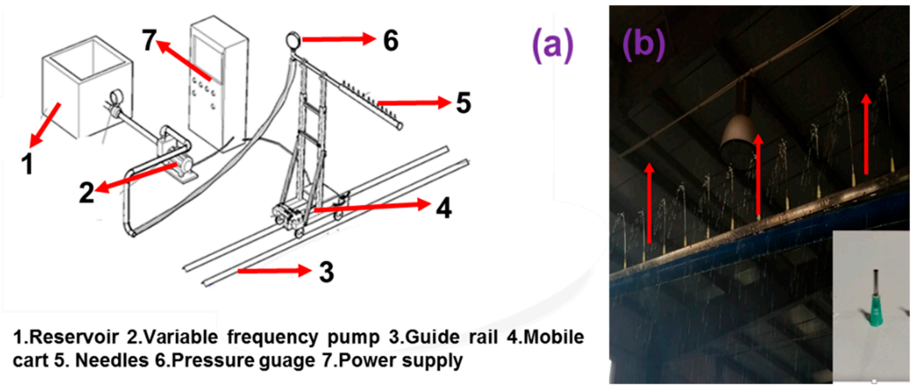

Figure 1. Regulation and controlling device of sprinkler irrigation droplets landing angle. (**a**) shows the overall structure of the device; (**b**) shows the working situation of the device.

Table 1. Structure parameters of the regulation and controlling device of the droplet landing angle.

Parameters	Model or Value
Trolley moving speed (m·s^{-1})	0.034
Length of guide rail (m)	5.00
Telescopic bracket maximum extension height (m)	4.50
Width of sprinkler water curtain (m)	2.50
Needle spacing (cm)	5.00
Nozzle diameter (mm)	2.00
Pressure gauge type and accuracy	YB150, Xi'an instrument factory, Measurement range (0–0.40 MPa), Precision (0.01 MPa)

In addition, the water delivery aluminum tube is round, and it is fixed in the telescopic bracket using screws, nuts, and clips. The outlet direction of the needles can be changed by loosening the screws and turning the water tube, and thus the landing angle of sprinkler irrigation droplets will be varied. Figure 2 shows the variation in the landing angle of sprinkler irrigation droplets. It should be emphasized that the droplet landing angle for treatment 1 is approximately vertical, and the needle outlet is upward. Droplets spray upward and then fall, and the normal operation state of the device (Figure 1b) is as mentioned above. Droplets landing angles of other treatments are achieved by gradually changing the outlet direction of the needles.

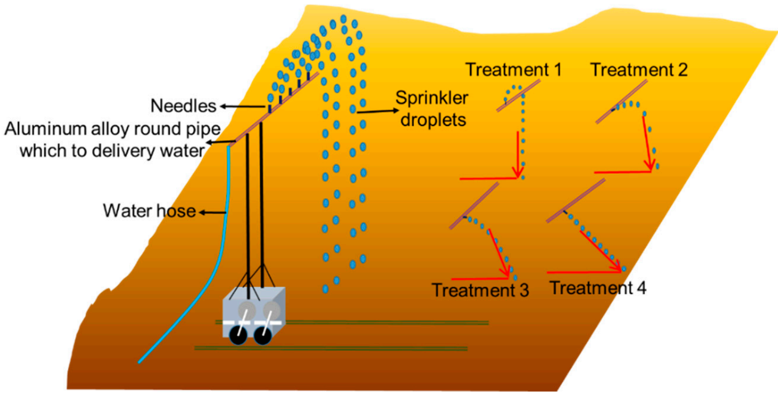

Figure 2. Variation of sprinkler irrigation droplets landing angle.

Since this study used only one variable, the droplet landing angles were regulated at a fixed working pressure with needles of a single diameter. Under a fixed working pressure (19.5 kPa) and nozzle diameter (2.00 mm), the sprinkler irrigation intensity for different treatments was 44.30, 43.96, 44.65, and 45.11 mm/h, and the uniformity coefficients of water distribution were 96.13%, 87.25%, 88.47%, and 86.56%, respectively, which were greater than the uniformity requirement of mobile sprinkler irrigation (≥85%) [27].

2.1.2. Layout of Maize Plants and Measuring Points

Maize plants are fixed on a movable bracket, on which some iron nails (length 15 cm, interval distance 10 cm) are welded. The height of the bracket is 50 cm, and the spacing of crossbars on the bracket is adjustable. Maize plants are placed following the planting spacing (60 × 30 cm) in the field during testing. Figure 3 shows the arrangement of maize plants and measurement points, with a total of 18 measurement points, and the size of each measurement point is 10 × 10 cm. A total of 16 maize plants are needed for the experiment, 4 plants are used to create the micro-scale spatial scope between maize plants, and the remaining are used as protection rows.

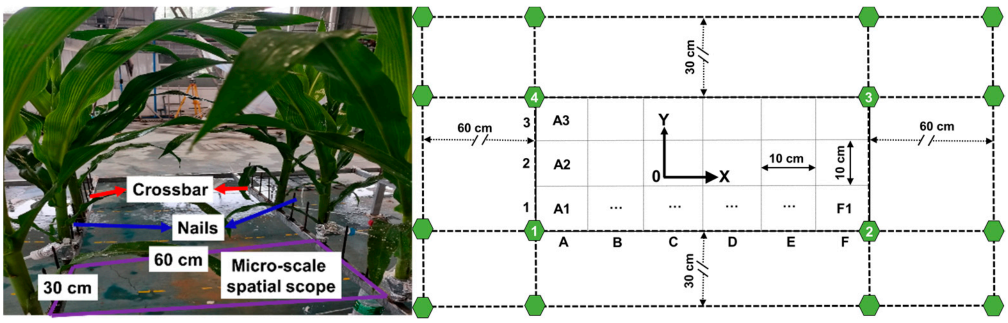

Figure 3. The arrangement of maize plants (**the left**) and measure points (**the right**). Capital letters in the figure represent the spatial distribution of different measurement points between maize rows, and the regular hexagons that are green-filled represent the spatial distribution of maize plants. The regular hexagons filled with green and Arabic numerals represent maize plants and the maize constitute a micro-scale area in the maize field.

2.2. Experimental Design

The experiment was carried out at the Institute of Water-Saving Agriculture (IWSA) in arid areas of China (IWSA). The maize (Zhengdan 958) was sown in the test field, with the maize plant and row spacing set at 30 cm and 60 cm, respectively. Maize plants with slightly different morphological parameters were selected for the indoor sprinkler irrigation experiment, which required the maize plants to be cut flush with a razor blade and fixed on the test bench. The maize stalk incisions were sealed with paraffin wax to prevent wilting of maize plants quickly. The sprinkler irrigation experiment was undertaken indoors with the device as described in Section 2.1.1, under different droplet landing angles (treatment 1, treatment 2, treatment 3, and treatment 4 (Figure 2)). In addition, canopy structure parameters of those maize plants were measured at the beginning and end of the experiment to ensure that no significant wilting of plants occurred during the experiment.

2.3. Measurement Parameters and Methods

2.3.1. Drop Size and Velocity

The information of the size and velocity of sprinkler irrigation droplets, within and without maize canopy, was collected using a two-dimensional video disdrometer (2DVD), developed by the Graz Institute for Applied Systems Technology Research, Austria [28]. The 2DVD was moved below the fixture (Figure 4a) when droplet information under the maize canopy was collected (Figure 4b). While droplet information was measured, the sprinkler irrigation droplet generation device moved one round-trip as one cycle within the set range, and the collection time for each measurement point was set as one cycle. Droplets' information was collected 18 times with and without maize canopy, for 36 collections per treatment.

(1) Individual droplet size

Two linear scanning cameras with photoelectric detection functions are installed inside the 2DVD. Droplet shape and size are recorded and collected when the water droplets pass through the camera testing area (100×100 mm^2), and then the three-dimensional shape of the water droplets are reconstructed. Their volumes are calculated using the four times water droplet shadow widths recorded by the two piecewise optical paths, respectively, and finally, drop size of the equal volume sphere is calculated. The unit is mm.

(2) Horizontal and vertical velocity of a single droplet

The horizontal and vertical velocities of droplets passing through the test area can be obtained by the built-in data processing software of the computer of 2DVD, where V_v is the vertical velocity and V_h is the horizontal velocity. The unit is m/s.

The working principle of 2DVD for collecting droplet information is described in detail in other previous literature and will not be further elaborated in this paper [1,29]. If researchers want to understand its structure and working method, please refer to the above literature.

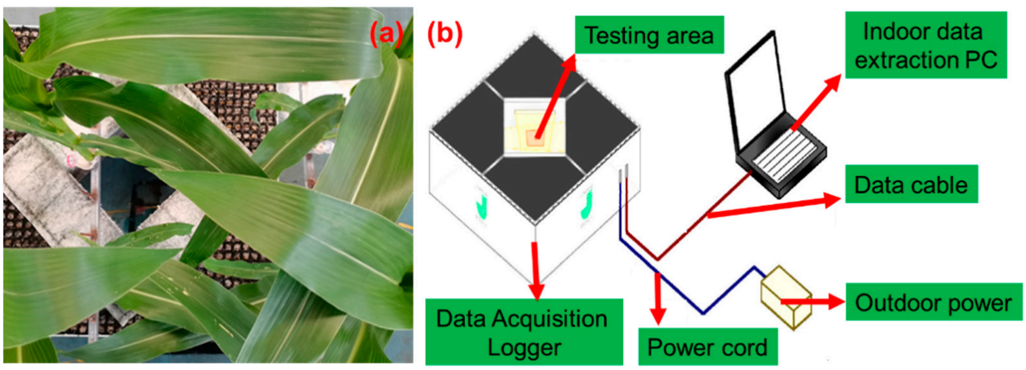

Figure 4. Droplet information acquisition equipment. (**a**) shows the actual arrangement of the maize plant with 2DVD during the experiment; (**b**) shows the arrangement of the droplet information collection device.

