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DYNAMIC SPREADING PROCESS OF PESTICIDE DROPLETS IMPACTING ONTO TARGET LEAF SURFACES

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Key words: Kresoxim-methyl droplets, Leaf surface, High-speed camera technique, Spreading process

Abstract

The study on dynamic spreading process of pesticide droplets impacting onto the leaf surfaces would potentially assist in efficiently spraying pesticides and finding out the method to decrease pesticide waste. To further understand the spreading process, relevant experiments were carried out. Firstly, the spreading processes of pesticide droplets impacting onto different target surfaces with different physicochemical properties were observed, it was obvious that spreading coefficient of pesticide droplets on different target surfaces were various. Afterwards, the droplets of kresoxim-methyl and distilled water impacted onto target surfaces, respectively. Because droplets possess different properties, the spreading speed and spreading coefficient of kresoxim-methyl droplets were greater than those of distilled water. Then, kresoxim-methyl droplets impacted onto target surfaces at speed of 1.87, 2.34 and 2.72 m/s, respectively. It was confirmed that the spreading coefficient of droplets showed positive correlation with the impact speed. At last, kresoxim-methyl droplets impacted onto target surfaces at different impact angle. It was proved that the greater the impact angle, the greater the spreading coefficient. Above all, properties of target surfaces, properties of droplets, impact speed and impact angle have great effects on spreading of pesticide droplets on target surfaces. It is of important significance for further research on dynamic trend, spreading process and kinetics of pesticide droplets impacting onto target surfaces. What is more, utilization efficiency of pesticides would be maximized in the future.

Introduction

In the process of pesticide spraying, pesticide droplets rapidly spread and deposit on the leaf surfaces is the most ideal state. The process is affected by many factors, for example, impact speed (Kwak *et al*. 2011), impact position, impact angle (Šikalo and Ganić 2006), properties of target surfaces (Yu *et al*. 2009), properties of droplets (Gaskin and Pathan 2006) and so on.

In recent decades, a lot of studies on behaviors of water droplets impacting onto the solid surface have been reported (Negeed 2010, Negeed *et al*. 2013, Gatne *et al*. 2009), including relatively little studies on behaviors of pesticide droplets impacting onto leaf surfaces (Mandre *et al*. 2009, Dong *et al*. 2014, Chen *et al*. 2011). Quan studied the effect of solid surfaces of different materials having different roughness and impact speed on wetting behavior of droplets on solid surfaces (Quan *et al*. 2009). The equation of critical impact speed deduced from the structural parameters of various super-hydrophobic surfaces was described by Jung and Bhushan (Jung and Bhushan 2008). Also the spreading process of droplets impacting onto solid surface was studied, including the effect of various factors on spreading factor of droplets (Bi *et al*. 2012).

Using high-speed camera to obtain dynamic image of droplets spreading on the inclined surface, the result showed that deformation degree of droplets increased as impact angle decreased in the range of 28° - 74.7° (Liang *et al*. 2013).

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Otherwise, the research on spreading process of droplets impacting onto the leaf surfaces of water spinach, wheat, soybean and so on showed that droplets could rebound from leaf surfaces of water spinach and wheat (Reichard *et al*. 1998). In the experiment of spray droplets impacting onto leaf surface of soybean, the result showed that when K < 57.7 ($K = \sqrt{We\sqrt{Re}}$, Sommerfeld number), the droplets easily deposit and retract, if K > 57.7 the droplets could splash; meanwhile if the leaf surface placed at 28° and 44° was densely villous (K < 57.7), there were splashing phenomena (Jia *et al*. 2013).

In precision agriculture, it is necessary to accurately spray pesticides so that the spray droplets deposit on leaf surfaces of target crops and spread. However, compared to most studies which were about the process of water droplets impacting onto solid surface, relatively little attention was paid to pesticide droplets. In this paper, using high speed imaging techniques to obtain the dynamic spreading process of pesticide droplets impacting onto leaf surfaces of targets, we further studied the spreading process. It has considerable practical significance.

Materials and Methods

Leaves of corn and pumpkin, glass slide were used as target surfaces. 0.5 g/l kresoxim-methyl compounded by 50% kresoxim-methyl water dispersible granule (in China) and distilled water were applied with a microsyringe to the target surface. The high-speed camera (Phantom v9.1, USA) was controlled with a PCC software.

