Review of the interaction mechanism for droplets and foliage under sprinkler irrigation and water-fertilizer integration

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Abstract: With a focus on the global tension between water resources and energy, the use of water-fertilizer integration technology in sprinkler irrigation has seen a rise. However, achieving efficient and effective fertilizer application remains a significant challenge. This study delved into the interaction mechanism between droplets and foliage during sprinkler fertigation, as well as discusses the application of water-saving and energy-saving irrigation methods in agriculture to address water crises and propel agricultural modernization. This study highlights two main aspects of this issue, that is, the droplet and foliage impact process, and the droplet and foliage dynamic interaction including foliar interception, leaf absorption, and leaf burning. Major challenges, such as inefficiencies in foliar interception and uncertainties in fertilization, have been identified, calling for further investigation into these areas. Moreover, perspectives to promote fertilization technology are proposed, including research on the dynamic impact of fertigation droplets on foliage, the development of universal models for leaf fertilizer retention, and the determination of critical fertigation concentrations under varying conditions to prevent leaf burning. This comprehensive review aims to provide a theoretical basis for establishing an integrated fertigation system for sprinkler irrigation and foster innovation in water-fertilizer integration technology.

Keywords: sprinkler irrigation, fertigation droplets, interaction mechanism, foliar process
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1 Introduction

The global tension between water resources and energy has prompted the widespread adoption of water-saving and energy-saving irrigation methods in agriculture. Encouraging the use of efficient irrigation practices has become a key solution for countries to alleviate water crises and achieve agricultural modernization[1-4]. However, there is a growing disparity between the rapid expansion of water-saving irrigation areas and technological improvements, and the slower progress in implementing regulatory measures.

Sprinkler irrigation and water-fertilizer integration involve spraying a mixture of water and fertilizer through nozzles onto the soil and crop canopy for absorption. This method provides crops with real-time water and nutrients, reduces labor input, and improves crop yield and quality. As modern agriculture increasingly emphasizing water conservation and facing labor shortages, mechanization, automation, and intelligence in irrigation and fertigation have become crucial for transforming agricultural production methods and ensuring productivity. The development of dissolved organic fertilizers and new foliar fertilizers has further popularized sprinkler fertilization[5-7].

Fixed or semi-fixed sprinkler irrigation systems facilitate multiple fertilizer applications. During this process, fertilizer droplets collide with the foliage. After splashing, rebounding, and deposition, they are intercepted by the foliage. The intercepted fertilizer can be directly absorbed by leaf surfaces and other young vegetative organs. This is an advantage of sprinkler irrigation and fertigation integration, differing from drip irrigation[8,9]. In traditional cultivation, however, the local farmers often employed extensive water and fertilizer management methods, determining the concentration and amount of fertilization based on empirical knowledge. Notably, this approach may lead to various issues and limit the further promotion and application of water-fertilizer integration technology[10-12]. Lower concentrations would increase application amounts and water loss, decrease crop yield and quality, and reduce water and fertilizer utilization efficiency. Conversely, excessive concentrations could increase the risk of leaf burning, resulting in reduced photosynthesis, wilting leaves, decreased crop yield, and hydrological and ecological risks in farmlands[13-15]. Therefore, determining the appropriate amount and concentration of fertilization based on the maximum spray retention is crucial for integrated water-fertilizer spraying in crop cultivation.

Generally, the maximum spray interception depends on the spray deposition and the foliage's water-holding capacity, significantly influenced by the impact dynamics of the fertilizer droplets[16-18]. The nutrients in the fertilizer intercepted on the leaf surface can be directly absorbed, improving the physiological characteristics and enhancing crop yield and quality. However, exceeding a certain nutrient concentration threshold may cause imbalances, resulting in damage and leaf burning. Leaf burning induced by fertilization is directly related to leaf absorption.

This study reviews the research progress on the interaction

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between droplets and foliage, encompassing the impact process, foliar interception, leaf absorption, and leaf burning. It emphasizes the need to investigate droplet and foliage interactions, as they directly influence the efficient and effective use of fertilizers. Furthermore, this study highlights the significance of predicting fertilizer retention and determining the critical fertilizer concentration, which are essential for the widespread adoption of sprinkler fertilization technology. Based on these findings, we propose perspectives that can provide a theoretical basis for formulating an integrated fertilization system for sprinkler fertilization and enhancing the application of this technology.

2 Droplet-foliage impact process

During sprinkler fertigation, liquid fertilizer is sprayed from a nozzle onto crop leaves, resulting in the splashing, rebounding, and deposition of droplets[19]. After single or multiple splashing and rebounding processes, droplets are deposited on the leaf surface to form foliar interceptions. The amount of interception is regulated by a complex set of physical and chemical factors, such as droplet characteristics, foliage characteristics, and the dynamic impact process between the droplet and the leaf surface. Once the maximum intercept value is reached, it does not increase further. This study has explored the key factors influencing the impact process and has provided a systematic explanation of the dynamic behavior of drops impacting foliage.

2.1 Influence of droplets and foliage characteristics

The impact process of droplets on a leaf surface is particularly complex, with the key influencing factors being the droplet and foliage characteristic parameters as shown in Figure 1[18,20,21]. Droplet characteristic parameters typically encompass physicochemical characteristics, such as surface tension, viscosity, density, and impact characteristics, including droplet diameter, impact angle, velocity, and contact angle. Physicochemical properties significantly affect the contact angle of drops on crop leaves, thereby influencing their adhesion[20,22].

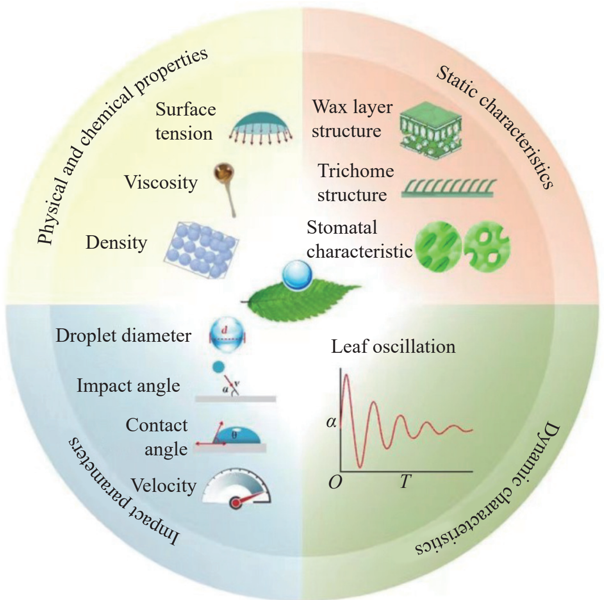


Figure 1 Factors affecting the droplet-foliage impact process

Trapaga and Szekely[23] found that surface tension plays a significant role in modulating droplet morphology. Hilz and Vermeer[24] reported that the liquid viscosity, surface tension, and density significantly influence spray deposition. Given that achieving efficient drop deposition is of considerable importance for fertilizer applications, an effective approach for enhancing droplet deposition involves the introduction of surface-active additives to lower the dynamic surface tension of drops[25,26]. Song et al.[27] analyzed the impact deposition mechanism of water droplets on rice leaves. These findings suggest that a combination of a flexible polymer (PEO) with substantial tensile viscosity and a surfactant (AOT) could prevent water droplet splashing, prolong the contact time, and enhance the wettability of water droplets on the leaves. Hoffman et al.[28] investigated the impact dynamics of aqueous surfactant solutions on hydrophobic surfaces and inferred the dynamic surface tension at millisecond timescales.

