

Article

The Spreading Characteristics of Droplets Impacting Wheat Leaves Based on the VOF Model

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Abstract: Given the problem that droplets cannot stay on the surfaces of leaves and wet them effectively, resulting in high levels of pesticide input and environmental pollution, this work studied the dynamic behaviors of droplets with different diameters (400–550 μm) falling on the surfaces of wheat leaves from different heights (2–16 cm) using contact angle-measuring instruments and a high-speed camera. The VOF method in Fluent software was used to establish a numerical model of droplets impacting the surfaces of wheat leaves. The results show that with an increase in the initial diameter and initial velocity of a droplet, the maximum diameter of the droplet during the spreading process also gradually increases. After a droplet impacts a wheat leaf, the droplet-spreading diameter first increases and then decreases. The maximum droplet spreading rate, β_{max} , increases with an increase in the Weber number, $\beta_{\text{max}} \in We^{\frac{1}{4}}$, which is consistent with the existing theory. The results of this study lay a foundation for studying the spread of droplets on the surfaces of leaves, which is conducive to improving the rate of pesticide utilization.

Keywords: droplet impact; deposition spreading; numerical simulation; VOF method



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1. Introduction

Pesticides play a central role in preventing and controlling agricultural pests, weeds, and diseases; thus, they are an important means of improving agricultural production. However, many pesticides are not used in crops, resulting in losses [1,2]. The problem of poor targeting in the application of pesticides is particularly evident in wheat crops. Wheat is one of the three major food crops. It is a narrow-leaf, upright, hydrophobic crop [3]. The critical surface tension of wheat leaves is small, and pesticide droplets struggle to wet and spread on the leaves. They can easily polymerize and escape the leaf surface [4]. When applying pesticides for plant protection, whether the liquid can accurately adhere to the leaf surface of the target crop for reasonable infiltration and spreading is an essential factor affecting yield.

The physical and chemical properties of the leaf surface, the droplet properties, and the impact characteristics are the main factors affecting the wettability of droplets on the leaf surface. Affected by the collision conditions, droplets can engage in spreading, splashing, rebounding, and other phenomena after collision [5–9]. Kim et al. [10] used a high-speed camera to record the whole process of single-size micro-droplets impacting a wall and obtained diffusion images of the droplets at different times. This showed that high-speed cameras can be used to study fuel spray behavior and the micro-droplet deposition process. Yang et al. [11] used a high-speed camera to study the impact process of droplets with

different diameters falling on the surfaces of strawberry leaves from different heights. The relationship between the total mass and the kinetic energy reflected by the splash droplets and the kinetic energy of the incident droplets was obtained, and the correlation between the initial velocity of a single droplet and its splash angle and diameter was explored. Subsequently, Yarin [12] reviewed the dynamic process of droplets impacting a thin liquid layer and a dry surface and discussed the causes and influencing factors of a droplet spreading and splashing during its impact on the wall in detail. The final state of the droplet after impacting the wall depends on the droplet impact velocity, the initial diameter of the droplet, the properties of the droplet (its density, viscosity, and elasticity), the surface tension of the droplet, and the roughness and wettability of the solid surface, etc. Since then, an increasing number of scholars have devoted themselves to studying the process of droplets impacting walls [13]. With the development of virtual simulation technology, many scholars have combined the theory of fluid dynamics with computer platforms to simulate the physical behaviors of droplets after impacting solid surfaces. In a numerical simulation, droplet parameters can be modified to simulate the droplet's motion under various conditions. The volume of fluid (VOF) method mainly simulates the droplet's impact [14,15]. Ilias et al. [16] used the VOF method in combination with the local mesh refinement technique to study the collision process of droplets impacting a solid dry surface, which improved the model's prediction accuracy and minimized the model's divergence. Bristot et al. [17] used the VOF method to simulate a transient two-phase flow in a bearing cavity, improving the accuracy of modeling flow in a bearing cavity. Chen et al. [18] used the VOF method to simulate the influences of surface tension and viscosity on the formation and transfer of microdroplets in rectangular microchannel tubes. Sun et al. [19] used the VOF method to simulate morphological changes in the droplet impact process, as well as the distribution of internal velocity and pressure. They explored the effects of a droplet's impact velocity, surface-wetting ability, and surface tension on droplet dynamics. The results are in good agreement with the results of high-speed cameras. Wang et al. [20] used the VOF method to simulate the movement process of oil droplets hitting a wall. They explored the influence of oil droplet diameter, impact velocity, and incident angle on the final droplet deposition state. Wang et al. [21] studied the spreading of droplets on free-sliding surfaces through experiments and numerical simulations and proposed a practical estimation model of $\beta_{\max}$ under a small Weber number ($We \leq 30$). Li et al. [22] used a high-speed camera to study the impact and sliding behavior of water droplets on the surfaces of injected lubricants (LISs). They showed that with an increase in the Weber number, the impact droplets' maximum diffusion diameter and contraction speed increased.

Although the above research on the impact of droplets on horizontal walls has been relatively complete, its application in the agricultural field is relatively scarce. Based on previous studies, this study explored the relationship between the Weber number of a droplet and the maximum spreading rate of a droplet via the spreading and deposition of droplets on the surfaces of leaves, sought the reasons for the low utilization rate of spray droplets, and then clarified the factors and laws affecting the spreading of droplets on the surfaces of wheat leaves and obtained the best droplet parameters, providing a theoretical basis to guide the development of liquid spraying devices.

2. Materials and Methods

2.1. Experimental Principles

In order to describe and characterize the wetting degree of a solid surface, the contact angle (CA) is defined as the angle θ between the gas-liquid tangent and the solid-liquid tangent. As shown in Figure 1, when θ is less than 90° , the solid surface is hydrophilic, which is called a hydrophilic surface; when θ is greater than 90° , the solid surface shows hydrophobicity and the solid surface shows hydrophobicity, which is called a hydrophobic surface. In particular, when θ is greater than 150° , the solid surface is superhydrophobic and is called a superhydrophobic surface [23].