The size of microsyringe was 1 ml (0.6 mm in diam and 70 mm in length of syringe needle). To ensure that the volume of droplets was very similar, uniform and slow force was required to produce droplets. The formula for calculating *R* was as follows:

$$R = \left(\frac{3R_1\gamma}{2\rho g} \right)^{1/3} \tag{1}$$

where *R* is the radius of droplets, mm; R_1 is the radius of syringe needle, mm; γ is the surface tension of droplets, mN/m; ρ is the density of droplets, g/cm^3; *g* is the acceleration of gravity, m/s^2.

The dropping height was set at 180, 280 and 380 mm, and the impact speed was calculated according to the follows (Kawanami *et al*. 1997)

$$v = \sqrt{\frac{g}{\alpha}(1 - e^{-2\alpha h})} \tag{2}$$

$$\alpha = \frac{3c\rho_{air}}{8\rho_d R} \tag{3}$$

where *R* is the radius of droplets, mm; *h* is the dropping height of droplets, mm; *g* is the acceleration of gravity, m/s^2; *v* is the impact speed of droplets onto surface, m/s; *c* is the air resistance coefficient; ρ_{air} is the density of air, kg/m^3; ρ_d is the density of droplets, kg/m^3.

In this experiment, leaves of corn and pumpkin in the exuberant growth period were obtained from greenhouse of College of Biological and Agricultural Engineering, Jilin University. The environmental temperature and humidity were 24 ± 1ºC and 65%, respectively. The droplets was regarded as sphere, and spreading coefficient was defined as

$$K = \frac{d_t}{d_0} \tag{4}$$

where K is the spreading coefficient; d_0 is initial diameter of droplets, mm; d_t is the spreading diameter of droplets at different moments, mm.

Fig. 1. Operation interface of PCC software controlling high-speed camera.

Droplets impacted onto the target surface at the speed of 1.87, 2.34 and 2.72 m/s. Moreover, angle of the inclined surface was 0°, 20°, 40° and 60°, respectively. Firstly, leaves of corn and pumpkin were smoothly stuck to the glass slide. Then the samples were placed on a turn table, the lens of high-speed camera was adjusted so that the samples clearly appeared in the visual field. Next, the movable bracket was adjusted to a predetermined height, where droplets dript from a microsyringe. The high-speed camera recorded the whole spreading process of droplets.

Results and Discussion

The surfaces were leaf surface of corn, leaf surface of pumpkin, and glass slide surface, respectively. They were applied to analyze the effect of surface properties on spreading process of droplets adhered to target surfaces.

Fig. 2 was a part of the spreading process of the kresoxim-methyl droplet impacting at speed of 1.87 m/s onto leaf surface of corn placed at angle of 0°. t = –1 ms represented the state of the droplet would immediately contact the leaf surface. When the droplet had just impacted onto the leaf surface (t = 0 ms), the contact area of droplet and leaf surface was small, droplet could be approximately considered as spherical. Then the droplet spread and reached the maximum diameter until 3 ms. The droplet began to retract at 4 ms. Next, it started to oscillate back and forth on the leaf surface of corn at 10 ms. Finally, at 8 s, the droplet still oscillated on the leaf surface, and could not reach an equilibrium state.

When the kresoxim-methyl droplet impacted at 1.87 m/s onto leaf surface of pumpkin placed at 0°, the spreading speed of droplet on leaf surface of pumpkin was very fast. At 1 ms, the droplet began to spread quickly and then the spreading diameter of droplet reached the maximum in 3 ms from Fig. 2. After that, the droplet was gradually absorbed, and there was no retraction phenomena in the whole process.