Sprinkler irrigation is a technique that offers precise control of water and fertilizer application, ensuring optimal conditions for crop growth by managing quantities and frequencies. This results in increased production and improved product quality. Nevertheless, the main challenge lies in achieving higher application efficiency and crop production under low-pressure conditions, considering rising energy costs and risks of foliage burning. Therefore, efforts are underway to optimize high-pressure sprinklers for use under low-pressure conditions.

Interest in low-pressure sprinkler applications to save irrigation water is gaining momentum. Several methods exist for improving the uneven distribution caused by operating impact sprinklers at low pressures. The installation of special-shaped nozzles, vanes, and fluidic devices on high-pressure sprinklers can enhance rotation stability and minimize variations in water distribution[29,30]. Low-pressure nozzles such as R3000 and R33 are extensively used in fixed and semi-fixed irrigation systems because of their affordability and superior performance.

To maximize effectiveness, it is essential to optimize the system design, select appropriate nozzle types, and improve the management of crops, soil, and weather conditions during operation[31-33]. Therefore, our attention is primarily directed toward the impact parameters of liquid droplets on leaf surfaces under varying conditions such as nozzle type and operating pressure. The relationship between impact parameters and various influencing factors has been extensively studied through theoretical analyses and experimental investigations.

Sayyadi et al.[34] found that the droplet size and velocity increased with increasing nozzle diameter at the same working pressure. Ge et al.[35] compared Nelson nozzles' characteristics with natural rainfall and discovered that the droplet velocity remained constant regardless of working pressure, close to the velocity of natural rainfall. Jiang et al.[36] conducted experiments on the effects of circular and noncircular nozzles on droplet properties, and established a logarithmic model between the droplet size and velocity. Hua et al.[37] studied the impact characteristics of water droplets with different nozzle shapes and established a predictive model for the droplet diameter and kinetic energy. Although there have been extensive investigations on droplet characteristics in irrigation and spraying processes, liquid fertilizer droplets possess distinct physiochemical and impact characteristics compared to water and pesticides. In contrast with conventional water irrigation and pesticide spraying, the parameters of fertilizer droplets during the synergistic use of water and fertilizer have not been extensively studied. Future research should focus on introducing physiochemical properties like surface tension and viscosity of liquid fertilizers into irrigation and spraying studies and delve deeper into analyzing droplet behavior when interacting with crop foliage.

Drop impact dynamics depend strongly on the static properties and dynamic features of the foliage, including the wax layer structure, trichome structure, stomatal characteristics, and leaf oscillation. This, in turn, affects the surface roughness and wettability of the leaves[38,39]. At present, studying plant leaf microstructures largely relies on complex and expensive methods such as scanning electron microscopy (SEM) and atomic force microscopy (AFM).

In a study published in 1997, Neinhuis and Barthlott[40] discovered that lotus leaves have micro-scale conical features and nano-scale protrusions. These features collectively contribute to the superhydrophobic and self-cleaning performance, commonly referred to as the “Lotus Effect”. Figure 2a shows the SEM images of the lotus leaf surface[41]. Kwon et al.[42], using SEM, observed differences in the transverse and longitudinal wax layer structures of rice leaves. This led to differences in the wettability of the leaf surface (Figure 2b). Wang[43] studied the microstructure of leaves from *Ligustrum lucidum* Ait. and *Viburnum odoratissimum* at different growth stages with AFM. The results showed that the distinct patterns in leaf surface roughness might be related to the effect of stomatal development and external environmental factors. Figure 2c shows the AFM images of the abaxial surface of the new leave of *Ligustrum lucidum* Ait. Zhu et al.[16] tested the different surface roughnesses and wax layer thicknesses of tea leaves along the transverse and longitudinal directions and analyzed the impact behavior of pesticide droplets on hydrophilic tea leaf surfaces (Figure 2d).

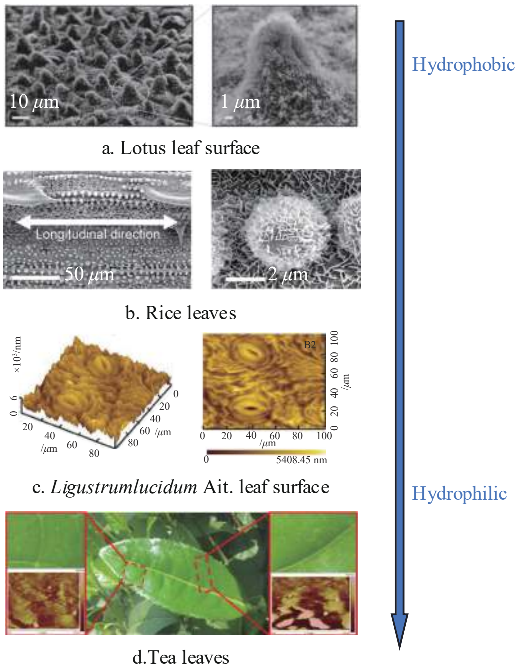


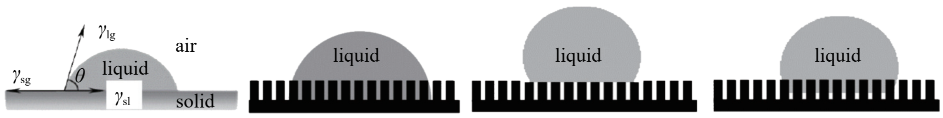
Figure 2 SEM images of the lotus leaf surface[41] and rice leaves[42], with AFM images of *Ligustrum lucidum* Ait.[43] and tea leaves[16]

Considering the level of parameter quantification, the structural characteristics of crop leaves can be categorized according to the static contact angle θ of droplets on the leaf surface. A variety of theoretical wetting models for θ have been proposed, focusing on the wettability of plant leaf surfaces. Young[44] first established a theoretical framework for determining the contact angles of pure liquids on smooth and homogeneous solid surfaces under ideal conditions. When a droplet is in equilibrium on the surface, the tangent line at the point where the liquid contacts the solid-gas interface represents the droplet’s surface. The angle between this tangent line and the solid surface, typically denoted as θ, is referred to as the contact angle (Figure 3a).

However, the presence of surface roughness or microstructure in most natural and artificial surfaces has a significant impact on the contact angle θ. Wenzel[45] modified Young’s equation by introducing the roughness coefficient r, that is, the ratio of the true contact area to the apparent contact area, $r>1$, and assumed that the liquid could completely fill the textures on the surface (Figure 3b). In certain cases, such as when the surface is highly hydrophobic, the droplets cannot fill the texture, resulting in trapped air beneath the droplets. Therefore, the liquid-solid contact surface was composed of a combination of solid and gas phases (Figure 3c).