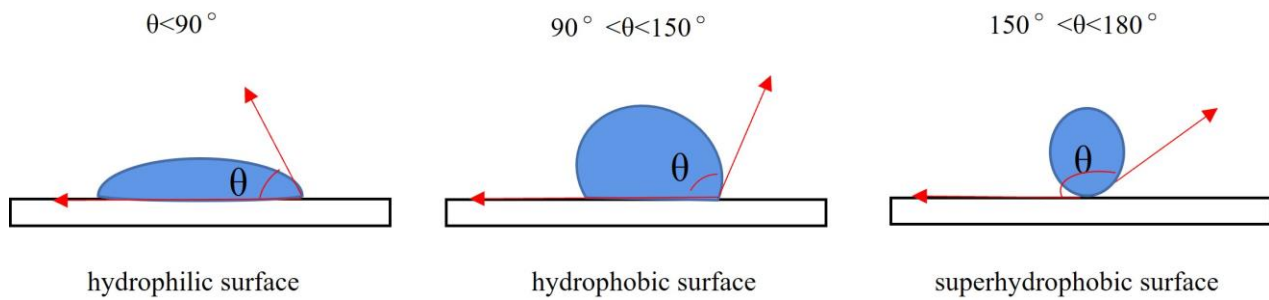


Figure 1. Division of surfaces with different degrees of wettability.

Since a droplet is not wholly standard and spherical during the free-dropping process, the equivalent diameter D_0 of a droplet was selected in this study to measure the change in the diameter of a droplet during the spreading process. The equivalent diameter is $D_0 = \sqrt[3]{D_h^2 D_v}$, where D_h is the horizontal diameter and D_v is the vertical diameter [24]. The conversion between different influence results can be quantified using dimensionless parameters. The dimensionless maximum diffusion diameter is an essential measure of droplet spreading. The dimensionless maximum diffusion diameter, $\beta_{\max}$, is defined as the ratio of the maximum diffusion diameter, $D_{\max}$, of the droplet to its initial diameter, D_0 , as shown in Figure 2: $\beta_{\max} = D_{\max}/D_0$ [25]. At present, researchers have proposed a large number of $\beta_{\max}$ quantitative models through the correction of surface energy, contact angle, and viscous dissipation. Clanet et al. obtained $\beta_{\max} \in We^{\frac{1}{4}}$, which agrees with the experimental data of a droplet impacting a hydrophobic surface and is widely used in related research [26].

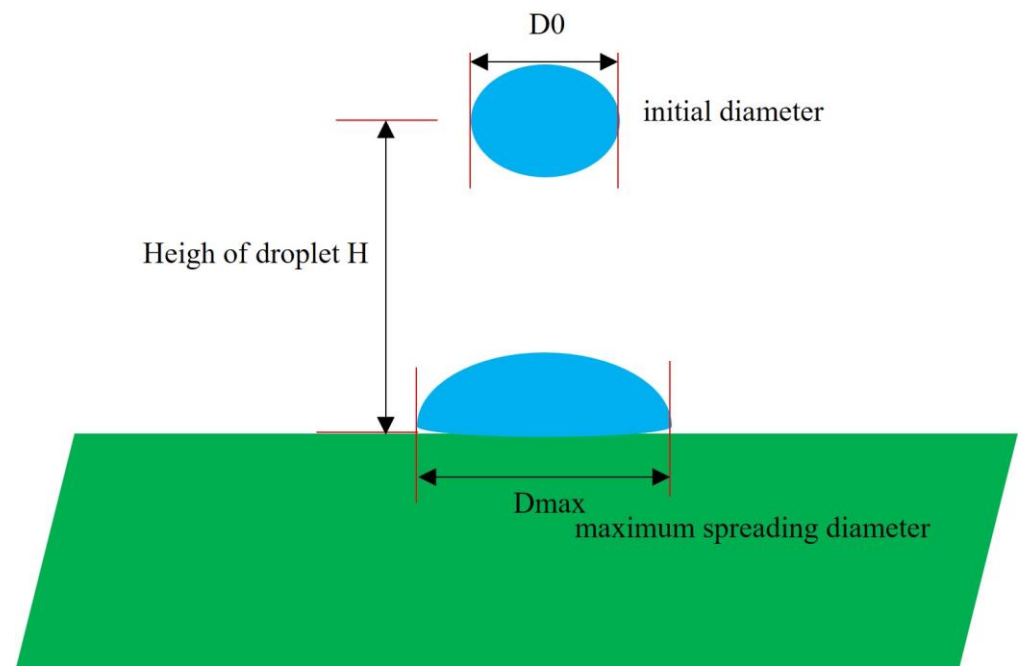


Figure 2. Schematic diagram of the initial diameter and maximum spreading diameter.

Currently, the dimensionless constants recognized to control the final state of droplet impact are the Weber number We , Reynolds number Re , and Ohne-Sorge number Oh , etc. The Weber number is a dimensionless number in fluid mechanics. When there are boundaries between different fluids, especially in multiphase flow problems, and when the curvature at the interface is large, the Weber number can be used to analyze fluid motion [19,27–29]. The Weber number represents the ratio of the inertial force and surface

tension. The smaller the Weber number is, the more critical the surface tension is. The Weber number is defined as follows [30–32]:

$$We = \frac{\rho D_0 V_0^2}{\sigma} \quad (1)$$

Among them, the We -Weber number is determined as follows:

ρ —liquid density (kg/m^3);

v_0 —droplet impact velocity (m/s);

D_0 —droplet diameter (m);

σ —fluid surface tension coefficient (N/m).