2.3.2. Morphological Parameters of Maize Canopy

(1) Leaf height and low: Height of the highest and lowest point of the maize leaf to the ground (cm).
(2) Leaf height distance: The distance from the highest point of the maize leaf to the stalk (cm), measured with a stainless steel tape measurer (accuracy 0.1 cm).
(3) Leaf azimuth: The angle formed by the central vein of the leaf and the positive direction of the *X*-axis (°), counterclockwise is positive, and the value range 0–360°. A protractor was used to measure (accuracy 0.1°).
(4) Maize canopy projection was measured using Canopeo software (which needs to be installed in advance on the cell phone) [30]. The measured result showed a canopy shade of 53.96% within the micro-scale space constituted by the maize plants selected for this study.

2.4. Calculation Methods

(1) Droplet size: The median diameter method was used in this paper to calculate the drop diameter of throughfall. The cumulative frequency of the drop size distribution was calculated by the weighted averaging method. When the cumulative frequency of the drop size distribution was 50%, the corresponding drop diameter was defined as the drop size (D_{50}, mm) [31]. D_{25} and D_{75} were the corresponding droplet size when the cumulative frequency of the drop size distribution was 25% and 75%, respectively [31]. Their computational approach was similar to D_{50}.
(2) Single droplet velocity: The resultant velocity was related to the horizontal and vertical velocity of a drop. Its calculation formula was shown as the following equation.

$$V_c = \sqrt{{V_v}^2 + {V_h}^2} \quad (1)$$

where V_c is the drop velocity (m·s^{-1}), V_v is the vertical velocity, and V_h is the horizontal velocity.
(3) Individual droplet landing angle: Based on the horizontal and vertical velocities of a droplet collected by 2DVD, its landing angle can be calculated by Equation (2).

$$\vartheta = \arctan\left(\frac{V_v}{V_h}\right) \quad (2)$$

where ϑ is the landing angle (°). In this study, the drop size distribution at different measurement points was graded at 0.50 mm interval, and the average value of all droplet angles in a diameter graduation range, in which there was the maximum kinetic energy, was used as the drop landing angle [32]. Consequently, after calculating, the droplet landing angles for treatments 1, 2, 3, and 4 are 81.69°, 71.33°, 60.58°, and 42.04°, respectively.
(4) Single drop kinetic energy: The formula for calculating the kinetic energy of a single drop was shown as the following equation.

$$K_{ed} = \frac{1}{12}\pi d^3 \rho_w {v_c}^2 \quad (3)$$

where K_{ed} is the single drop kinetic energy (J), d is the drop diameter (mm), and ρ_w is the water density (kg·m^{-3}).
(5) Drop velocity: In this paper, the equivalent velocity was used to assess the velocity of the throughfall droplets population. The equivalent velocity was related to the total kinetic energy and total quality of the droplets population, and its value was calculated as follows.

$$V_{eq} = \sqrt[2]{\frac{2\sum_{i=1}^{n} K_{ed}}{\rho_w \sum_{i=1}^{n} \frac{\pi d_i^3}{6}}} \quad (4)$$

The resultant velocity, horizontal and vertical velocities of the throughfall drop population, were obtained using Equation (4), except that the horizontal and vertical velocities of the droplet population were calculated using the sum of the kinetic energy of the droplet population in the horizontal and vertical directions.

(6) Drop size distribution: The drop size distribution of the drop population was generally characterized by droplet number density ($mm^{-1} \cdot m^{-3}$) and relative droplet volume (dimensionless) [31]. The drop size distribution at the measurement point in this paper was described by droplet relative volume (i.e., volume ratio) and its calculation formula was shown below.

$$V(D_j) = \frac{\sum_i^{N_j} V_i}{V_{total}} \tag{5}$$

where i represents the ith drop in the drop group; j represents the jth drop diameter classification, and the size of each droplet classification is set to 0.50 mm in this study, N_j is the number of droplets in the jth diameter classification, V_i is the volume of the ith droplet in the drop group; V_{total} represents the total volume of droplets in the drop group.

2.5. Data Analysis

Statistical significance between data was obtained by Duncan's multiple range test, and the level of significant difference was set at 5%. Statistical analyses of data were performed with SPSS 22.0 (SPSS Inc., Chicago, IL, USA) software. Spatial distribution of azimuth and leaf height distance of maize leaves were plotted with Microsoft Office Visio (2019) software. All graphs were plotted with Sigmaplot 10.0 (Systat Software, San Jose, CA, USA), except for the spatial distribution figures illustrated with the R language package.

3. Results and Discussion

3.1. Spatial Variation Mechanism of Throughfall Drop Size

3.1.1. Variation of Throughfall Drop Size

Table 2 summarizes the effect of maize canopy and change in sprinkler irrigation droplet landing angle on the value and spatial distribution of physical parameters (size, velocity, and the landing angle) of penetration rain droplets at 18 measurement points among the micro-scale spatial area. Based on the data presented in Table 2, it is clear the maize canopy and the sprinkler irrigation droplet landing angle significantly impact the diameter of penetrating rain droplets. When the landing angle was 81.69°, 71.33°, 60.58°, and 42.04°, the variation ranges of D_{50} of throughfall droplets under the maize canopy and their percentages to uncrowned were 1.64–3.40 mm (49.10–101.80%), 1.68–3.25 mm (51.20–99.09%), 1.42–3.31 mm (43.03–100.03%), and 1.03–3.12 mm (31.12–94.26%), respectively. The mean values of D_{50} and standard deviation, and their proportion to no crown were 2.58 ± 0.56 mm (77.25%, 81.69°), 2.53 ± 0.52 mm (77.13%, 71.33°), 2.47 ± 0.54 mm (74.85%, 60.58°), and 2.37 ± 0.36 mm (71.60%, 42.04°), respectively. In addition, since there were almost no differences in the physical parameters of sprinkler irrigation droplets and plant canopy morphological parameters under different treatments during experimenting, with treatment 1 (81.69°) as the control group, the influence of variations in the landing angle of sprinkler irrigation droplets was analyzed in this paper. Compared with 81.69°, the mean values of D_{50} decreased by 0.05, 0.11, and 0.21 mm for 71.33°, 60.58°, and 42.04°, and the corresponding mean values of D_{50} were 0.98, 0.96, and 0.92 times higher than those of the control group, respectively.

Table 2. Physical parameters of droplet inside and outside maize canopy.

Physical Parameters of Throughfall	Under Maize Canopy					Without Canopy
	Mean Value	Standard Deviation	CV (%)	Maximum Value	Minimum Value	
Drop diameter (D_{25}) (mm)						
Treatment 1	1.34	0.26	19.40	2.11	0.86	2.16
Treatment 2	1.31	0.23	17.56	2.09	0.83	2.14
Treatment 3	1.26	0.22	17.46	2.16	0.76	2.02
Treatment 4	1.19	0.16	13.45	2.17	0.65	2.17
Drop diameter (D_{50}) (mm)						
Treatment 1	2.58	0.56	21.71	3.40	1.64	3.34
Treatment 2	2.53	0.52	20.55	3.25	1.68	3.28
Treatment 3	2.47	0.54	21.86	3.31	1.42	3.30
Treatment 4	2.37	0.36	15.19	3.12	1.03	3.31
Drop diameter (D_{75}) (mm)						
Treatment 1	3.56	0.96	26.97	3.78	2.75	3.82
Treatment 2	3.47	0.91	26.22	3.69	2.63	3.79
Treatment 3	3.38	0.86	25.44	3.77	2.56	3.85
Treatment 4	3.24	0.52	16.49	3.65	1.98	3.84
Drop velocity ($m \cdot s^{-1}$)						
Treatment 1	4.86	0.63	12.96	5.87	4.12	5.88
Treatment 2	4.76	0.67	14.08	5.78	3.71	5.75
Treatment 3	4.59	0.67	14.60	5.77	3.64	5.97
Treatment 4	4.42	0.58	13.12	5.17	3.23	5.87
Drop horizontal velocity ($m \cdot s^{-1}$)						
Treatment 1	—	—	—	—	—	—
Treatment 2	1.45	0.23	15.86	1.85	0.99	1.84
Treatment 3	2.22	0.32	14.41	2.65	1.75	2.98
Treatment 4	3.17	0.47	14.83	3.83	2.31	4.24
Drop vertical velocity ($m \cdot s^{-1}$)						
Treatment 1	—	—	—	—	—	—
Treatment 2	4.54	0.64	14.10	5.48	3.53	5.59
Treatment 3	4.01	0.60	14.96	5.20	3.20	5.08
Treatment 4	3.07	0.39	12.70	3.67	2.26	4.05
Droplet landing angle (°)						
Treatment 1	81.90	1.21	1.48	83.89	79.66	81.69
Treatment 2	72.30	1.64	2.27	76.58	70.35	71.33
Treatment 3	63.70	3.68	5.78	70.12	59.45	60.58
Treatment 4	44.08	2.55	5.78	49.51	41.26	42.04

Note: CV is the spatial coefficient of variation, i.e., this is the ratio of the standard deviation of the data to the mean (in %). — indicates that the data had no reference value.