Cassie and Baxter[46] derived the Cassie-Baxter equation from a thermodynamic standpoint, which is suitable for describing composite contacts on any surface. The wetting mode is one of the most important means of controlling droplets through interfacial phenomena. The Wenzel wetting mode exerts a strong pinning effect on the droplet contact line. This results in lower mobility of the droplet, and it is an ideal wetting state in the field of irrigation and fertilization. Based on an analysis of the surface free energy and energy barrier, the factors affecting the wetting mode and triggering the transition between the Cassie and Wenzel states have been widely studied (Figure 3d). Lafuma and Quéré[47] discovered that when a droplet is subjected to physical compression, a Cassie-Wenzel transition may occur. Ren[48] computed the transition states, energy barriers, and minimum energy path during the Cassie-Wenzel wetting state transition process and found that the wetting transition involves a series of intermediate metastable states.

Typically, when $0°<\theta<30°$, the leaf surface is considered super-hydrophilic because of its smooth and hydrophilic trichomes. When $30°<\theta<90°$, the leaf surface is classified as hydrophilic because of its smooth wax layer. Meanwhile, when $90°<\theta<150°$, the leaf surface is deemed hydrophobic because of the presence of epidermal cell protrusions or wax-hooked hair. When $150°<\theta<180°$, the leaf surface is super-hydrophobic because of its multi-level hydrophobic structure[49,50]. These fundamental models aid in understanding the diverse wetting phenomena in agriculture, and serve as a guide for achieving different control effects on the dynamic behavior of droplets on leaf surfaces. In this context, precise control of droplets can be achieved in different processes.



a. Young wetting mode | b. Wenzel wetting mode | c. Cassie wetting mode | d. Transition wetting mode

$\cos\theta=\frac{\gamma_{sg}-\gamma_{sl}}{\gamma_{lg}}$ $\cos\theta_w=r\cos\theta$ $\cos\theta_c=f(\cos\theta+1)-1$

Note: θ, θ_w, and θ_c represent Young’s contact angle, Wenzel’s contact angle, and Cassie-Baxter’s contact angle, respectively; γ_{sg}, γ_{sl}, and γ_{lg} are the tensions at the solid-gas, solid-liquid, and liquid-gas interfaces, respectively; f is the fraction of the solid-phase area in the composite contact surface.

Figure 3 Sketch of different wetting modes[51]

The current research emphasis is on studying the static characteristic parameters of detached plant leaves through observation. However, in nature, plant leaves are typically suspended and exhibit dynamic oscillation characteristics when subjected to droplet impact. Therefore, further research should focus on investigating the dynamic characteristic parameters of leaf surfaces during droplet impact using numerical simulations and experimental methods. This should be built upon prior studies on static characteristic parameters to provide a deeper understanding of the topic.

2.2 Droplet impact process

When droplets impact solid surfaces, inertial, viscous, and capillary forces govern the behavior of the droplets. The inertial force is primarily determined by the kinetic energy and influences the droplet spreading stage. Viscosity regulates the viscous dissipation, whereas surface tension provides the energy necessary for droplet deformation and propels the recoiling stage. This can result in three potential outcomes, that is, shattering, bouncing, and deposition[52-54]. In the field of drop impact dynamics on solid surfaces, researchers have conducted various experimental, theoretical, and numerical investigations.

Worthington[55] documented diverse splash phenomena caused by drop impacts. Given the widespread occurrence and intricate nature of the drop impact process, numerous experiments have been conducted to investigate the dynamic spreading, receding, and bouncing behaviors of drops upon impacting solid surfaces. The impact process is primarily influenced by the hydrodynamic characteristics of the droplets and the dynamic and static properties of the surface. Experiments are also conducted according to these variables. During the experiments, to reduce the number of variables involved, the fluid characteristics of the droplets are usually represented by several dimensionless parameters as listed in Table 1.

Table 1 Dimensionless parameters of fluid characteristics

Parameter	Formula	Implication
Weber number (*We*)	$We=\rho v^2 D/\gamma$	Relation between inertia and surface tension
Reynolds number (*Re*)	$Re=\rho vD/\mu$	Relation between inertia and viscosity
Capillary number (*Ca*)	$Ca=\mu v/\gamma$	Relation between viscosity and surface tension
Bond number (*Bo*)	$Bo=\rho g D^2/4\gamma$	Relation between gravity and surface tension

Note: ρ, v, D, γ, μ, and g are the mass density, impact velocity, initial diameter, surface tension, dynamic viscosity, and gravity acceleration of the drop, respectively.

As research deepens, the surfaces transition from solid planes and inclined walls to actual crop leaf surfaces. Šikalo and Ganić[56] used high-speed photography to observe the microphenomena of droplets impacting different solid surfaces, including water, isopropanol, and glycerol. They investigated how droplet characteristics influenced whether droplets deposited, splashed, or rebounded on the surfaces. The results highlighted the crucial role of the Weber number in these interactions (Figure 4a). Moon et al.[57] investigated the temporal evolution of droplets on flat textured surfaces. Owing to the surface geometry, the spreading droplet exhibited a wavy shape. Meanwhile, it assumed various shapes and experienced a pinch-off phenomenon during the receding phase (Figure 4b).

When applying irrigation and fertilization through spraying, the droplets impact the crop leaves at a certain angle. Findings from the literature on droplet impacts on inclined surfaces can provide valuable references[42,56,58]. Kwon et al.[42] studied water droplet impacts on rice leaves at various inclinations and orientations (Figure 4c). Three distinct impact behaviors were observed based on the normal component of the Weber number (We_N), whereas the contact distance largely depended on the tangential Weber number (We_T).

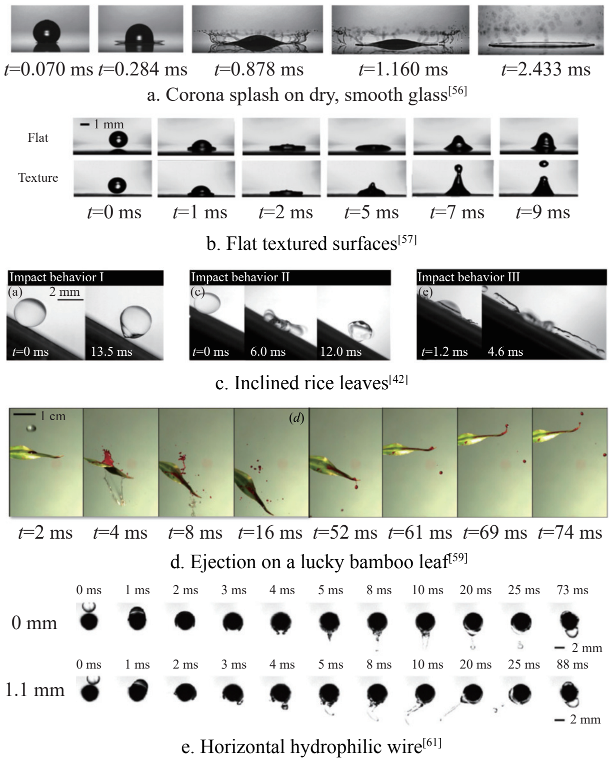


Figure 4 Dynamics of droplet impact process on various surfaces

Compared with fixed planes and inclined walls, the impact of liquid droplets on curved surfaces and actual crop leaves is more complex. Recently, some researchers have conducted experimental studies[59-61]. Gilet and Bourouiba[59] investigated the dynamic evolution of the droplet impact and fragmentation on flexible leaves. They analyzed the influence of leaf size, mass, and flexibility, resulting in two types of droplet fragmentation scenarios and spreading modes, that is, crescent moon ejection and inertial detachment, as shown in Figure 4d. Chen et al.[61] explored droplet impact on a horizontal hydrophilic wire through experiments and examined the effects of eccentricity, Weber number, and wettability. The results demonstrated that eccentricity and *We* simultaneously affected the maximum spreading coefficient and spreading time. The evolution of the drop impact morphology under different eccentricity conditions is shown in Figure 4e.