2.2. Visualization Test Scheme of Droplets Impacting Wheat Leaves

The experiment was carried out in the equipment creation room of the National Information Agricultural Engineering Technology Center of Nanjing Agricultural University. The experimental environment comprised a temperature of 25 degrees Celsius and standard pressure (0.1 MPa). In order to record the process of droplets impacting the surfaces of wheat leaves, a contact angle measuring instrument and a high-speed camera machine were used as experimental devices. The experimental device is shown in Figures 3 and 4. The contact angle-measuring instrument model was an SDC-200S (contact angle-measuring device), which comprised an injection system, a light source system, a sample stage, a video acquisition system, and analysis software. The wheat leaves were fixed on the sample table by adhering them to the slide. The specifications of the needles used in the injection system were 0.4, 0.45, 0.5, and 0.55 mm. The high-speed camera was used at a shooting speed of 10,000 frames/s to record the process of droplets of different sizes hitting the surfaces of wheat leaves at different speeds.

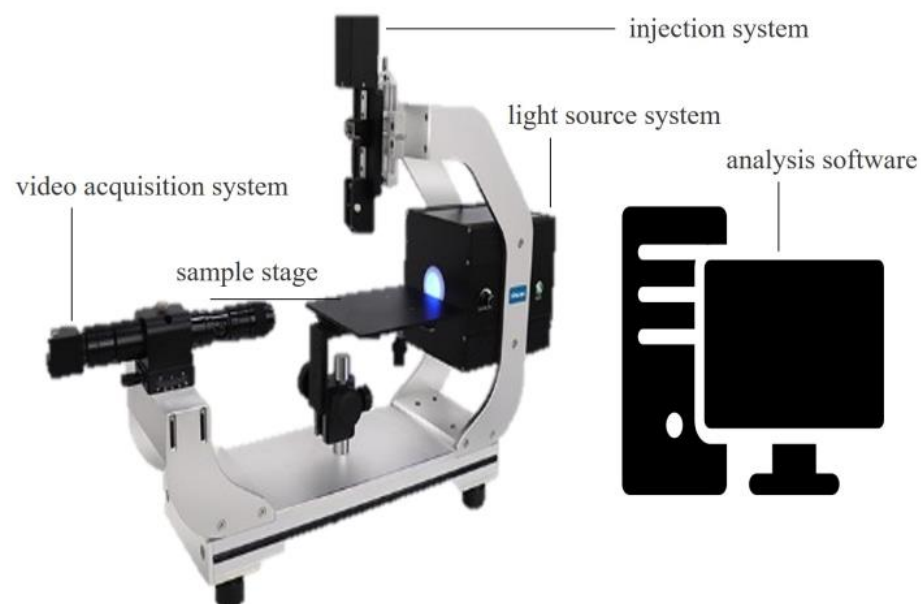


Figure 3. The experimental device for contact angle measurement.

The experimental working medium was pure water. The density of the pure water was $\rho = 997 \text{ kg}/\text{m}^3$, and the surface tension was $\sigma = 0.0728 \text{ N}/\text{m}$. Needles of different sizes produced droplets of different diameters. The droplet impact velocity can be controlled by adjusting the needle's height relative to the wheat leaf's surface. Five different heights of 2, 4, 7, 8, and 16 cm were set, respectively, and the corresponding droplet velocities ranged from 0.6 m/s to 1.78 m/s. In order to analyze the droplet diameter at each stage of the droplet, this study used MATLAB software to save the video in frames, which not only met the requirements of the analysis but also improved the image resolution. After obtaining

a picture of each frame, the images were calibrated and analyzed via Image J software. Due to the air resistance and the energy dissipation due to droplet vibration, using the formula $mg = \frac{1}{2}mv^2$ to calculate the impact velocity of a droplet will lead to significant error. Therefore, this experiment calculated the droplet impact velocity by extracting ten pictures before the droplet hit the surface.

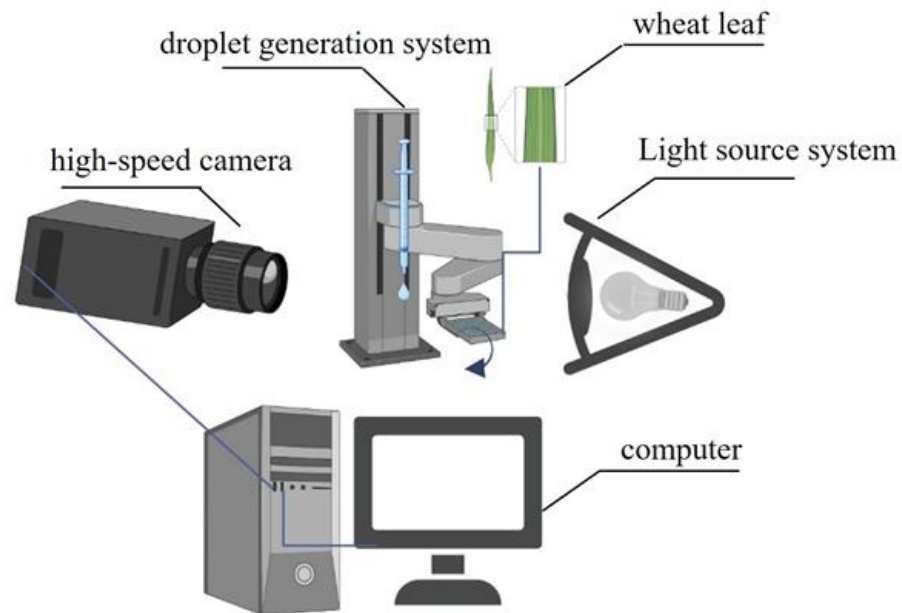


Figure 4. The experimental device utilizing the high-speed camera machine.

2.3. Experimental Materials

Wheat leaves are fragile and curl easily, and experiments in which droplets directly impact leaves cannot be carried out. Therefore, a slide (250 mm × 760 mm × 2 mm) was selected as a bearing substrate for use during the experiment. A double-sided adhesive was pasted onto the surface of the glass slide; wearing suitable gloves on both hands, the experimenter slowly spread cut wheat leaves (50 mm × 400 mm) out over the slide, as shown in Figure 5. In this study, pot-cultivated Yangmai 13 wheat leaves at the jointing stage were selected as the research object. The surfaces of the prepared wheat leaves were scanned via electron microscopy. Figure 6 shows that the front and back sides of the wheat leaves demonstrate villi.