The overall results of this study showed that the drop size of penetrating rain under the maize canopy was all less than or equal to uncrowned, and the smaller the sprinkler irrigation drop landing angle, the drop diameter of penetration rain also tended to decrease. Consequently, the existence of the maize canopy and the reduction of sprinkler irrigation droplet landing angle had a certain degree of negative impact on D_{50} of penetrating rain droplets. In other words, maize crown and the decreasing of sprinkler irrigation droplet landing angle positively affected the prevention of large sprinkler irrigation droplets impacting the surface soil directly and the formation of soil spattering and erosion. The above conclusions were not limited to D_{50} but also D_{25} and D_{75}.

Figure 5a presents the effect of the variation of sprinkler irrigation droplet landing angle on the drop characteristics of throughfall. According to the data presented in Figure 5a, there was a good correlation between the sprinkler irrigation droplet landing angle and the drop diameter (R^2 closed to 1). The smaller the sprinkler irrigation droplet landing angle, the smaller the droplet size of throughfall (D_{25}, D_{50}, and D_{75}).

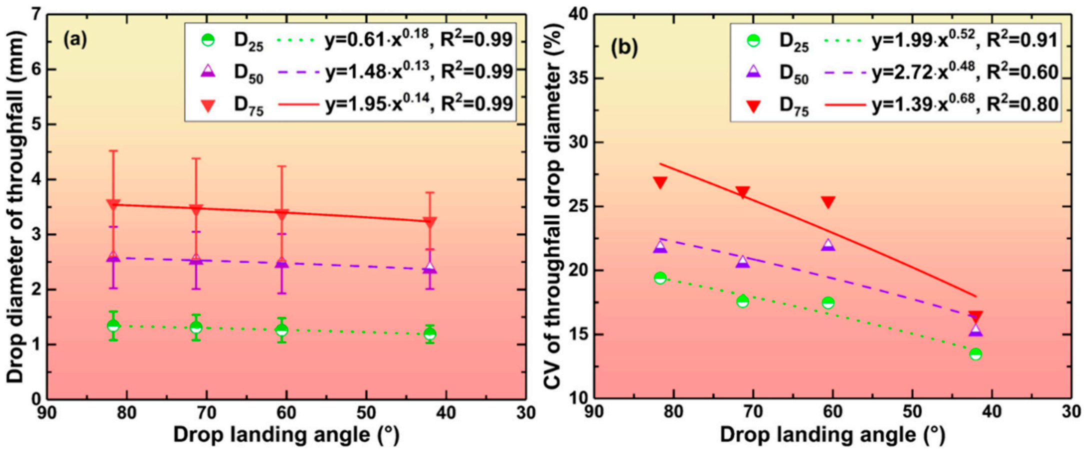

Figure 5. Inter-relationship among drop diameter of throughfall and its CV, and the drop landing angle. (**a**) presents the relationship between droplet size of throughfall and the droplet landing angle; (**b**) presents the relationship between the CV value of throughfall droplet particle size and the droplet landing angle.

Although the results of this study are consistent with those obtained by Zapata et al. [12], who studied the effect of maize canopy on the size of sprinkler irrigation droplets with a stationary sprinkler irrigation system as an experimental condition, the conclusions of more existing studies differ significantly from this paper [18,20,21,33,34]. The effect of maize canopy on D_{50} with maize plants as a research object was revealed by Frasson and Krajewski [21], Armstrong and Mitchell [34]. Their experimental results showed that the D_{50} of penetration rain droplets was significantly greater than that in the absence of canopy, and the same conclusion was also better verified in studies with the canopy of forest tree [18,32] and soybean [33]. The reason for the above phenomenon may be that the diameter range of sprinkler irrigation droplet used in this study (0.10–6.00 mm) was significantly broader than in previous studies (0.50–2.00 mm) [18], and the drops dripping from maize leaves could not escape from the influence of the above drop size range. Consequently, the D_{50} of throughfall droplets tended to decrease compared to uncrowned.

3.1.2. Spatial Variation of Throughfall Drop Size

The spatial distribution patterns of water volume and kinetic energy of penetrating rain are the results of the combined effect of the plant canopy structure and the physical parameters of droplets [11,12], and the drop size of penetration rain under maize canopy should be no exception. Figure 6 presents the spatial distribution of the leaves and canopy projection, and Figure 7 presents the results of the effect of maize canopy structure and the change in sprinkler irrigation droplet landing angle on the spatial distribution of D_{50} of penetrating rain droplets. In addition, if the droplet landing angle is <45°, the component of drop velocity or kinetic energy intensity in the horizontal direction begins to be greater than that in the vertical direction, and the spatial distribution of the physical parameters of throughfall droplets may vary significantly at this node. Results of previous literature indicated that the more horizontal the droplet flight trajectory tended to be, the greater the probability of its capture by the plant canopy [12]. Consequently, a comparative analysis of the effect of the variation of sprinkler irrigation droplets landing angle on the spatial distribution of drop size of penetrating rain should be carried out at 45° as a node.

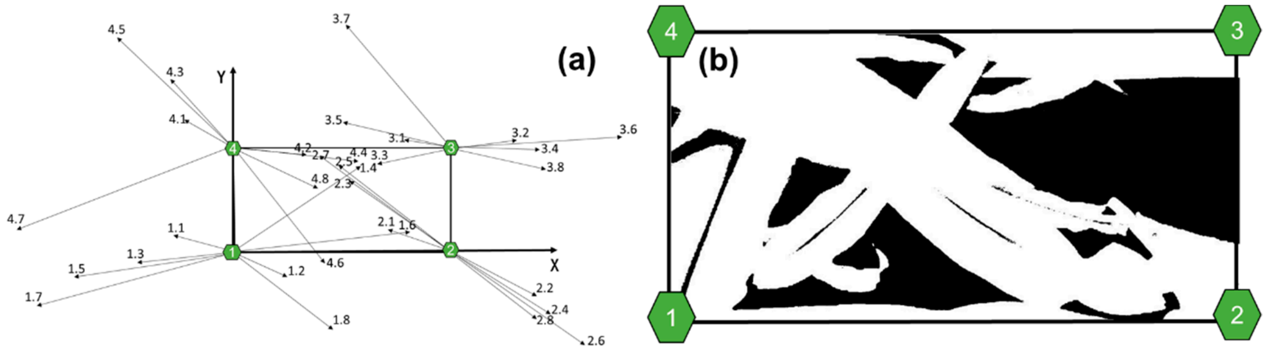

Figure 6. Spatial structure of maize canopy. (**a**) Spatial distribution of maize leaves; (**b**) maize canopy projection. 1–4 indicate the distribution of maize selected for the experiment in the micro-scale spatial range.

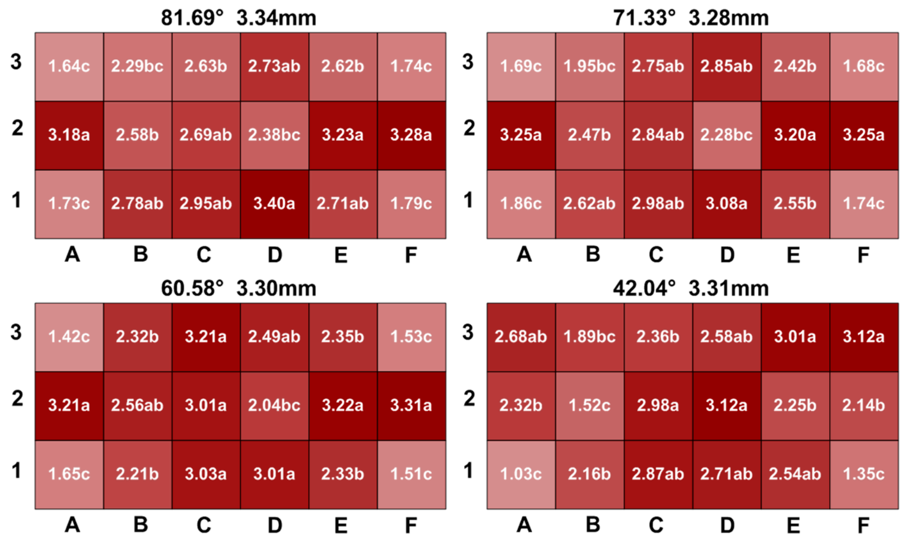

Figure 7. Spatial distribution of drop diameter (D_{50}) of throughfall. Different letters indicate significant difference between data in each treatment (p < 0.05). The data, directly above each subplot, represent the mean value of the landing angle and D_{50} of sprinkler irrigation droplets when there was no maize crown.

As shown in Figure 7, when the sprinkler irrigation droplet landing angle was >45°, there was a positive correlation between the D_{50} values and the distance of the measurement point from the maize stalk, i.e., the farther away from the stalk, the larger the D_{50} value. The spatial distribution of D_{50} had a good correspondence with the spatial distribution of maize leaves and canopy projection (Figure 6), specifically the sparser the maize leaves, the less the canopy projection area, and the larger the D_{50}. These results indicated that when the droplet landing angle was >45°, the spatial distribution of D_{50} was more likely to be influenced by maize canopy spatial structure rather than the droplet landing angle. The results were also consistent with previous studies carried out with forest trees and maize plants [11,18,19,35]. However, if the sprinkler irrigation droplet landing angle was <45°, D_{50} no longer had the regularity as mentioned above. The larger D_{50} of penetration rain droplets was mainly distributed in the upper location of the maize canopy void, and its spatial distribution tended to shift toward the direction of droplet incidence (between plants, from position 1 to position 3). Therefore, when the water droplet landing angle is <45°, the sprinkler irrigation droplet landing angle became the primary variable affecting the spatial distribution of D_{50} of throughfall droplets.