Based on the integration and analysis of numerous experimental results, various theoretical models have been proposed. In modeling the splashing stage, Mundo et al.[62] proposed a mathematical model for droplet shatter based on the energy balance:

$$K = We^{1/2}Re^{1/4} > K_{crit} \tag{1}$$

where, K is the impact parameter and K_{crit} is the critical shutter threshold. When $K>K_{crit}$, the droplets spatter; otherwise, they rebound or deposit. K depends on the droplet characteristic parameters, whereas K_{crit} is associated with foliage characteristic parameters, such as surface roughness and wettability. K_{crit} is typically performed by fitting experimental data, which can be time-consuming and laborious. To simplify this issue, Forster et al.[63]

proposed a method for estimating K_{crit} based on the static contact angles of droplets in an acetone solution.

For hydrophilic surfaces,

$$K_{crit} = -0.584\left(CA_{20\%\ acetone}\right) + 147 \quad (2)$$

For hydrophobic surfaces,

$$K_{crit} = -0.9227\left(CA_{50\%\ acetone}\right) + 160 \quad (3)$$

However, these models only determine whether a splash occurs and do not provide further analysis of secondary droplet formation. Given that these secondary droplets can significantly influence deposition, further research should focus on analyzing the process of secondary droplet fragmentation during impact. Dorr et al.[64] introduced the splashing diffusion factor f ($0<f\leq1$) to measure the timing of fragmentation. Here, a smaller value of f indicates an earlier shatter and less kinetic energy consumption. During droplet splashing, only a fraction of the sub-droplets usually detach from the target surface, whereas the rest remain adhered to it. This phenomenon can be characterized by the pinning proportion parameter p ($0\leq p<1$), where p=0 indicates complete shatter and p>0 indicates partial shatter. The calculation of parameters f and p affects the number of secondary droplets produced during splashing, and their impact characteristic parameters. Huet et al.[65] developed an image analysis method based on high-speed photography experiments to quantify the parameter p and pinning volume during bounce or splash. The pinning volume can be significant and is primarily affected by the impact process. The exact mechanisms leading to partial drop pinning on a complex surface such as a leaf require further examination. Therefore, no theoretically derived method could determine the parameter values of f and p, which is an important direction for future research.

In terms of building mathematical models for droplet bouncing or deposition, Mao et al.[66] explored the influence of impact parameters on droplet maximum spreading and rebound through extensive experiments. They improved the prediction formula for maximum spread diameter and proposed a rebound model based on energy conservation.

$$E^*_{ERE} = \frac{1}{4}\left(\frac{d_m}{D}\right)^2(1-\cos\theta) - 0.12\left(\frac{d_m}{D}\right)^{2.3}(1-\cos\theta)^{0.63} + \frac{2}{3}\left(\frac{D}{d_m}\right) - 1 \quad (4)$$

where, d_m is the maximum spreading diameter of a droplet. During $E^*_{ERE} > 0$, the droplet bounces off the surface; during $E^*_{ERE} \leq 0$, it remains on the surface. However, their model only considered the situation in which droplets impact flat surfaces vertically. Dorr et al.[67] introduced modifications to the rebound model for various inclination angles. Ding et al.[68] investigated the impact behavior of a water droplet on small cylindrical superhydrophobic targets and found that a larger We accelerated the droplet spreading, leading to a rebound phenomenon. They established a droplet rebound model based on the critical We and the diameter ratio of the target droplet diameter.

In the field of fertigation, there is greater focus on fertilizer droplet deposition on crop leaves. The maximum spreading factor β, which denotes the ratio of the maximum spreading diameter to the initial diameter of the drop, has a direct impact on the wetting effect of fertilizer on plant leaves. Therefore, many researchers have established a relationship between β and We and Re through theoretical analysis or semi-empirical formulas. Table 2 outlines the classical models for predicting β.

Most impact models are algebraic idealized models combined with empirical fitting of high-speed photography test data. While these models offer simple calculations and insights into the outcomes of droplet surface impact, they lack detailed information on velocity, pressure, and stress distributions throughout the entire process. To further determine the underlying mechanisms of droplet impact deposition, numerical simulation methods based on computational fluid dynamics (CFD) have been used. Selective but not limited studies include different methods for interface tracking, including the Volume of Fluid (VOF), Level Set (LS), Coupled Level Set, Coupled Level Set and Volume of Fluid (CLSVOF), and lattice Boltzmann methods (LBM). A critical challenge lies in accurately predicting the gas-liquid interaction at a three-phase contact line, particularly the dynamic contact angle θ_d during the spreading and receding stages, which significantly influences the impact process[69].

Table 2 Classical models for predicting β

Model	Formula	Instruction
Richard et al.[70], Eggers et al.[71]	$\beta \sim We^{1/2}$	Impact in the capillary regime, assuming a pure transfer of kinetic energy into surface energy, energy conservation is simply $\rho D^3 v^2 \sim \gamma d_m^2$
Clanet et al.[72]	$\beta \sim We^{1/4}$	Impact in the capillary regime, following the conservation of momentum and volume
Chandra and Avedisian[73]	$\beta \sim Re^{1/5}$	Impact in the viscous regime, the kinetic energy is dissipated by viscosity, which is expressed as $\rho D^3 v^2 \sim \mu(v^2/h)d_m^3$

Note: h is the thickness of the droplet at maximum spreading.

Therefore, it is important to consider this dynamic condition in CFD simulations. Pasandideh-Fard et al.[74] used the VOF method and introduced θ_d to enhance the droplet contact diameter prediction on a flat solid surface. Roisman et al.[75] developed a new algorithm for modeling the dynamic contact angle based on the instantaneous velocity of the contact line. This was applied to the VOF model to simulate droplet diffusion on a dry solid surface at low Weber numbers. Yokoi et al.[76] integrated a dynamic contact angle model to the CLSVOF method to study droplet impact behavior. Malgarinos et al.[77] proposed a new wetting force model (WFM) to simulate the deposition process of droplets impacting solid dry surfaces, where the simulation results were more suitable for medium-low Weber numbers. Ahamd et al.[78] used the LBM method to investigate the oblique impact of two successive droplets on flat surfaces. The results indicate that the impact behavior of two successive droplets differs from a single droplet due to coalescence.