Figure 5. Leaves of wheat.

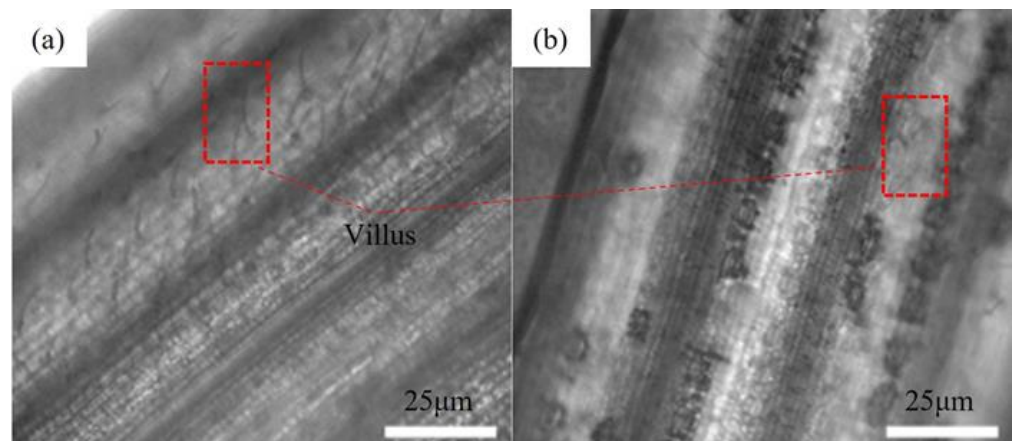


Figure 6. Micrographs of wheat. (a) Front of the wheat leaf; (b) back of the wheat leaf.

3. Numerical Model

3.1. Model Establishment

In this study, based on the VOF method, a numerical calculation model of pure water droplets hitting a blade surface was established. Figure 7 provides a schematic diagram of the numerical model. It was assumed that the droplet is only affected by gravity during the falling process and hits the blade surface. The droplet diameter was D_0 , the impact velocity was V_0 , and the plate was the blade surface.

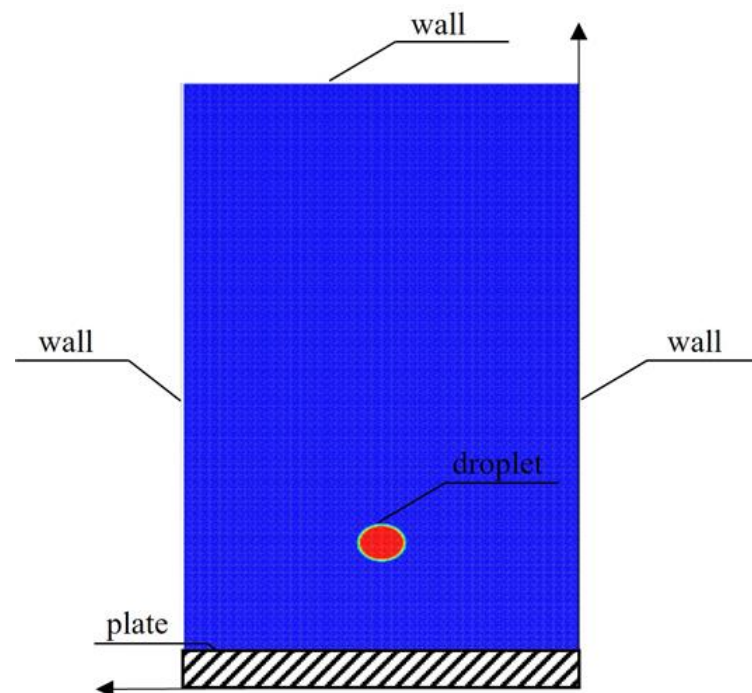


Figure 7. The schematic diagram of a numerical calculation model for a droplet impacting the blade surface.

Based on the physical characteristics of the droplet falling process and for simplicity of calculation, a two-dimensional model was selected for calculation. ICEM15.0 software was used to mesh the area, and the calculation area was a structured grid. The width of the calculation area was 20 mm, and the height was 40 mm. Water was selected as the droplet material, and the VOF method was used to carry out the numerical calculation. The spreading conditions of droplets with different diameters, impact velocities, and Weber numbers hitting the blade surface were studied.

The continuity equation of the VOF method is as follows [33]:

$$\frac{\partial}{\partial t} \alpha_q + v_q \nabla \cdot \alpha_q = \frac{S_{\alpha_q}}{\rho_q} + \frac{1}{\rho_q} \sum_{p=1}^n (m_{pq} m_{qp}) \quad (2)$$

In this formula, ρ_q is the density of the q phase, which refers to the density of the liquid phase in this paper; m_{qp} is the mass transport from the q phase to the p phase; m_{pq} is the mass transport from the p phase to q phase; and α_q is the volume fraction of the q phase in the unit.

For an n -phase system, the average density of the volume fraction in the unit is as follows:

$$\rho = \sum \alpha_q \rho_q \quad (3)$$

In the momentum equation obtained in the entire computational domain, the velocity field is shared by all phases, and the momentum equation depends on the volume fraction of all phases passing through properties q and u .

$$\frac{\partial}{\partial t} (\rho v) + \nabla \cdot (\rho v v) = -\nabla p + \nabla \cdot [u (\nabla v + \nabla v^T)] + \rho g + F \quad (4)$$

The energy equations are also shared as follows:

$$\frac{\partial}{\partial t} (\rho E) + \nabla \cdot [v (\rho E + p)] = \nabla \cdot (k_{eff} \nabla T) + S_h \quad (5)$$

The model pre-processing was set as follows: the time type in Fluent software was selected for transient calculation, the gravity acceleration was turned on, and the vector was set to -9.81 m/s^2 in the direction of the center of the Earth. The laminar flow model was selected, and the liquid water material was added to the material to initiate the multiphase flow. The VOF model was selected for the multiphase flow model, and the phase number was two. The first phase material was set to air, and the second was set to water. The surface tension model was initiated in the interaction between phases, and the surface tension coefficient was set to 0.0728 N/m . The boundary conditions of the solution area were as follows: all the boundaries were set as the wall surface, the wall surface adopted a non-slip boundary, the plate was the wheat blade, the surface roughness was set to 1023 nm , and the roughness constant was set to 0.5 . The coupling algorithm for pressure and velocity adopted the PISO format, the calculated time step was $1 \times 10^{-5} \text{ s}$, and the total calculation time was 0.015 s . The physical parameters of the water droplets are shown in Table 1. PATCH defined the shapes of the water droplets and the collision speed after initialization.