As the data shown in Table 2, the spatial coefficients of variation of D_{50} of penetration rain droplets under different treatments were 21.71% (81.69°), 20.55% (71.33°), 21.86% (60.58°), and 15.19% (42.04°), respectively. Moreover, the sprinkler irrigation droplet landing angle had a good correlation with CV, the smaller the sprinkler irrigation droplet landing angle, the minor the CV (Figure 5b). The correlation between the above variables was not only limited to D_{50}, D_{25} and D_{75} also had the same potential law.

The effect of wind direction on the spatial distribution of throughfall under natural rainfall conditions was carried out by Zheng et al. [11] and Zhang et al. [36]. Their results indicated that the penetrating rain volume on the leeward side under the plant canopy was significantly higher than that on the windward side. The above findings were consistent with the spatial distribution of D_{50} in this study when the sprinkler irrigation droplet landing angle was <45°. Nevertheless, they did not specify what caused the phenomenon, because the plants were tilting toward the wind direction under natural conditions. For this study conducted under windless conditions, the droplet flight path was largely unaffected by external environmental factors, and the indoor experimental condition was also valuable in analyzing the factors causing the spatial variation of the penetrating rain droplets. From the physical perspective, the little effect of leaf's disturbance on droplets' original flight path may be a robust explanation for the above phenomenon.

3.1.3. Spatial Variation of Drop Size Distribution of Throughfall

The drop size distribution is generally considered as the vital data support for understanding the mechanism of spatial variation in the drop size of penetration rain [35]. Figure 8 presents the drop size distribution of different measurement points in the micro-scale spatial area within and without canopy, and Figure 9 shows the volume ratios in the different drop diameter scopes. The purpose of plotting Figure 9 is to clarify further how the volume share of droplets in different drop size ranges vary as the measurement point changes.

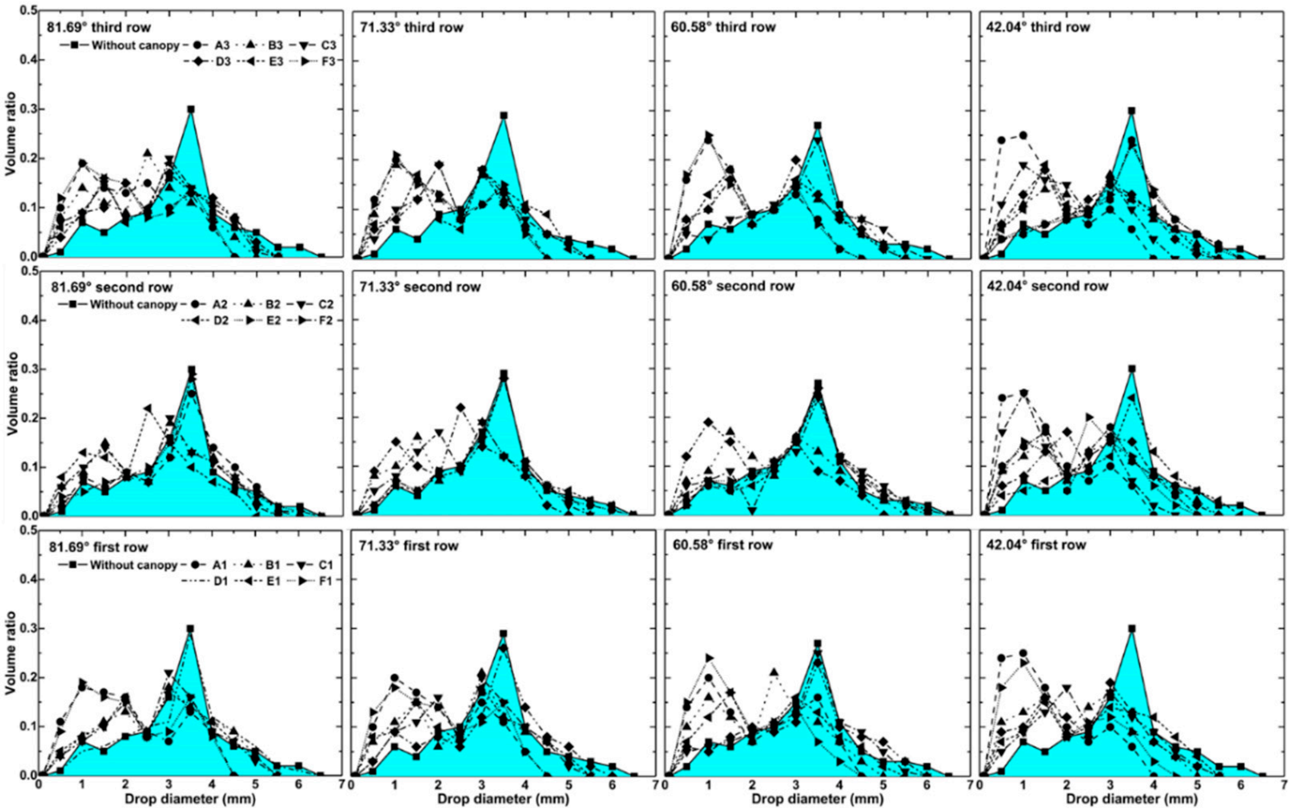

Figure 8. Spatial variation of drop size distribution of throughfall with different treatments. The filled part, shown in each subplot, is the drop size distribution for different treatments without maize crown.

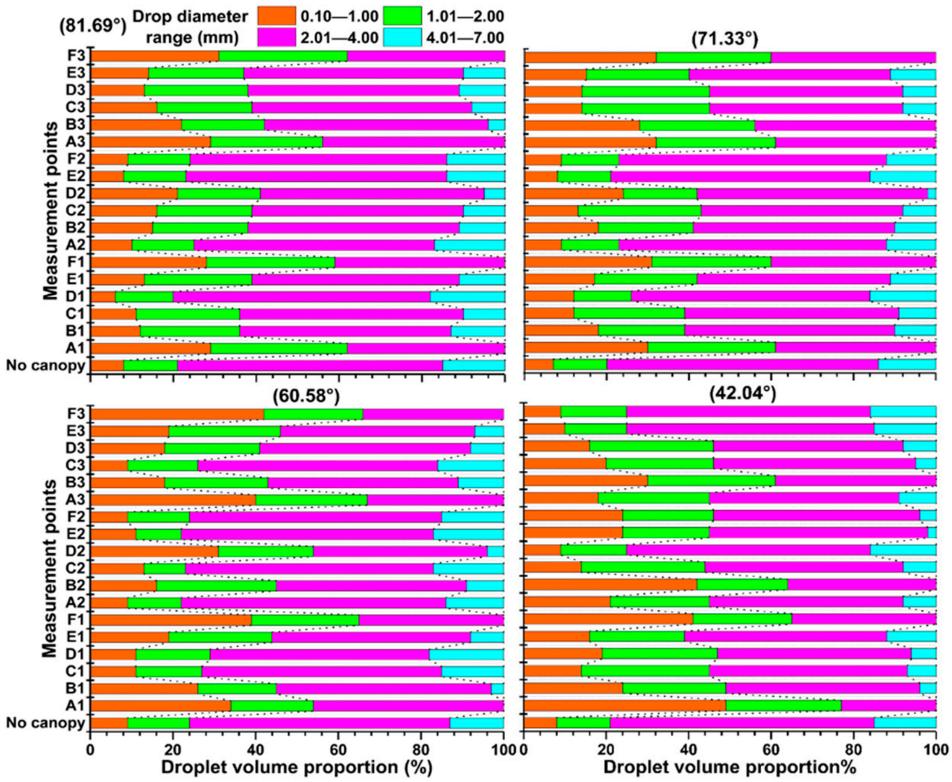

Figure 9. Volume proportion of droplets in different diameter ranges under different treatments.

The significant differences in the percentage of drop volume with droplet size less than 2.00 mm, at different measurement points and treatments, is shown in Figure 9. The fluctuations of share of droplet volume with diameter less than 2.00 mm ranged from 20–62% (81.69°), 21–61% (71.33), 22–67% (60.58°), and 25–77% (42.04°), respectively. The mean values of proportion of that droplet volume and their percentages of uncrowned for different treatments were 39.78% (189.43%, 81.69°), 41.28% (206.40%, 71.33°), 42.61% (177.54%, 60.58°), and 46.61% (221.95%, 42.04°), separately. Consequently, the volume shares of small droplets showed a pattern of larger values within canopy than uncrowned, and the smaller the landing angle of sprinkler irrigation droplet, the larger these values. Maize canopy and the variation of the sprinkler irrigation droplet landing angle increased the volume share of small droplets in penetrating rain. Meanwhile, the volume proportion of large drops should also be considered because of their greater soil splash capability [17]. The mean values of the volume share of droplets with drop size greater than 4.01 mm, corresponding to different treatments, were 11.57%, 11.14%, 10.23%, and 8.57%, respectively. From the experimental data, compared with the smaller size droplets, the volume percentage of large drops showed the opposite variation pattern.