Compared to solid surfaces, the droplet impact on plant leaves is a more complex dynamic process that is affected by both droplet and foliage characteristic parameters[79]. Gilet and Bourouiba[59] studied the dynamic evolution of splash ejection after a single droplet impacted a leaf, producing two dominant fluid fragmentation scenarios: crescent moon ejection and inertial detachment. Dorr et al.[67] investigated droplet impacts on real leaves, that is, cotton, rice, and wheat leaves with various spray formulations and leaf characteristics. They proposed a modified mathematical model of droplet shatter, bounce, and deposition, considering different leaf inclination angles and droplet impact trajectories. Delele et al.[80] utilized the VOF method to simulate the dynamic impact behavior of water droplets on hydrophilic and hydrophobic plant leaves, that is, apples, pears, leeks and cabbage. The study analyzed the effects of droplet impact velocity, diameter, and leaf characteristics on the impact process, revealing that droplets tended to deposit and rebound on hydrophilic and hydrophobic surfaces, respectively. Zhu et al.[16] proposed the CLSVOF interface tracking method to study the impact dynamics of three pesticide droplets on the transverse and longitudinal leaves of hydrophilic tea trees. They further analyzed the liquid phase pattern, surface wettability, pressure, and velocity distribution. The calculated predictions matched the published data. Liu et al.[81] used the VOF method to investigate the impact process of droplets on virtual tea leaves and explored the effects of the impact angle, leaf curvature, and gravity on the droplet flow field. Their results indicated that smaller impact angles resulted in a more pronounced droplet slip phenomenon. With increasing droplet size, gravity played a greater role in the droplet movement. Table 3 summarizes the numerical simulation approaches and range of conditions for the representative studies.

Table 3 Approaches used and the range of conditions of representative studies for liquid droplet impingement

Year	References	Model	Contact angle model	Surfaces	Liquid droplets	d_0/mm	v_0/m·s^{-1}	Experiments
1996	Pasandideh-Fard et al.[74]	VOF	Constant equilibrium angle/ dynamic from experiment	Stainless steel surface	Water	2.05±0.03	1.0	Own
2008	Roisman et al.[75]	VOF	θ_d, Kistler's law	Stainless steel surface	Water	2.50	0.16-0.48	Own
2009	Yokoi et al.[76]	CLSVOF	θ_d, Modified Tanner's law	Chemically treated silicon wafer	Water	2.28	1	Own
2014	Malgarinos et al.[77]	VOF	θ_d, WFM	Solid dry surface	Water	2.28-3.76	0.08-1.64	Published data
2016	Delele et al.[80]	VOF	Static contact angle	Leaf of apple, pear, leek and cabbage	Water	0.05-0.80	0.1-10.0	Own
2018	Zhu et al.[16]	CLSVOF	θ	Tea leaf	Pesticide	0.3	4	Published data
2018	Ahamd et al.[78]	LBM	θ	Inclined flat surface	Liquid	Re=80, We=40		Published data
2022	Liu et al.[81]	VOF	θ	Virtual tea leaf	Water	0.3, 0.5	3	Own

Note: θ, θ_d represent static contact angle and dynamic contact angle, respectively.

Plant leaves exhibit several dynamic characteristics. The aforementioned study primarily focused on the impact analysis of plant leaves fixed on a plane but failed to investigate the dynamic impact process of suspended leaves. These studies overlooked the process of multiple droplets shattering and bouncing, subsequently forming deposition. To enhance the validity of future research, it is imperative to investigate phenomenon such as multiple droplets shattering and rebound while analyzing the dynamic characteristics of leaves and conducting research on the dynamic impact process of droplets and leaf surfaces.

3 Droplet-foliage dynamic interaction

3.1 Crop foliar interception

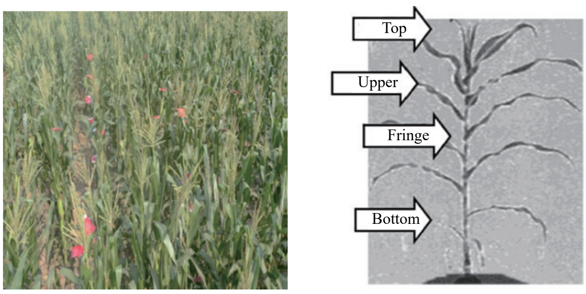
Droplets impact crop leaves and cause droplet shattering, bouncing, and deposition, resulting in foliar interception. Maximum foliar interception is known as leaf retention. Foliar interception is mainly affected by the water-holding capacity of the leaf surface. This is influenced by droplet and foliage characteristics, and the impact process. Prior research has largely focused on the formation mechanisms, measurement methods, and model construction of canopy interception at the macroscale[82-84]. However, limited research has been conducted on how leaf surface wettability, droplet characteristics, and environmental factors affect foliar interception as a microscale representation of crop canopy interception. As foliar interception directly affects leaf absorption and leaf burning, it is necessary to conduct in-depth research on the microscale interception of fertilizers on leaf surfaces.

The amount of foliar interception is primarily influenced by the water-holding capacity of the leaf surface, which varies depending on the foliage characteristics. Leaf wettability, determined by factors like wax layer structure, trichome structure, and stomatal characteristics, plays a crucial role in this phenomenon. Environmental factors also affect leaf wettability by influencing leaf surface structure and morphology[85]. To determine the underlying mechanisms, Wilson et al.[86] studied the effects of leaf position, density, and age on potato foliar water interception. Their findings indicated that the upper canopy leaves had stronger water-holding capacities than the lower leaves, randomly distributed leaves performed better than dense leaves, and old leaves were stronger than new ones. Wang et al.[87] measured the maximum water retention capacity of 21 plant leaves using submerging and spraying methods and preliminarily discussed the effect of leaf surface wettability on foliar interception, noting variations in water droplet forms after interception affecting measurement results.

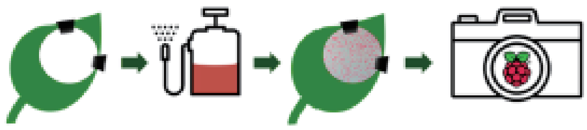
Compared to water interception, nutrient interception on leaf surfaces during fertigation is more complex and influenced by factors such as droplet characteristics, impact progress, and technical fertigation parameters[88]. For precise foliar fertilization through irrigation spraying, attention should be given to fertilizer droplet deposition and nutrient interception on leaf surfaces to ensure efficient utilization. Lu et al.[89] analyzed how droplet size, velocity, surface tension, and application rate influence maximum leaf retention capacity, indicating that the stable retention capacity initially increased with increased droplet size, velocity, and application rate before stabilizing. Qin et al.[90] replaced pesticides with a tracer solution and employed an N-3 unmanned aerial vehicle (UAV) for low-altitude spraying to study spraying parameters such as working height and lateral spray swath during spray droplet deposition. Zheng[91] suggested that leaf deposition could quantitatively evaluate the efficacy of plant-protection UAV variable-rate spraying operations and recommended the selection of nozzles with higher initial spray droplet velocities during actual operations. Zhang et al.[92] established a prediction model integrating droplet interception and impact models for rice plants in plant-protection UAV spray technology. However, they neglected the effects of secondary droplets generated by the bounce on deposition. Ding et al.[93] proposed an improved method for determining droplet deposition on virtual rice leaves, emphasizing the importance of the injection height and angle for enhanced deposition efficiency.