Table 1. Physical parameters related to droplets.

Droplet Parameter	Value
Density ($\rho/\text{kg}\cdot\text{m}^{-3}$)	995.8
Viscosity ($\mu/\text{mPa}\cdot\text{s}$)	0.98
Surface tension ($\sigma/\text{mN}\cdot\text{m}^{-1}$)	73.42

3.2. Model Verification

In order to verify the numerical model of droplets impacting the blade surface, a numerical simulation of a droplet impacting the front of a wheat leaf at $Weber = 4.95$ was carried out. The experimental and simulated results are shown in Figure 8. It can be seen from the diagram that after the droplet hits the blade surface, it experiences the spreading and retracting stages. In the spreading stage, the lateral diameter of the droplet gradually increases, and the longitudinal diameter gradually decreases. In the retracting stage, the lateral diameter of the droplet becomes smaller, the longitudinal diameter increases sharply,

and the droplet reaches stability. The experimental results are in good agreement with the simulation results.

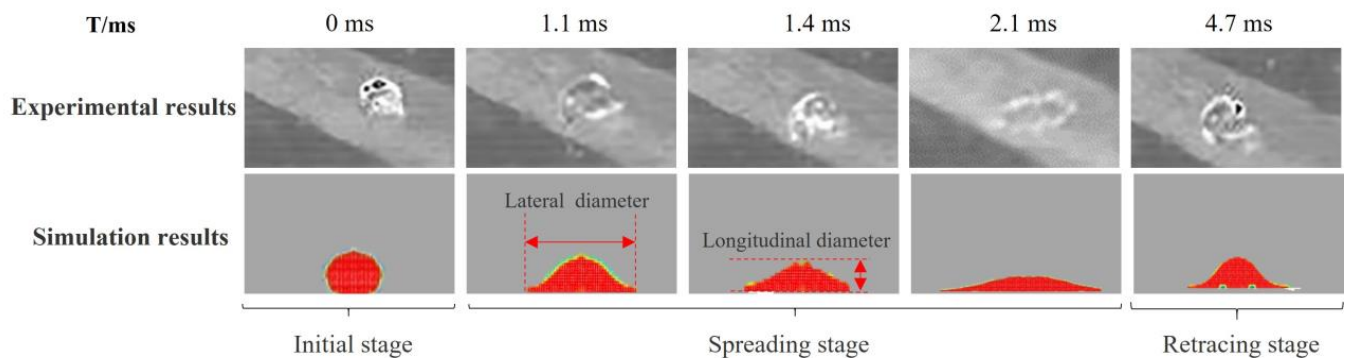


Figure 8. Comparison of the experimental results and simulated results.

4. Results and Discussion

4.1. Spreading Characteristics of Droplets on a Wheat Leaf Surface

The static contact angles of the droplet on the front of the wheat leaf, the back of the wheat leaf, and the smooth surface of the slide are shown in Figure 9. The static contact angle of the droplet on the front of the leaf is 118.313° , the static contact angle on the reverse side of the leaf is 118.871° , and the static contact angle on the slide is 20.125° . The results show that there is little difference between the front and back sides of the wheat leaves with respect to the wettability of the droplets. However, due to the presence of villi on the surfaces of the wheat leaves, the degree of roughness is high, resulting in a significant increase in hydrophobicity compared with the slide.

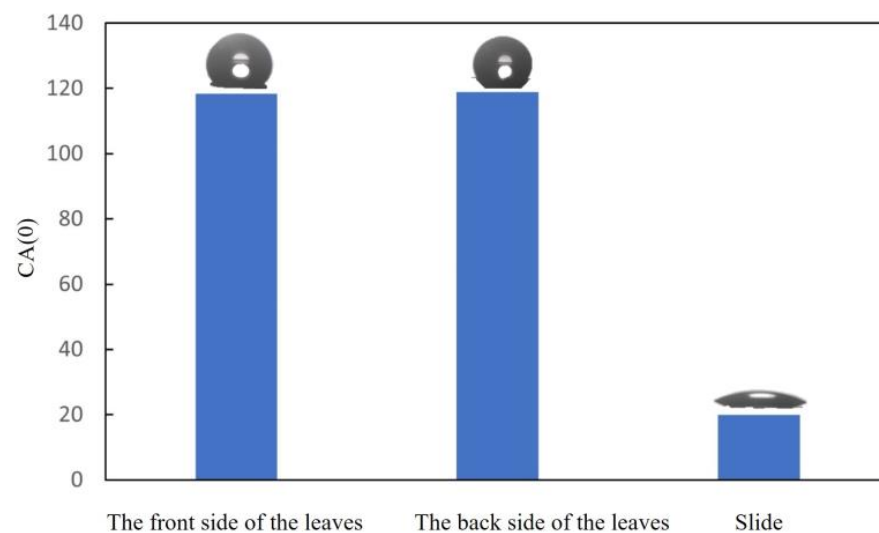


Figure 9. A diagram of droplet contact angles on the surfaces of wheat leaves and glass slides.

The relationship between the droplet's Weber number and contact angle is shown in Figure 10. It can be seen from the figure that as the Weber number of a droplet increases, the contact angle shows a decreasing trend when the droplet hits the wheat leaf, and the difference in the contact angle between the front and the back sides of the wheat leaf is not apparent. However, when the droplet hits the vein on the back side of the leaf, the droplet will be split into two droplets by the vein, as shown in Figure 11, which is consistent with the research results of Song et al. [34].