Furthermore, as the distance of the measurement points from the maize stalk changed, the volume share of drops in different size ranges was also alterated. As shown in Figure 9, when the sprinkler irrigation droplet landing angle was >45°, the volume share of droplets size less than 2.00 mm in the penetrating rain showed a spatial distribution pattern of smaller values the further away from the maize stalk, while the larger droplets (>4.01 mm) showed an opposite trend. For example, when the sprinkler irrigation droplet landing angle was 60.58°, the volume proportion of droplet diameter smaller than 2.00 mm, at A3, B3, C3, D3, E3, and F3, were 67%, 43%, 26%, 41%, 46%, and 66%, while the percentage of drop size larger than 4.01 mm was 0%, 11%, 16%, 8%, 7%, and 0%, respectively. The association of Figures 7 and 9 could reveal that the spatial distribution regularity of D_{50} of throughfall droplets is well consistent with the volume share of drops size greater than 4.00 mm, but opposite to that of drops size less than 2.00 mm. Therefore, the spatial variation of the volume share of droplets in the different size ranges was the root cause of the spatial variability in the D_{50} of the penetrating rain droplets. When the sprinkler irrigation droplets landing angle was <45°, although the spatial distribution of the volume proportion in the different droplet size ranges no longer had the pattern mentioned above, the various mode of the D_{50} of penetrating rain droplets was still consistent with the volume share of drop size greater than 4.00 mm.

Throughfall is the water formed by the interaction between sprinkler irrigation droplets and plant leaves, and its drop size distribution differs from uncrowned [12]. For sprinkler irrigation droplets, two main movement behaviors of droplets occur when droplets strike maize leaves: the breaking up of large drops and the convergence of tiny droplets. Fragmentation is the process by which larger drops with sufficient velocity upon impact with a maize leaf are broken up into more smaller droplets (splash droplets) [37]. In contrast, convergence is the process by which some tiny droplets continue to collect at a location on maize leaf to form one or many larger drops and then drip down along the leaf edge or tip [18]. Since there are significant gaps in maize canopy (Figure 6b), we must also consider the sprinkler irrigation droplets that are not in contact with the maize canopy (direct or free penetration rain droplets). Therefore, the composition of the penetrating rain droplets population should contain dripping, splashing, and free penetrating rain droplets [12]. To provide a more visual description, a schematic diagram is shown in Figure 10.

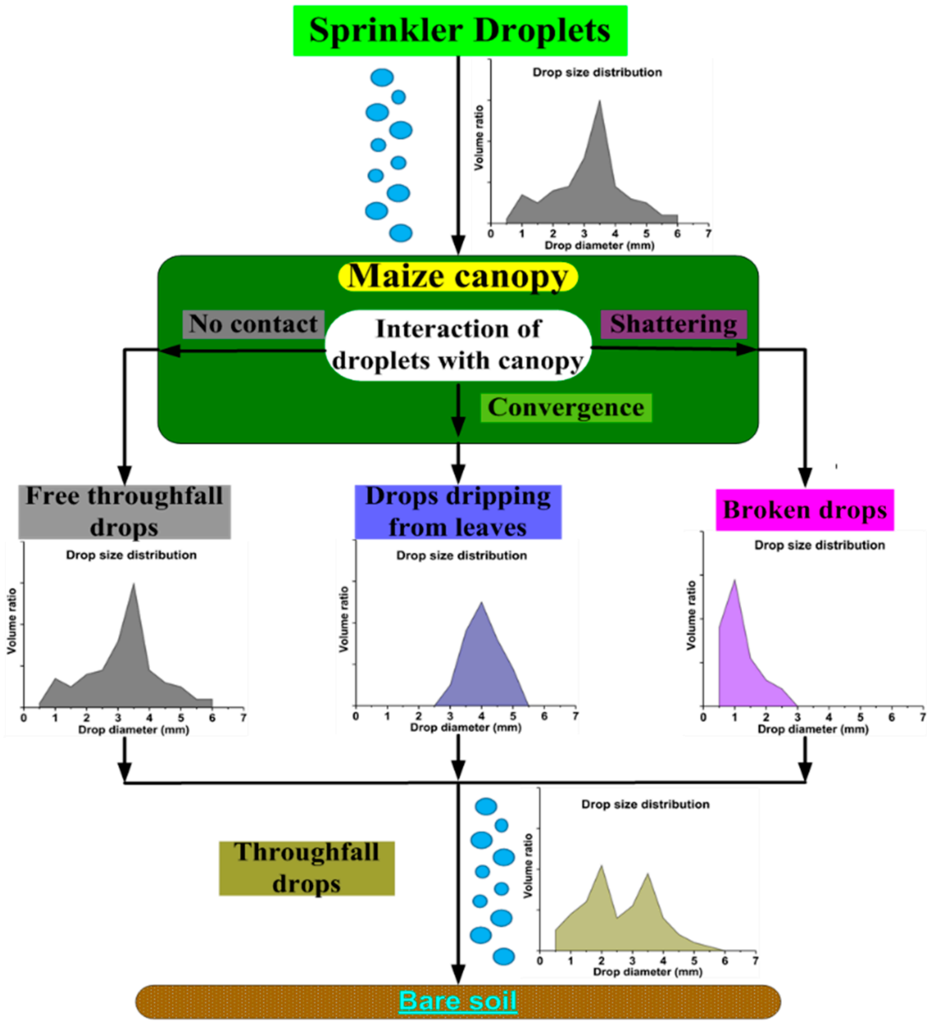

Figure 10. Component of drop size distribution of throughfall.

This study showed that the closer to the maize stalk, the larger the volume share of tiny-sized droplets in penetrating rain, and the opposite for large drops. As shown in Figure 3 (right) and Figure 6b, the presence of maize leaf projection at A3, B3, and C3 indicated that the penetrating rain at these points is bound to include both broken and coalesced drops. The condition where the sprinkler irrigation drop landing angle was 60.58° was illustrated in Figure 8. A bimodal trend of drop size distribution was shown at A3, and a new emerging peak in volume ratio was presented at smaller drop diameter. The same appearance was also observed at B3. However, the drop size distribution at C3 was almost no different from that in the absence of a canopy, the single-peaked trend maintained still, and the peak in the volume ratio of throughfall droplets was present at the large drop size. The maize canopy structure generally showed a spatial distribution pattern closer to the stalk's greater canopy thickness. The effect of canopy thickness on the size and number of penetrating rain droplets was studied by Nanko et al. [38] and Zapata et al. [12]. Their results showed that reducing canopy thickness indirectly increased the volume share of large drops in penetrating rain droplets, due to smaller canopy thickness directly increasing the accessibility of large drops. The distance from the maize stalk and the projected area of the maize leaves are in the order of A3 > B3 > C3, and the volume share of droplets size smaller than 2.00 mm also shows the same order, while drops with size larger than 4.01 mm present a converse sequence. Consequently, the formation mechanism of the drop size distribution of throughfall under maize canopy should be described as large drops breaking up in contact with the lower leaves in the canopy to form a more extensive volume ratio of smaller droplets. The reason for a large number of tiny droplets may be that the closer to the maize stalk, the greater the chance of large droplets being broken up. For the measurement points (C3), being farther away from the maize stalk, the sprinkler irrigation droplets are less disturbed by the leaves, and the chance of large drops being broken to form tiny droplets is so slight, such that there is no significant difference in the drop size distribution compared to when there is no canopy.

3.2. Spatial Variation Mechanism of Throughfall Drop Velocity

3.2.1. Variation of Throughfall Drop Velocity

The mean or median value is generally adopted to evaluate the velocity of droplets population [12]. The number of small droplets is usual larger in penetrating rain, however, their kinetic energy is such smaller. For example, when drops of 0.50 mm and 4.00 mm in size fall from a height of 1 m, their corresponding kinetic energy is 1.31×10^{-7} J and 2.96×10^{-4} J. If the mean or median value is used to assess the overall speed level of the droplet group, the effect of large drops on soil splashing erosion will be obscured unintentionally [39]. Therefore, in this paper, the droplets population was treated as a moving individual, and its velocity was evaluated with an equivalent approach.

Based on the data presented in Table 2, it could be seen that the maize canopy and the change of sprinkler irrigation droplet landing angle has a significant effect on the drop velocity of throughfall. The variation ranges of droplets velocities and their proportions to uncrowned under different treatments were 4.12–5.87 m/s (70.07–99.83%, 81.69°), 3.71–5.78 m/s (64.52–100.52%, 71.33°), 3.64–5.77 m/s (60.97–96.65%, 60.58°), and 3.23–5.17 m/s (55.03–88.07%, 42.04°), respectively. The mean values and standard deviations, and their percentages of uncrowned were 4.86 ± 0.63 m/s (82.65%, 81.69°), 4.76 ± 0.67 m/s (82.78%, 71.33°), 4.59 ± 0.67 m/s (75.88%, 60.58°), and 4.42 ± 0.58 m/s (75.30%, 42.04°), separately. In addition, as shown in Figure 11, the velocity of penetrating rain droplets under maize canopy tended to decrease as a power function with decreasing sprinkler irrigation droplet landing angle, while the elimination degree of the speed of sprinkler irrigation droplets by the maize canopy showed a linear increase. Moreover, the velocity variation in the vertical direction was consistent with the resultant velocity, while the change of velocity in the horizontal direction was the opposite.