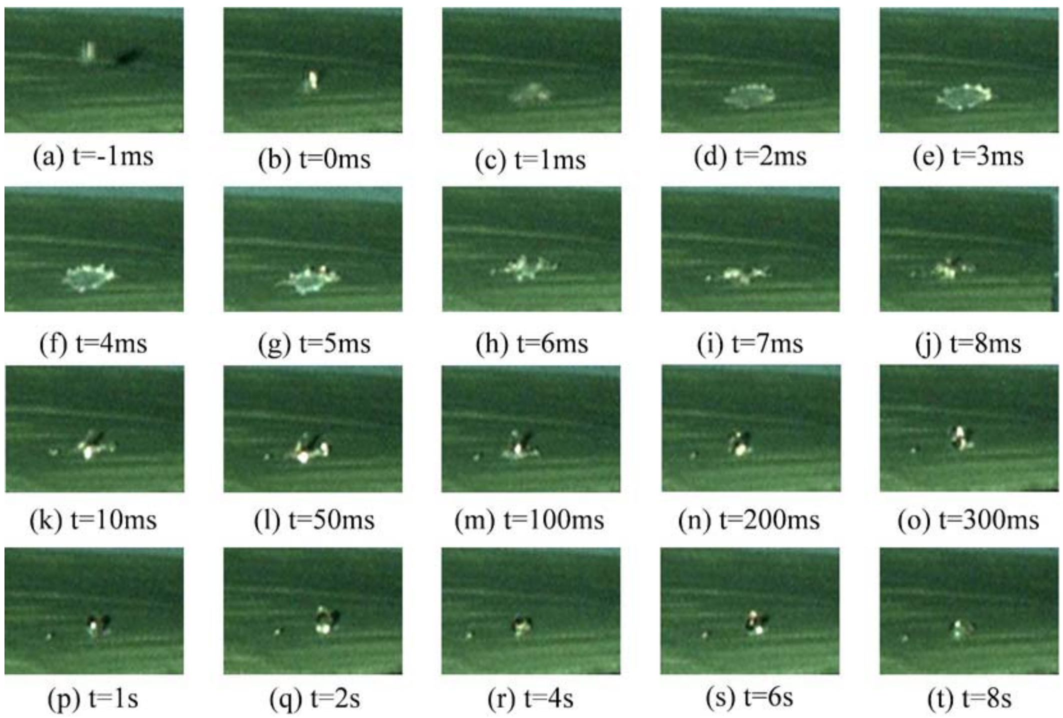

Fig. 2. The spreading process of the kresoxim-methyl droplet impacting onto leaf surface of corn (at a speed of 1.87 m/s, at an angle of 0°).

When t = 0 ms, the droplet had just struck to the glass slide surface, and became conical. At t = 1 ms, the droplet began to spread on the glass slide surface. There were no retraction and oscillation phenomena in the whole spreading process. The droplet gradually deposited on glass slide surface with the time.

Fig. 3 showed the spreading process of kresoxim-methyl droplets impacting at speed of 1.87 m/s onto leaf surfaces of corn and pumpkin, glass slide surface arranged at 0°. Along with the time, the droplet began to gradually spread on target surface. The initial spreading coefficient of the droplet on leaf surface of corn was the maximum, followed by glass slide surface and leaf surface of pumpkin. Moreover, the droplet oscillated back and forth on leaf surface of corn, but there were no oscillation phenomena on leaf surface of pumpkin and glass slide surface. It could be due to the differences of chemical component and structure of three target surfaces. The dense burrs on leaf surface of pumpkin contributed a lot to the spreading of the droplet. While glass slide surface was hydrophilic, droplet could easily spread on it. A lot of soft epidermal hair on leaf surface of corn would lead to slow the droplet spreading.

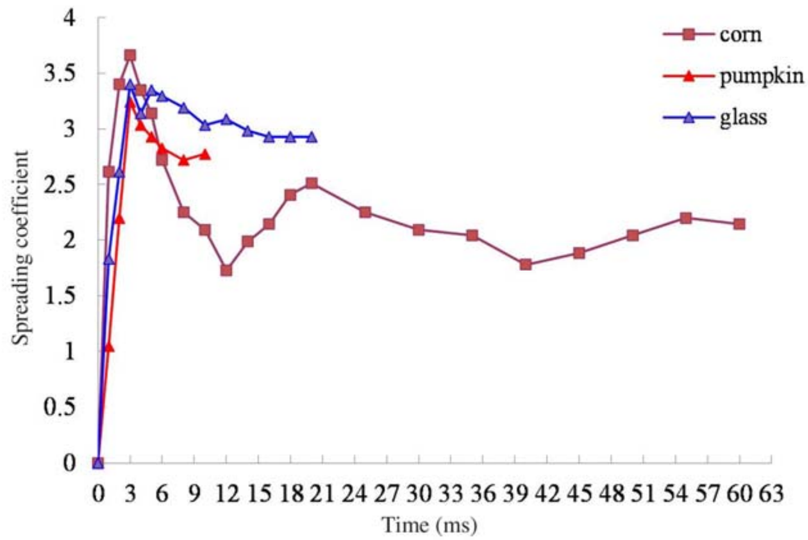

Fig. 3. Spreading coefficient of kresoxim-methyl droplets impacting onto different target surfaces (at s speed of 1.87 m/s, at sn angle of 0°).