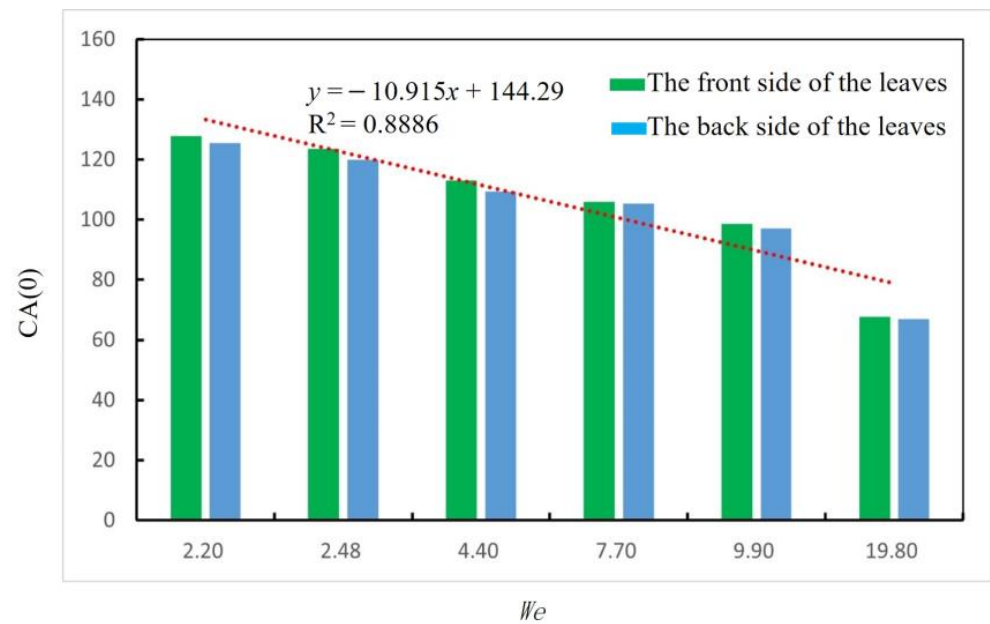


Figure 10. The relationship between a droplet's Weber number and contact angle.

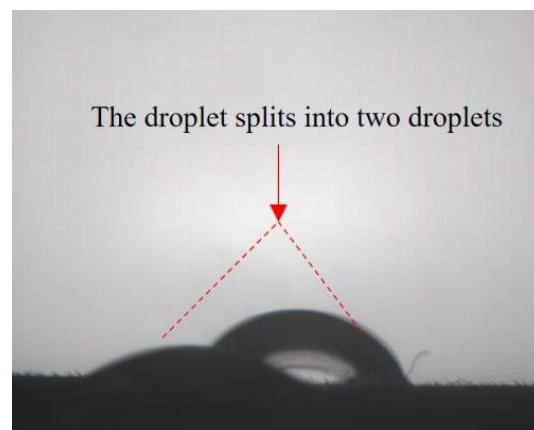


Figure 11. The schematic diagram of a droplet splitting at the vein of a leaf.

In this experiment, the impact velocity of the droplet was changed by adjusting the droplet's height, and the droplet's initial diameter was adjusted by changing the size of the needle to adjust the Weber number of the droplet. The droplet spreading process is shown in Figure 12. This experiment found that the droplet diameter first increased and then decreased during its process of impacting the wheat surface. This is because the droplet was in free-fall motion before hitting the wheat surface, and its gravitational potential energy was converted into kinetic energy. After hitting the wheat surface, the droplet laterally diffuses, and the kinetic energy of the water droplet is partially converted into surface energy and partially dissipated. The droplet velocity then becomes smaller, and the lateral diameter becomes larger. After the water droplet reaches the maximum diameter, the surface energy overcomes the adhesion of the surface and converts it into kinetic energy. The droplet begins to retract, the lateral diffusion diameter of the droplet becomes smaller, and the height becomes higher until it reaches a stable stage. With an increase in the Weber number, a droplet will produce coronal droplets after hitting the surface of the wheat leaf (red arrow in Figure 12). With an increase in the Weber number, the time at which the coronal droplets appear occurs earlier, and the duration becomes longer. This is because as the Weber number increases, the kinetic energy of the droplet also increases so that the kinetic energy after the droplet hits the surface of the wheat is significantly enriched and

expands to the edge in addition to overcoming the surface energy of the droplet, which also lengthens the droplet spreading time (the duration of the droplet corona) [21,35].