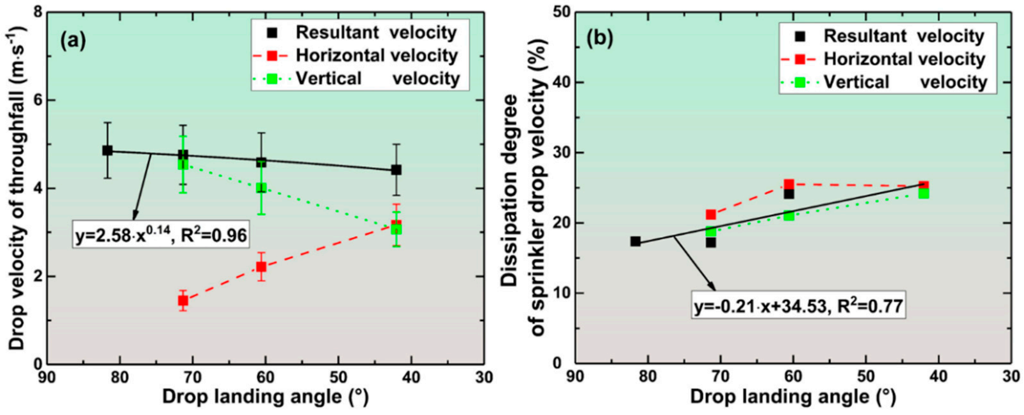

Figure 11. Relationship between the sprinkler irrigation droplets landing angle and velocity of throughfall droplets. When the sprinkler irrigation droplet landing angle is 81.69°, the difference with natural rainfall is not significant [2], therefore, droplet's equivalent velocities in horizontal and vertical direction are not calculated, respectively. (**a**) the relationship between droplet velocity of throughfall and the landing angel of sprinkler droplets. (**b**) the relationship between dissipation degree of velocity and the landing angel of sprinkler droplets

In addition, the effect of variation in sprinkler irrigation droplet landing angle on the droplets velocity of penetrating rain was analyzed in this paper, with treatment 1 (81.69°) as the control group. Compared to 81.69°, the velocity of throughfall droplets was reduced by 0.10, 0.17, and 0.17 m/s for 71.33°, 60.58°, and 42.04°, respectively. Their velocities were 0.98, 0.94, and 0.91 times higher than the 81.69° for the three treatments. Therefore, the results mentioned above indicated that the smaller the sprinkler irrigation droplets landing angle, the lower the velocity of penetrating rain droplets, and the same effect was seen in the maize canopy.

The above results indicated that the velocities of throughfall droplets were less than or equal to that in the absence of canopy at all treatments. Sprinkler irrigation droplets velocities are decreased by maize canopy notably. Unfortunately, research on the effect of plant canopy on droplet velocity is scarce rarely, and only the drop velocity of a single droplet size and its corresponding drop dripping height was analyzed by few studies [18]. Although the results of this study are consistent with those of Zapata et al. [12], who used the median velocity of droplet populations as a crucial indicator. The median velocity, used in their research, may represent the velocity of small droplets, which may result from the fragmentation of large drops hitting leaves at the lower part of the maize canopy. Consequently, it may be inappropriate to draw hasty conclusions from only a few studies, and more research time and effort may be needed to investigate the mechanisms by which maize canopy affects sprinkler irrigation droplet velocity in detail.

3.2.2. Spatial Variation of Throughfall Drop Velocity

Figure 12 presents the effects of the presence of the maize canopy and the variation of the sprinkler droplet landing angle on the spatial variation of droplets velocity of throughfall. Comparing Figures 7 and 12, it can be seen that the spatial distribution patterns of velocity and D_{50} of droplets were in good agreement and correspond well to the spatial distribution of the maize canopy structure (Figure 6) when the sprinkler irrigation droplet landing angle was >45°. Its specific pattern was not repeated redundantly. The results of this research are consistent with previous studies. The spatial distribution correlation of the leaf area index of plant canopies concerning the droplets' kinetic energy of penetrating rain was clarified by Liu et al. [19] in an agroforestry complex system. Their results showed that the droplets' kinetic energy of throughfall corresponded well to the leaf area index, i.e., the greater the leaf area index and the greater the canopy thickness, the lower the droplets' kinetic energy of penetration rain. Furthermore, with a single plant as their study subject, Nanko et al. [18] showed the similarity with our result in describing the regularity of droplets' different velocities corresponding to different falling heights. Therefore, the leaves closed to the maize stalk broke up the large drops and reduced the droplets' velocity, while dissipating the striking kinetic energy of the sprinkler irrigation droplets.

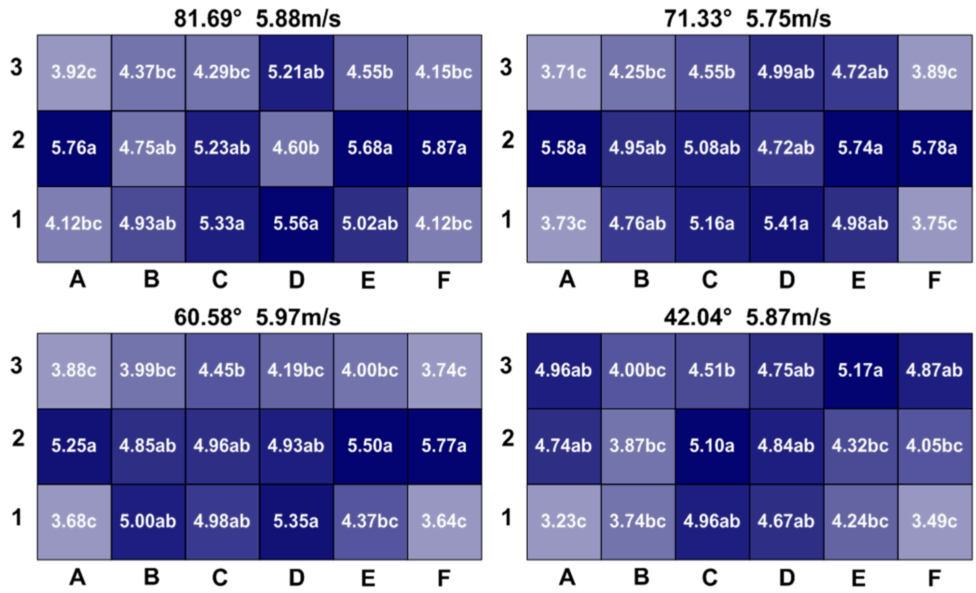

Figure 12. Spatial distribution of velocity of throughfall droplets. Different letters indicate significant difference between data in each treatment ($p < 0.05$). Data directly above each subplot represent the landing angle and resultant velocity of sprinkler irrigation droplets when canopy is not present.

In addition, the CV of the droplets' velocity of penetrating rain under different treatments was 12.96% (81.69°), 14.08% (71.33°), 14.60% (60.58°), and 13.12% (42.04°), respectively. The correlation between CV and the sprinkler irrigation droplet landing angle was not noticeably significant.

3.2.3. Spatial Variation of Drop Velocity Distribution of Throughfall

Drops of different sizes correspond to different terminal velocities [24], and the drop size distribution of sprinkler irrigation droplets could be changed by maize canopy significantly [12]. Corresponding to the drop size distribution, the droplet population at different measurement points under the maize canopy should also have its corresponding drop velocity distribution.

As seen in Figure 13, the drop velocity distribution of sprinkler irrigation droplets was calculated with the mean and equivalent methods, respectively. A comparison of the two showed that the drop equivalent velocity distribution was significantly smaller than that of the mean value in the small droplet size range (<2.00 mm), however, if the droplet size was more extensive (>4.00 mm), the difference between the two was not significant. The results showed that the drop equivalent velocity distribution mainly clarified the energy-carrying capacity of drops in the different sizes, and the larger drop velocity was significantly highlighted because of their higher soil splashing erosion ability. After the above analysis, it was perceived clearly that the drop equivalent velocity distribution may be closer to the actual condition droplet striking the soil surface.

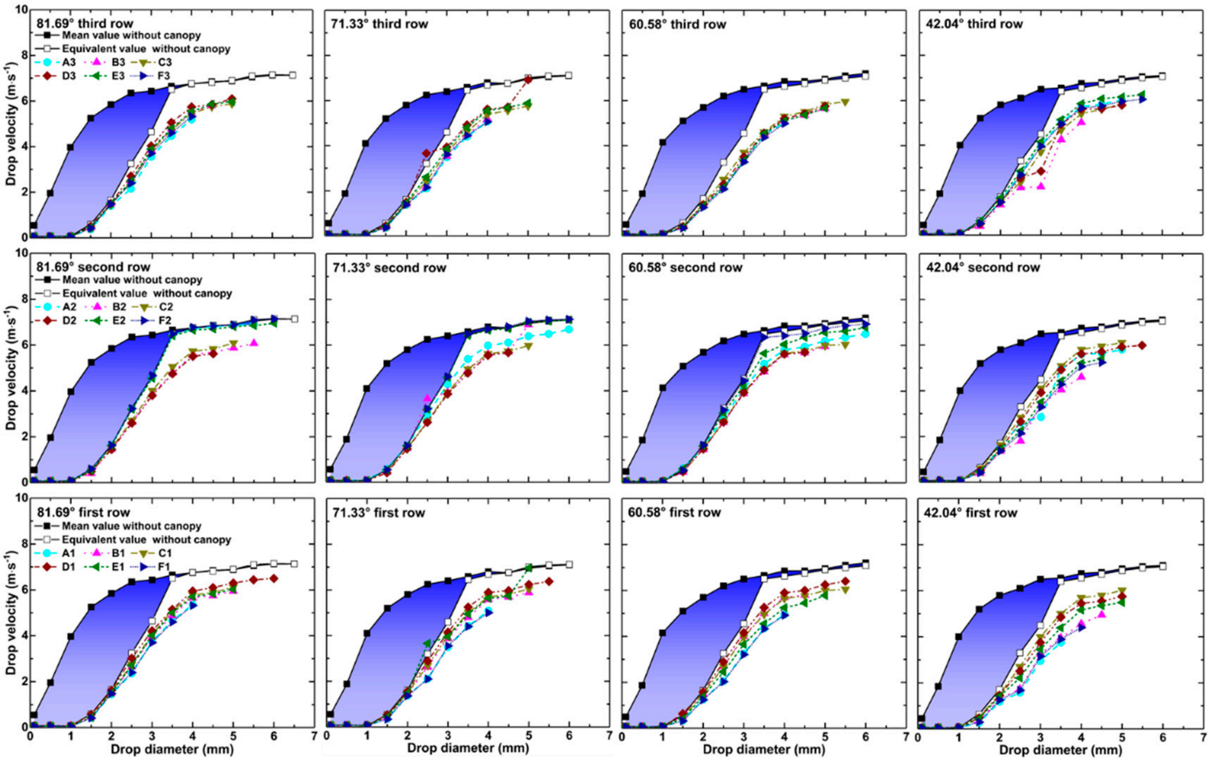

Figure 13. Spatial variation of drop velocity distribution of throughfall with different treatments. In this paper, drop equivalent velocity in each diameter interval is calculated for a graded range of 0.50 mm, separately. Taking the equivalent velocity of droplets at 3.00 mm as an example, the kinetic energy is calculated using the sum of kinetic energy of each droplet in the drop diameter range of 2.51–3.00 mm, and the quality is calculated in the similar method. In addition, the filled part in each subplot is the difference between the mean velocity and the equivalent value without canopy.