Current research has primarily focused on the deposition of crop protection sprays in ideal conical spray scenarios. Compared to crop-protection spraying, fertigation droplets are larger and have higher kinetic energies. When they contact the leaf surface at a smaller impact angle, a high-energy impact occurs, resulting in varied retention effects and leaf retention capacities. Therefore, it is essential to integrate the droplet characteristic parameters of fertigation and develop models for foliar interception and the prediction of nutrient retention capacity in fertigation.

Measurement methods for leaf retention capacity are also crucial factors affecting the study of retention patterns. In experiments, it is common to directly measure the leaf retention capacity by collecting droplets. Qin et al.[90] used circular polyester cards as soluble fluorescent tracer receivers to determine droplet deposition per unit area and analyzed the distribution of droplet deposition between different layers in maize canopies. The field experiment setup (Figure 5a) involved placing receivers at various parts of the crops to measure droplet deposition on the polyester cards using fluorescence analysis. Zwertvaegher et al.[94] measured spray deposition using water-sensitive papers and analyzed their uniformity. These papers can be easily attached to any crop, and the color of the coating changes from yellow at pH 3.0 to blue at pH 4.6. However, false positives were sometimes obtained as a blue spot could appear due to factors like water vapor in the air or dew on the crop, not just the liquid mixture[95,96]. To address this issue, Menger et al.[97] added fluorescent dyes to a solution sprayed onto filter paper, captured images, and analyzed the retention patterns through image processing (Figure 5b). Bueno et al.[98] conducted field experiments to establish spray drift curves suitable for soybean crops under meteorological conditions in Brazil. Figure 5c depicts the field experiment setup, with the filter paper placed downwind. The deposits were evaluated using a fluorescent tracer applied to the filter paper through fluorimetry analysis.



a. Polyester cards experiment setup[90]



b. Fluorescent dye paper-based method[97]

c.View of the filter papers[98]

Figure 5 Measurement methods for leaf retention capacity

Although all these methods use samplers to replace crop leaves, which have sufficient absorption properties and prevent rebound, they still exhibit some errors compared to the actual leaf retention capacity. Further research is needed to develop accurate measurement methods for leaf retention capacity during field fertigation.

3.2 Leaf absorption

Foliar fertilizers can enhance crop yield and quality by enabling direct absorption and use of nutrients by leaves during sprinkler fertigation, thereby improving their physiological characteristics. However, excessive fertilizer concentration or exposure to high temperature and sunlight during leaf absorption can alter the physiological characteristics of the leaves, hinder photosynthesis, change leaf respiration and transpiration, affect nutrient migration, and result in symptoms such as reddening or browning necrosis[99].

Foliar fertilizers are increasingly used worldwide[100]. The process of foliar nutrient absorption is dynamic and intricate, and is influenced by several factors, including foliage characteristics, physical and chemical properties of the fertilizer solution, and ambient temperature. These determinants affect the efficiency of foliar fertilizers, physiological characteristics of leaves, and crop quality[101]. Contemporary research on leaf absorption has focused predominantly on the mechanisms underlying the influence of leaf characteristics on nutrient absorption[102].

Leaf characteristics that influence leaf absorption include cuticle structure, trichome structure, and stomatal characteristics[103]. The cuticle is the primary barrier for plants to interact with, absorb, and accumulate nutrients from the external environment while also controlling water and organic matter loss. It is a heterogeneous ultrastructure that can be broadly divided into three regions, that is, epicuticular wax (EW), cuticle proper (CP), and cuticular layer (CL)[104]. The wax layer is composed of two layers, that is, the epicuticular wax layer, which forms a distinctive wax film on the cuticle matrix, displaying an amorphous film, particulate, or crystalline structure contingent upon the varying chemical components, and the inner wax layer, which lies embedded within the cuticle and exhibits an amorphous configuration[102].

Holloway[105] discovered that the epicuticular wax layer plays a vital role in regulating the wettability of plant surfaces. Empirical research has indicated that the structural morphology of the wax layer can be affected by agricultural solution spraying[106]. This may result in deficient deposition or diffusion of spray droplets in some instances, whereas the inner wax layer determines epidermal permeability. Owing to the complex structure and chemical composition of the cuticle, predicting the environmental micro-interface behavior of nutrients within it is exceptionally intricate[107]. Currently, our understanding of the nanoscale structure and chemical heterogeneity of the cuticle remains limited and requires additional research to establish nutrient penetration models inside the cuticle.

In studies focusing on trichome structures, Li et al.[108] evaluated the absorption of foliar-applied Zn via ion mass spectrometry and observed Zn accumulation in some glandular trichomes of soybean, but not in tomato leaves. Kim et al.[109] analyzed the effects of trichome structure and wettability on the water absorption performance of cactuses. This study has shown that hydrophobic trichomes and trichome clusters facilitate the absorption of fog and dew drops.

Initially, researchers believed that the specific structure of stomata could prevent aqueous solutions from penetrating and that only when external pressure is applied or surfactants are added to reduce surface tension could foliar-applied solutions be absorbed through the stomata[110,111]. However, subsequent experimental reports from different backgrounds have shown the stomatal absorption of water, nutrients, and fluorescent tracers without the use of surfactants. Solutions can spontaneously penetrate stomata via diffusion, whereas the presence, density, and degree of stomatal aperture may affect the penetration rate of substances applied to the foliage[112,113]. Burkhardt et al.[114] re-evaluated the stomatal absorption of aqueous solutions using anions with varying solubilities, further analyzing their impact on the leaf physiology of apples and tomatoes, while also visually observing crucial processes. These results confirm that aqueous solutions can be absorbed through the stomata. Xia et al.[115] posited that leaf stomatal conductance is the primary channel for nutrient and gas exchange between plants and their external environment. They recommended a model to optimize the response of *Camellia oleifera* leaf stomatal conductance in the hilly regions of southern China by incorporating the CO_2 concentration difference between the stomata.

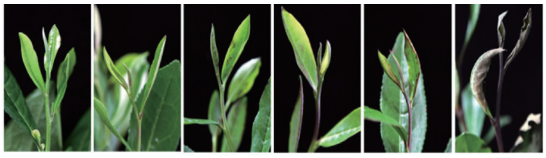
Focusing on foliar nutrient absorption during sprinkler fertigation, Jordan et al.[116] conducted a foliar tolerance test using reused municipal and synthesized saline water. These findings indicate that Na^+ and Cl^- absorption through the leaf surface is the primary cause of foliar damage and yield reduction. Li et al.[117] found that increasing fertilizer application had no substantial effect on winter wheat yield. Although the stem nitrogen content and uptake increased with increasing fertilizer application, the increase in nitrogen uptake was lower than the increase in fertilizer use. Excessive nitrogen application can also result in leaf burning. Li et al.[118] used ^{15}N isotope tracing technology to investigate the effects of different urea spraying concentrations on nitrogen uptake and use in cotton. The findings indicated that foliar urea spraying could increase chlorophyll content and leaf area, promote nitrogen absorption and use, and increase the plant height and total biomass of cotton plants. The spray concentration was set to 1%. Zhao et al.[12] explored the effects of urea spray concentration on the physiological characteristics and yield of summer maize using field experiments. These results suggest that the effects of foliar urea absorption on photosynthetic capacity are associated with nitrogen deficiency. The time of urea spraying should be determined according to crop fertilizer requirements.