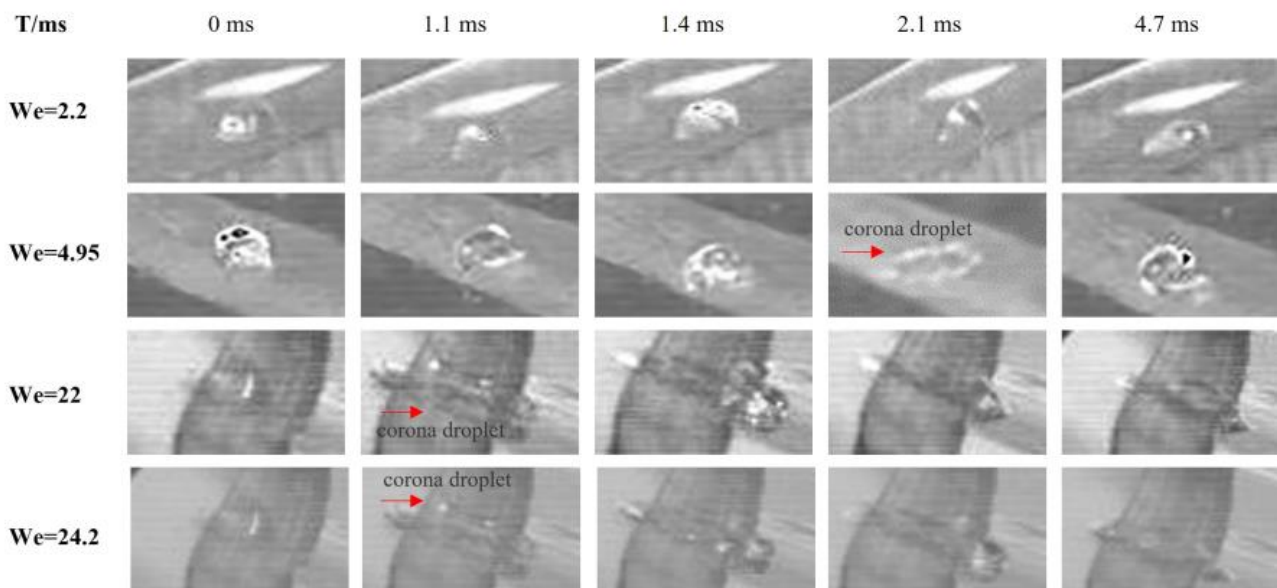


Figure 12. The process of droplets with different Weber numbers spreading on wheat leaf surfaces.

In order to study the factors affecting the maximum spreading diameter of the droplets, in this experiment, droplets with different parameters impacting the surfaces of wheat leaves were extracted and analyzed. The relationship between droplet velocity, initial droplet diameter, and the maximum spreading diameter of the droplet is shown in Figure 13. It can be seen from the figure that as the droplet impact velocity increases, the maximum spreading diameter of the droplet gradually increases; as the initial diameter of the droplet increases, the maximum spreading diameter of the droplet also gradually increases; and as the droplet velocity increases, the droplet diameter has an increasing effect on the maximum spreading diameter.

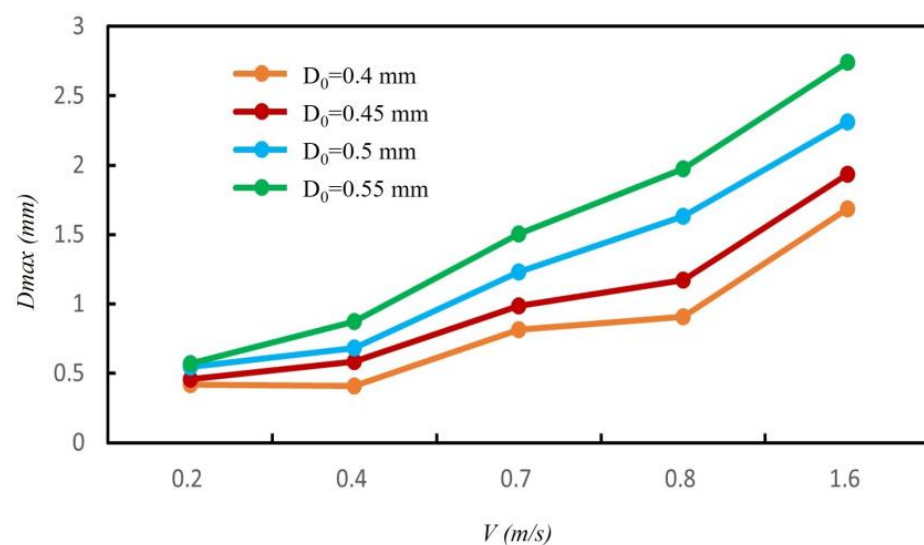


Figure 13. The relationship between droplet impact velocity, initial diameter, and maximum spreading diameter.

4.2. The Relationship between a Droplet's Weber Number and Maximum Spreading Rate, $\beta_{\max}$

Figure 14 shows a simulation of the process of droplets with different Weber numbers spreading on a horizontal surface. After 5 ms, the droplet shape does not change, so 5 ms is defined as the time at which the droplet reaches a stable state. Subsequently, the droplet parameters at 5 ms were selected to calculate the maximum droplet spreading rate, $\beta_{\max}$. It can be seen from the figure that after the droplet hits the surface, the equivalent diameter of the droplet first increases and then decreases. The lateral diameter of the droplet first increases and then decreases, while the longitudinal diameter decreases first and then increases. This is because the droplet diffusion undergoes a process of spreading-retracting-stability [27]. This is consistent with the experimental results in Figure 12. However, compared with the experimental results, the simulation results take a longer time to reach the stable stage. This is because the air resistance of the droplet falling process is not considered in the numerical simulation, resulting in more kinetic energy being released when droplets of the exact parameters impact the blade surface, thus increasing the droplet spreading time.

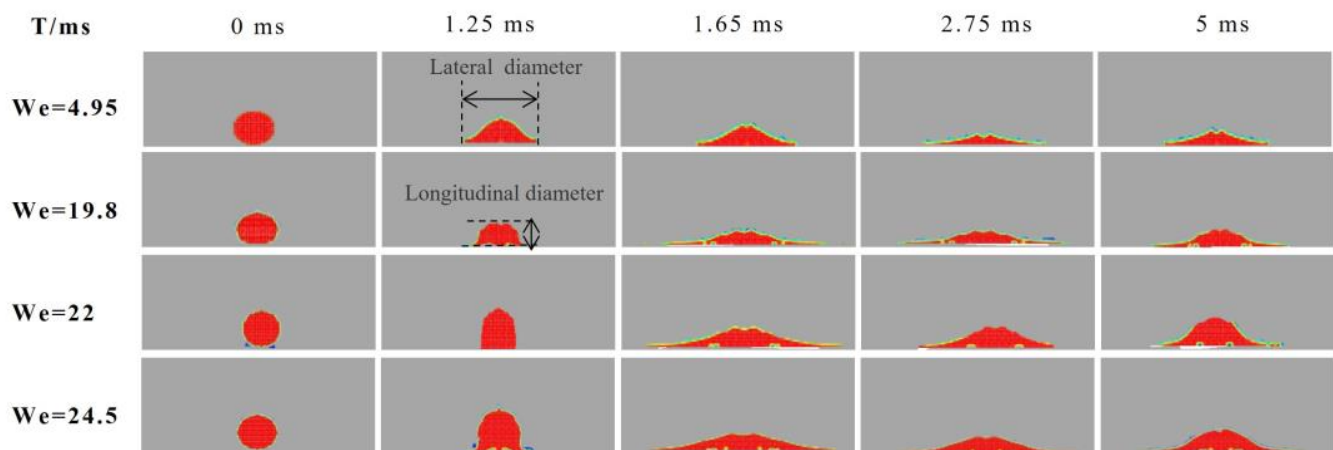


Figure 14. The simulated process of droplets with different Weber numbers spreading as they impact the blade surface.