The drop velocity distribution at different measurement points varied as the distance of the measurement point from the maize stalk changed. As shown in Figure 13, when the sprinkler irrigation droplet landing angle was >45°, the difference in the velocity distribution of small droplet (<2.00 mm) at each measurement point was not distinct. However, if the droplet size was >2.00 mm, the drop velocity distribution at different measurement points showed significant differences, i.e., the farther away from the maize stalk, the larger the velocity of drop in larger size. When the sprinkler irrigation droplet landing angle was 60.58°, the six measurement points on the first row taken as an example, the droplet velocities of A1, B1, C1, D1, E1, and F1 under the droplet size of 3.00 mm, 4.00 mm, and 5.00 mm were 3.25, 4.00, 3.97, 4.16, 3.65, and 3.21 m/s (3.00 mm); 4.95, 5.70, 5.65, 5.90, 5.25, and 4.92 m/s (4.00 mm); —, —, 6.00, 6.25, 5.78, and — m/s (5.00 mm, — indicates that no droplets in that size were present in the droplet population at that measurement point), respectively. Comparing the data in Figures 12 and 13, it should be seen that the spatial distribution pattern of throughfall drop velocity corresponded well to the drop velocity distribution in drop size being >2.00 mm. The results indicated that the spatial variation of the drop velocity distribution was a good match with that of the droplet velocity of penetration rain, and the velocities of large drops had an excellent response to the difference of the drop velocity distribution at different measurement points.

When the sprinkler irrigation droplet landing angle is <45°, although the spatial distribution pattern of throughfall droplet velocity changed significantly, the factor affecting the spatial variability of drop velocity was still the difference in the large drop velocity.

3.3. Spatial Variation Mechanism of Throughfall Drop Landing Angle

3.3.1. Variation of Throughfall Drop Landing Angle

In this research, the soil splashing-erosion rate, under different sprinkler irrigation droplet landing angles, was measured with spatter cups [40], and the spatial distribution of soil particles around these cups was recorded. The soil spattering rate was 89.50, 102.48, 134.25, and 167.96 g/m^2/h at 81.69°, 71.33°, 60.58°, and 42.04° for the sprinkler irrigation droplet landing angle, respectively. In addition, other treatments were 1.15, 1.50, and 1.88 times higher than the control (81.69°). The results showed that if the operating pressure of the device and application rate were constants, the amount of soil splash erosion tended to increase as the sprinkler irrigation droplet landing angle decreased gradually. Similar results were reported by Cruse et al. [41]. To vividly describe the effect of soil splash erosion under different treatments, a schematic diagram is shown in Figure 14.

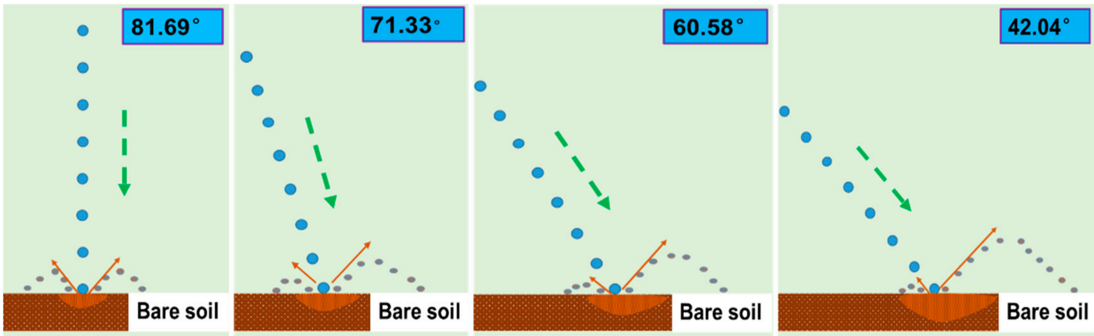

Figure 14. Splash erosion schematic diagram of sprinkler irrigation droplets with different landing angles attacking bare soil.

The existence of maize canopy may affect the flight path of the sprinkler irrigation droplets and the droplet landing angle of throughfall should be changed. The data in Table 2 showed that the variation ranges of the droplet landing angle of throughfall and their proportions to uncrowned, corresponding to the different treatments, were 79.66–83.89° (97.51–102.69%, 81.69°), 70.35–76.58° (98.63–107.36%, 71.33°), 59.45–70.12° (98.13–115.74%, 60.58°), and 41.26–49.51° (98.14–117.77%, 42.04°), respectively. The mean values and standard deviations, and their proportions to uncrowned were 81.90 ± 1.21° (100.26%, 81.69°), 72.30 ± 1.64° (101.36%, 71.33°), 63.70 ± 3.68° (105.15%, 60.58°), and 44.08 ± 2.55° (104.85%, 42.04°), respectively. In addition, there was an increasing trend in the average landing angles' proportion to uncrowned ($y = 110.96 - 0.13x$, $R^2 = 0.75$) as the sprinkler irrigation droplet landing angle decreased. Although maize canopy and the reduction in sprinkler irrigation droplet landing angle had some positive effect on the increasing of the droplet landing angle of throughfall, they did not vary the magnitude of their values essentially. Therefore, some of the sprinkler irrigation droplets would still impact the soil at a small angle after passing through the maize canopy.

3.3.2. Spatial Variation of Throughfall Droplets Landing Angle

As shown in Figure 15, the pattern of "small in the middle and large on both sides" was summarized, regarding the spatial distribution regularity of the droplet landing angle of throughfall under different treatments. Among the maize rows, it was mainly showed that if measurement point was further away from the maize stalk, the droplet landing angle of throughfall would be smaller. More importantly, the spatial pattern did not change as the variation of the sprinkler irrigation droplets landing angle. In contrast to size and velocity of throughfall droplets (Figures 7 and 12), the spatial distribution of the landing angle showed a diametrically opposite pattern. In addition, although there was a statistically significant difference in the droplet landing angle of throughfall at different measurement points, the difference in value was not significant.

The corresponding spatial coefficients of variation (CV) of the droplet landing angles of penetrating rain, under different treatments, were 1.48%, 2.27%, 5.78%, and 5.78% respectively. CV had an excellent negative correlation with the sprinkler irrigation droplet landing angle ($y = -0.12x + 11.44$, $R^2 = 0.68$).

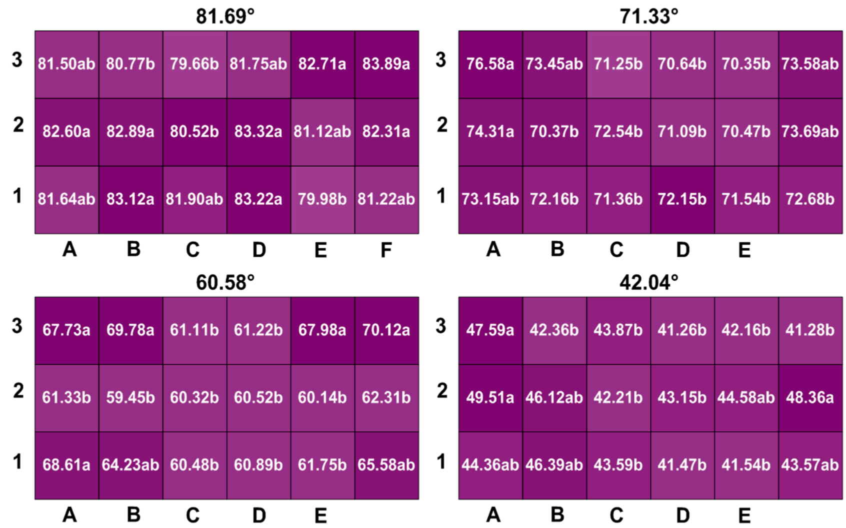

Figure 15. Spatial distribution of droplet landing angle of throughfall. Different letters indicate significant difference between data in each treatment ($p < 0.05$).

3.3.3. Spatial Variation of Drop Velocity and Kinetic Energy of Throughfall

Figure 16 presents the flight paths of droplets during maize sprinkler irrigation. It is generally accepted that the greater the plant canopy thickness or leaf cover, the greater the disturbance to the droplets as they pass through the canopy, i.e., a sprinkler irrigation droplet with a slight landing angle will strike the ground in an approximately vertical flight path after passing through a thicker maize canopy [18]. The flight paths or landing angles of throughfall droplets, at different measurement points (A, B, and C), are depicted in Figure 16, respectively. However, compared to Figure 16, the measured data showed that the droplet landing angle of penetrating rain at measurement points A and B did not change substantially (Figure 15).