Hu et al.[119] investigated changes in the yield and quality of spring tea under different biogas slurry application rates. Their findings showed that the maximum biogas slurry application rate enhanced both the yield and quality of spring tea, potentially because of the large amount of nitrogen absorbed by the tea trees sprayed with biogas slurry. Arsic et al.[120] used multiple methods to investigate the foliar fertilizer absorption behavior of spring barley under nutrient deficiency conditions. They also used laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) to visualize the absorption pathways of P and Mn ions through the leaves, showing new links between foliar characteristics, foliar-applied ion absorption pathways, and the restoration of affected physiological processes in nutrient-deficient leaves.

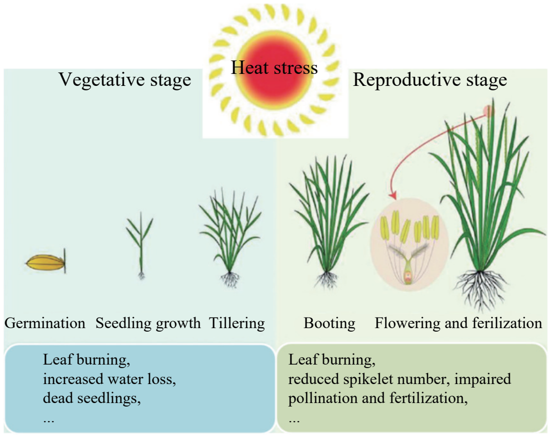
To summarize, current research on sprinkler fertigation has mostly focused on the effect of foliar nutrient absorption on crop growth. However, the amount and pathways of foliar nutrient absorption remain unclear. Most studies on foliar nutrient absorption have been conducted *ex vivo* in laboratory settings using methods such as radioactive labeling or fluorescent tracers. Because of their complex and potentially damaging pretreatments, these approaches cannot accurately assess nutrient distribution, absorption rates, and pathways on plant leaf surfaces. In the future, researchers should actively seek new methods and technologies, such as in situ detection techniques, to conduct more thorough investigations of foliar nutrient absorption, absorption rates, and pathways and further investigate the effects of different fertilizer concentrations, environmental temperatures, and foliar interception amounts on leaf physiological characteristics. This is crucial for studying the mechanism of foliar nutrient absorption and the emergence of leaf burning symptoms.

3.3 Leaf burning

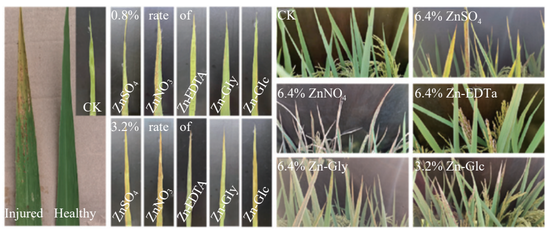
Leaf burning is a physiological phenomenon that results from the chemical composition, intense light, or high temperatures, causing discoloration, damage, and necrosis of plant leaf tissue. It not only diminishes crop yield but also reduces the ornamental and commercial value of plants[121]. To date, research on leaf burning symptoms and influencing factors has predominantly focused on high temperatures, drought stress, and sunburn[122]. Li et al.[99] investigated the stress state of tea leaves after high temperature treatment and the resulting damage to their photosynthetic systems. The results showed that the photosystem I had a higher tolerance to heat stress, and its ability to resist strong light damage was enhanced. In contrast, photosystem II was more sensitive to high temperatures, resulting in weakened resistance to strong light damage. Based on the visible symptoms of heat damage in the tea plants, burns were categorized as mild, moderate, or severe. Changes in the phenotype of the tea leaves are shown in Figure 6a.



a. Tea leaves[99]



b. Rice leaves under heat stress[123]



c. Rice leaves under Zn fertigation[13]

Figure 6 Morphological and physiological characteristics of crop leaves in response to leaf burning

Tian et al.[121] discovered that under sunlight exposure during summer and autumn, the chlorophyll content of the leaves decreased, the photosynthetic capacity and stress resistance of tea trees weakened, and leaf burning occurred easily. Xu et al.[123] reviewed the morphological and physiological characteristics of rice at different growth stages under heat stress conditions. During the vegetative stage, heat stress (42°C-45°C) causes leaf burning, increased water loss, impaired seedling and root growth, and death of seedlings. Rice is more susceptible to heat stress during the reproductive stage. Heat stress triggers a decrease in chlorophyll content, and a reduction in the ratio of variable fluorescence to maximum fluorescence (F_v/F_m) and the photosynthetic rate. The morphological and physiological characteristics of the rice under heat stress are shown in Figure 6b.

Leaf burning caused by fertigation is directly related to leaf absorption. When the fertilizer solution concentration exceeds a certain threshold, the balance of nutrients in the leaf tissue is disrupted, resulting in burning symptoms. The occurrence of leaf burning depends on the spraying performance and is influenced by multiple factors such as fertilizer type, application rate, concentration, timing, spraying method, and frequency.

Maas[124] analyzed data from 71 agricultural crops and found that the rate of absorption increased with increasing ion concentration and environmental temperature. Additionally, the frequency of spraying impacted the accumulation rate of salt ions, contributing to varying degrees of leaf burning. Ebert and Downer[125] demonstrated that the selection of the sprayer and application volume could alter droplet spectral properties, including droplet size, number, and velocity. This, in turn, affects the deposition distribution of pesticide droplets on target surfaces. The concentrated deposition resulting from these factors can cause leaf burning. Zhang[6] experimentally found that higher nitrogen concentrations in summer corn foliage primarily caused burning at the leaf edge and tip. However, the photosystem activity and photochemical efficiency of the non-burned areas significantly increased after one day of fertigation. A urea concentration of 0.4% was identified as the critical concentration for leaf burning. Xu et al.[13] conducted field experiments on rice sprayed with Zn fertilizer using different Zn sources, spraying rates, methods and frequencies. The results showed that UVA-based spraying significantly reduced the risk of residual fertilizer owing to its low Zn input and high Zn recovery rate. During the experiment, leaf burning symptoms were observed after fertigation, and photosynthetic performance was measured. The safe Zn application rate threshold of the chelated Zn fertilizer was 0.8%, approximately double that of $ZnSO_4$ and $ZnNO_3$. SPAD and net photosynthetic rate decreased with increasing Zn application rates, depending on the type of fertilizer used. Figure 6c shows the leaf burning phenomenon photographed after seven days of foliar Zn fertigation.

Current research on leaf burning caused by fertigation has mainly focused on the appearance and photosynthetic characteristics after burning. However, there is a lack of quantitative studies on the relationship between leaf burning and leaf absorption. There is also relatively limited understanding of the mechanisms by which factors such as fertilizer concentration and environmental temperature affect leaf burning.