When spraying pesticides, increasing the maximum spreading coefficient of pesticide droplets can cause pesticides to achieve more complete contact with crops, improving the crops' efficiency at absorbing the pesticides. When viscous dissipation is neglected, the maximum spreading coefficient of the low-viscosity liquid impinging upon the surface can be deduced according to the law of the conservation of energy, $\beta_{\max} \in We^{\frac{1}{2}}$, and according to the law of the conservation of momentum, $\beta_{\max} \in We^{\frac{1}{4}}$. Figure 15 shows the variation in the maximum spreading coefficient of the droplet with the Weber number. The blue dashed line represents the relationship curve between We and $\beta_{\max}$ in the experiment, and the red line represents the line of $We^{\frac{1}{4}}$. It can be seen from the figure that when the Weber number is small, the maximum spreading rate of the droplet increases slowly with the increase in the Weber number. This is because the spreading of a droplet at a low Weber number is dominated by capillary forces [26,36]. The existing theory shows that the maximum spreading rate of a droplet under an inertial force is consistent with $\beta_{\max} \in We^{\frac{1}{4}}$ [37,38]. It can be seen from the diagram that the experimental results of this experiment conform to the rule of $\beta_{\max} \in We^{\frac{1}{4}}$.

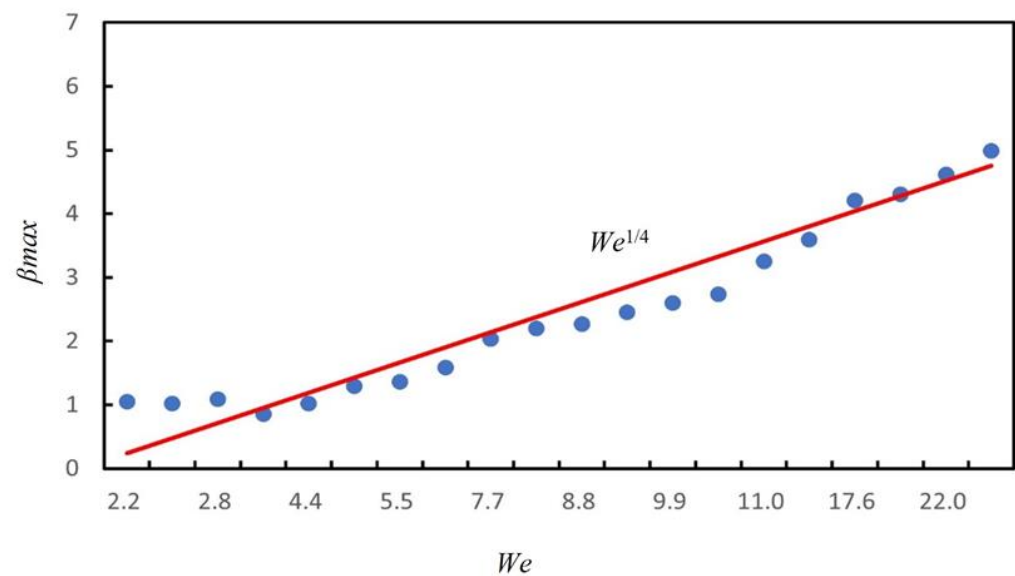


Figure 15. Relationship between droplet $\beta_{\max}$ and Weber number.

5. Conclusions

Based on the combination of experiments and numerical simulations, this work studied the deposition and spreading of single droplets on the surfaces of wheat leaves, explored the relationship between the maximum spreading diameter of a droplet and the droplet's velocity and diameter, and clarified the relationship between the maximum spreading rate of a droplet and the droplet's Weber number. The following conclusions were obtained:

1. When a droplet hits the front side and back side of a leaf (non-ridge), the contact angle does not differ greatly, and the contact angle gradually decreases as the droplet's Weber number increases. When droplets hit the ridge on the back side of a wheat leaf, the droplets split in two.
2. After a droplet hits the surface of a wheat leaf, the droplet will form a coronal droplet and then continue spreading to reach its maximum spreading diameter before retracting until it reaches a stable stage. As the Weber number of the droplet increases, its spreading time the droplet becomes longer.
3. With an increase in a droplet's impact velocity, the droplet's maximum spreading diameter gradually increases. As the initial diameter of the droplet increases, the maximum spreading diameter of the droplet also gradually increases. As the droplet velocity increases, the droplet diameter has an increasing influence on its maximum spreading diameter.
4. The numerical simulation results show that the maximum spreading rate of droplets increases with an increase in the Weber number, which is consistent with $\beta_{\max} \in We^{\frac{1}{4}}$, which is also consistent with the existing theory. It is suggested that when creating a droplet-generating device, the Weber number of the droplets should be increased as much as possible while considering the droplet size to obtain the maximum droplet spreading diameter and improve the droplet utilization rate.

Studying the spreading characteristics of droplets on the surface of wheat leaves is of great significance to agricultural spraying. This paper briefly discusses the influence of droplet parameters, especially the droplet Weber number, on the maximum spreading diameter of droplets. However, there are many more factors affecting droplet spreading, such as the influence of droplet chemical properties, surfactants, environmental temperature and humidity, etc. In future research, the influence of various factors should be considered comprehensively to make the research more comprehensive.

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