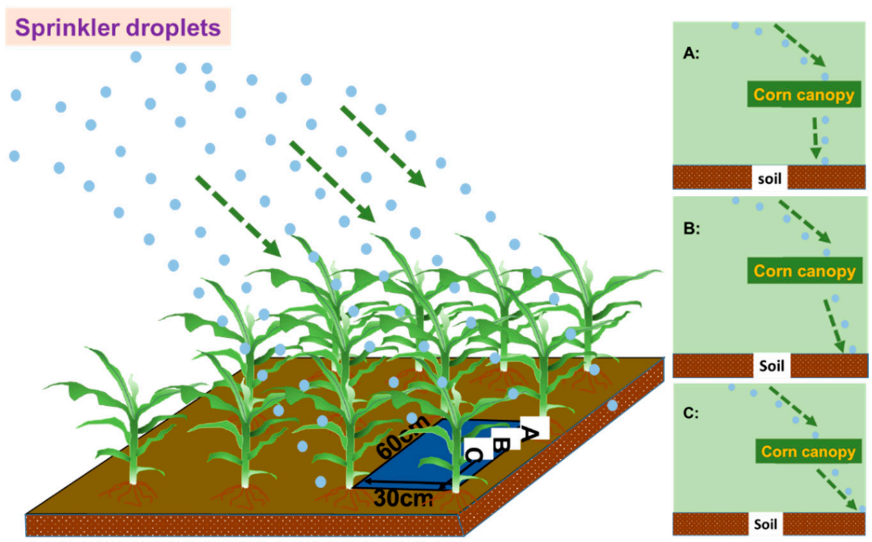

Figure 16. Schematic diagram of effect of maize canopy on sprinkler irrigation droplets landing angles.

The droplet average landing angles in different sprinkler irrigation droplet size ranges was analyzed by Gong [32] and significant differences in the droplet landing angle in different size ranges were found. Additionally, the droplets striking kinetic energy has a significant effect on soil particle transport, bulk density, aggregate size, and water infiltration parameters [6,42]. Therefore, in this research, it was more representative to use the mean value of the droplets landing angles with more considerable impact kinetic energy.

To clarify the spatial variation mechanism of the droplet landing angle of throughfall, the sprinkler irrigation droplet landing angle of 60.58° seen as an example, the relationship among the kinetic energy, droplets landing angle, and the drop diameter within and without maize canopy at measurement points A1, B1, and C1 was analyzed. As shown in Figure 17, compared to the uncrowned, the impacting kinetic energy at different measurement points was still concentrated in the drop size range of 3.01–3.50 mm. This result indicated that, despite the presence of maize canopy, several large drops with high kinetic energy still stroke the soil surface after passing through the canopy.

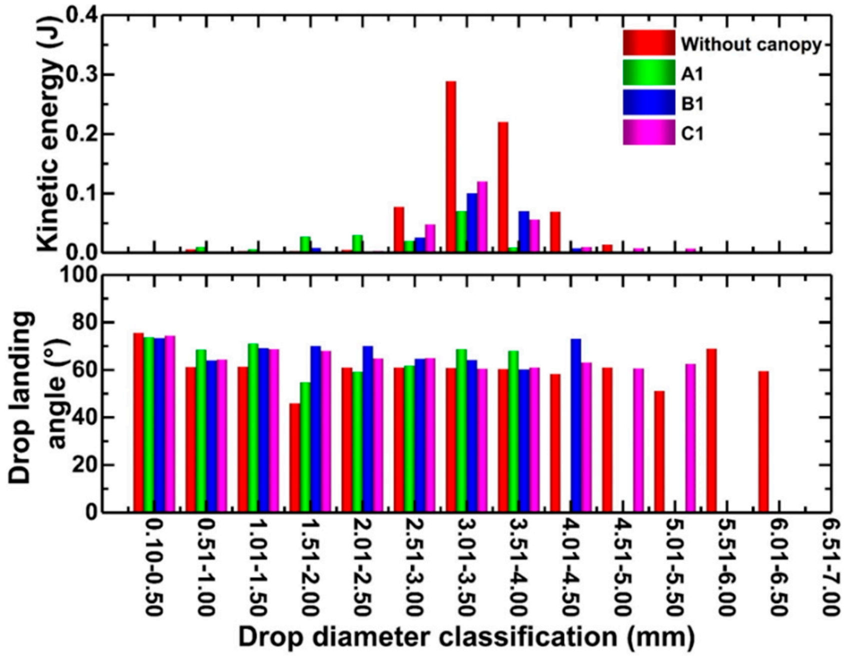

Figure 17. The kinetic energy and landing angle of droplets in different diameter ranges.

If the sprinkler irrigation droplets are disturbed by maize leaves, the individual droplet's velocity and kinetic energy will decrease gradually. Table 3 presents the mean values of individual droplet's velocity and kinetic energy for the particle size range of 3.01–3.50 mm. As the data in Table 3 shown, the velocities and kinetic energy of individual droplets were less than uncrowned. The spatial distribution of individual droplets' velocity and kinetic energy was similar to the droplet landing angle, as shown explicitly with C1 > B1 > A1. These results indicated that the droplets, at A1, B1 and, C1, were all disturbed by the maize leaves, and the measurement point was closer to the stalk, the disturbance would become more significant. Combined with the data in Figures 15 and 17, these results suggested that the effect of the maize leaves on the droplets in 3.01–3.50 mm was not sufficient to alter their landing angle or flight path entirely.

Table 3. The mean velocity and kinetic energy of a single drop in different diameter ranges.

Drop Diameter Range (mm)	Drop Velocity ($m \cdot s^{-1}$)				Kinetic Energy ($\times 10^{-4}$ J)			
	Without Canopy	Within Canopy			Without Canopy	Within Canopy		
		A1	B1	C1		A1	B1	C1
3.01–3.10	6.49 ± 0.13	5.54 ± 0.21	5.89 ± 0.17	6.04 ± 0.31	3.11 ± 0.06	2.29 ± 0.08	2.60 ± 0.06	2.68 ± 0.09
3.11–3.20	6.51 ± 0.08	5.47 ± 0.19	5.92 ± 0.13	5.94 ± 0.28	3.51 ± 0.11	2.49 ± 0.07	2.89 ± 0.09	2.91 ± 0.12
3.21–3.30	6.54 ± 0.07	5.58 ± 0.16	5.85 ± 0.15	6.11 ± 0.35	3.87 ± 0.09	2.81 ± 0.09	3.09 ± 0.06	3.35 ± 0.09
3.31–3.40	6.59 ± 0.11	5.21 ± 0.09	6.02 ± 0.23	6.12 ± 0.18	4.29 ± 0.12	2.71 ± 0.09	3.56 ± 0.07	3.68 ± 0.13
3.41–3.50	6.61 ± 0.15	5.68 ± 0.14	5.94 ± 0.14	6.07 ± 0.22	4.71 ± 0.14	3.51 ± 0.16	3.81 ± 0.13	3.95 ± 0.15

Note: The data in the table is the mean ± standard deviation.

Sprinkler irrigation droplets with smaller landing angles have a greater impact force in the horizontal direction, and the stripping effect of the horizontal force on the soil surface, which could result in an increase of soil particle transport rate [7,41], is significantly greater than the vertical force. It is usually assumed that the plant canopy could change the flight path of the droplet significantly. However, our research showed that although the maize canopy had an enormous influence on individual droplets' velocity and kinetic energy under sprinkler irrigation, the sprinkler irrigation droplets' landing angles cannot be altered completely. There are more gaps within the maize canopy, the distance between leaves at different locations is remote, and the maize plants of this study are at the jointing stage with a poorly sealed canopy. The sprinkler irrigation droplets have more access to arrive at the soil surface. In addition, the kinetic energy of a large drop is thousands or tens of thousands of times than that of small droplets, and its velocity is significantly greater than that of small droplet. Consequently, large drops have great soil splash capacity and the ability to pass-crown. Furthermore, the direct or free throughfall droplets (large sprinkler irrigation droplets) might be included in the droplet population for calculating droplet landing angle. Therefore, taking the high irrigation guarantee rate and irrigation efficiency of sprinkler irrigation units into account, and avoiding the occurrence of sprinkler irrigation droplet erosion as much as possible, it should be recommended that sprinkler heads with larger landing angle or smaller droplets diameter selected when sprinkler irrigation would be applied to development maize plants. In addition, our findings might be needed by researchers even more when developing new sprinkler heads, as the landing angle is a critical physical parameter for sprinkler irrigation droplets.

4. Conclusions

The effect of maize canopy and variation in droplet landing angle on the physical parameters (size, velocity, and landing angle) of sprinkler irrigation droplets was evaluated in this paper. The spatial variation mechanism of the droplet's physical parameters of throughfall under maize canopy was explored. The results were described as follows.

(a) Maize canopy and the decreasing of the sprinkler irrigation droplets landing angle had a positive and notable effect on reducing the size and velocities of penetrating rain droplets. However, the throughfall droplets' landing angles were only minor variations.
(b) When the sprinkler irrigation droplets landing angle was >45°, the spatial distribution of throughfall droplets' size and velocities corresponded well with the canopy structure and leaf projection area, i.e., the further away from the maize stalk, the larger the size and velocity of throughfall droplets. Nevertheless, if the landing angle of sprinkler irrigation droplets was <45°, the spatial distribution mentioned above was mainly affected by the droplet landing angle.
(c) The spatial variations of size and velocities of throughfall droplets at different measurement points was attributed to the change of the larger droplets' volume proportion and the equivalent velocity. Although the maize leaves had a certain degree of

perturbation effect on the velocities and kinetic energy of the larger kinetic energy droplets, the flight path of these drops did not need to be altered significantly.

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