4 Discussion: problems and prospects

Inefficiencies in foliar interception, leading to wasted fertilizer and water loss, and leaf burning or low fertigation concentration resulting from uncertainties in fertilization, have emerged as primary factors limiting the widespread use of fertigation. Therefore, it is crucial to integrate the characteristics of liquid droplets and foliage, understand foliar interception rules during the process of water-fertilizer integration, and comprehend the mechanism of leaf burning. The state-of-the-art studies were reviewed from two main aspects of this issue, and the interaction mechanism of droplets and foliage from this perspective is illustrated in Figure 7. These studies have deepened our understanding of the complex interactions between fertigation droplets and foliage and have contributed to a more in-depth exploration of the key factors in fertilization and irrigation processes. Despite the significant advances in this field, several challenges warrant further systematic exploration.

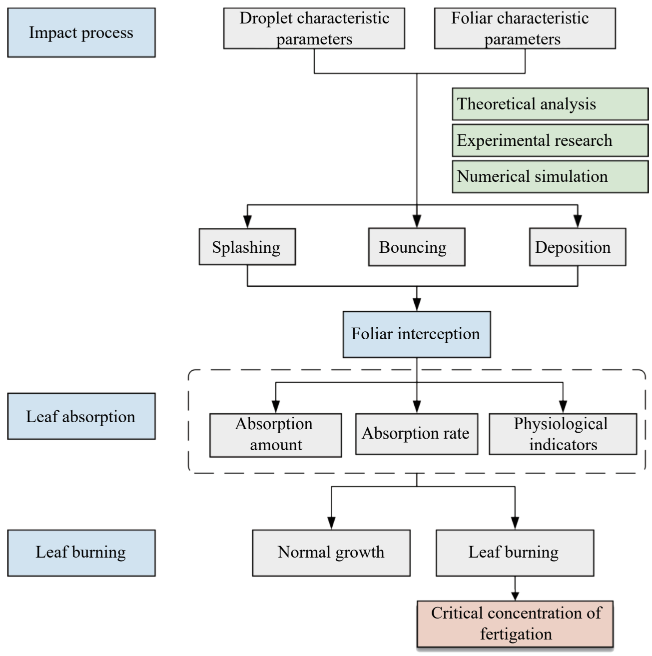


Figure 7 Interaction mechanism of droplets and foliage

1) Particular attention has been paid to recent theoretical, experimental, and numerical efforts to explore the dynamic behavior of droplets and foliage. However, to the best of our knowledge, research on the droplet impingement process during sprinkler fertilization is lacking. The droplet size in sprinkler fertigation is typically large, resulting in a high kinetic energy upon contact with the leaf surface at a small impact angle, leading to a high-energy impact. Plant leaves in nature are generally fixed by roots and suspended on branches, which impart dynamic characteristics that cause leaf oscillations upon droplet impact. Further numerical and theoretical efforts are required to analyze the dynamic characteristics of foliage and investigate the dynamic impact of fertilizer droplets on foliage. Current research has predominantly focused on the results of the initial impact, overlooking the process of multiple droplets shattering and rebounding, which leads to deposition. A schematic of the impact process is shown in Figure 8. To enhance the effectiveness of future research, it is essential to study phenomena such as multiple droplets splashing and rebounding while also considering the dynamic surface characteristics of leaves for further analysis.

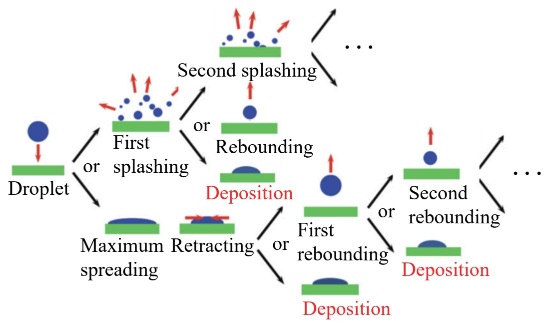


Figure 8 Schematic diagram of the impact process

2) During sprinkler irrigation and fertigation, foliar interception is influenced by the impact process. Existing mathematical models are only discrimination formulas that determine whether the

corresponding impact behavior occurs or not, without calculating the actual deposition amount. Future research should combine experimental data and image recognition technology to further understand the droplet impact process, establish the relationship between the impact behavior and actual deposition amount, and thus comprehend the law of leaf interception. This will enable us to develop universal theoretical models that can predict leaf fertilizer retention by integrating foliar characteristic analyses. Upon understanding foliar interception laws, it is crucial to consider the influence of canopy structure on leaf interception and analyze the macroscopic canopy deposition under different sprinkler conditions, thus enhancing the practical importance of the sprinkler fertigation scheme.

3) Currently, the amount of nutrient absorption and the corresponding pathways for foliar interception under different fertilizer concentrations and ambient temperatures remains unclear. Future studies should explore the relationship between nutrient absorption rates and foliar interception in response to varying fertilizer concentrations and interception levels. It is essential to investigate the underlying mechanisms that influence foliar interception, leaf absorption, and leaf burning. Ultimately, it is necessary to determine the critical fertigation concentration required to prevent leaf burning under different spraying conditions. These efforts provide a theoretical foundation for the precise establishment of an integrated fertilization system.

5 Conclusions

This review provides a comprehensive analysis of the dynamic interactions between droplets and foliage during sprinkler fertigation. By analyzing and comparing relevant literature, the study summarizes the current state of two main aspects of this issue, the major challenges, and the proposed solutions for future research.

This article commences by reviewing the recent experimental, theoretical, and numerical efforts to explore the impact process and its underlying mechanisms. The experimental results, theoretical models and numerical methods have revealed the complex mechanisms of fertigation droplets on foliage, influenced by various droplets and foliage characteristics.

Moreover, this study analysed the dynamic interaction between the droplet and foliage, including foliar interception, leaf absorption, and leaf burning, which are influenced by the impact process. It discusses the challenges that hinder the widespread use of fertigation, such as inefficiencies in foliar interception and uncertainties in fertilization, which require further exploration.

In conclusion, this paper proposes future perspectives to promote fertigation technology, such as research on the dynamic impact of fertilizer droplets on foliage, the development of universal models for leaf fertilizer retention, and the determination of critical fertigation concentrations under varying conditions to prevent leaf burning.

The advancement and application of water-fertilizer integration technology in sprinkler irrigation have notably advanced in recent years. However, achieving efficient and effective fertilizer application requires a deeper understanding of the principles of foliar interception through innovative technologies and an investigation into the underlying mechanisms governing foliar interception, leaf absorption, and leaf burning. Utilizing 3D modeling of oscillating blades can further explore the dynamic impact. Advancements in image recognition technology and data analytics can aid in establishing the relationship between impact behavior and actual interception amount. Accurate measurement methods, such as in situ detection techniques, are invaluable for studying the mechanism of foliar nutrient absorption and the onset of leaf burning symptoms. Continuous technological advancements and improvements in agricultural practices hold promise for enhancing the precision and targeting of fertigation, thereby mitigating fertilization uncertainties. This progress will provide theoretical support for addressing practical production issues, fostering innovation, and facilitating the large-scale development of water-fertilizer integration technology.

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