Corn leaves were chosen as the testing material to study the effect of different impact positions on droplets spreading.

As shown in Fig. 4, when t = 0 ms, the droplet contacted leaf surface of corn. From 1 ms to 3 ms, the spreading diameter of the droplet reached the maximum. Because the droplet impacted onto leaf vein of corn, the droplet began to break into some small droplets which dispersed along the vein at 4 ms, while a few droplets rebounded. After 15 ms, a few droplets reached ends of the leaf along the vein and left from the leaf surface. At t = 8 s, there were only several small droplets stayed on the leaf surface, and most small droplets broke away from the leaf surface.

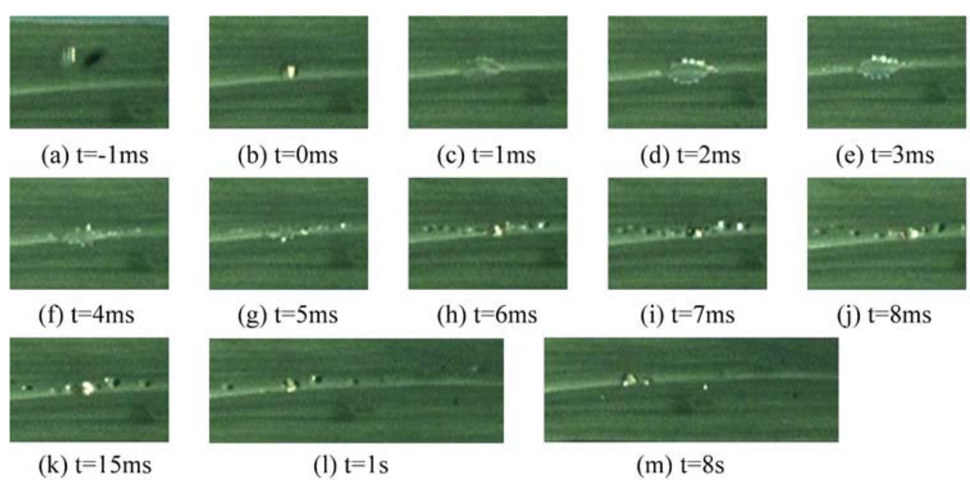

Fig. 4. The spreading process of the kresoxim-methyl droplet impacting onto leaf vein of corn (at a speed of 1.87 m/s, at an angle of 0°).

As shown in Figs 2 and 4, different impact positions of droplets impacting onto leaf surface of corn lead to different spreading processes of droplets. The two droplets began to spread at 0 ms. After 4 ms, the behaviors of the two droplets were different. The droplet that impacted onto leaf surface of corn began to oscillate. After 8 s, they did not completely spread. While the droplet that impacted onto leaf vein of corn began to break at 4 ms. Most small droplets broke away from the leaf and only a few stayed on the leaf surface at 8 s. It could due to the different positions of droplets impacting onto leaf surface of corn lead to the different force applied on the droplet. When the droplet impacted onto leaf vein of corn, the impacting force was greater than that of droplet impacting onto leaf surface of corn.

In this experiment, droplets consisted of kresoxim-methyl solution and distilled water, respectively. The properties of them are as follows.

Table 1. The properties of distilled water and kresoxim-methyl.

Liquid	Density kg/m^3	Surface tension mN/m	Viscosity Pa·s
Distilled water	998	72	1.005×10^{-3}
Kresoxim-methyl	1258	36.8	-

The kresoxim-methyl droplet impacted onto the leaf surface of pumpkin horizontally arranged at the speed of 2.34 m/s, it deposited fast on the leaf surface in 3 ms (Fig. 5). If the droplet consisted of distilled water, it gradually spread in 1 - 3 ms, and then started to retract followed by spreading. That is to say, there were oscillatory phenomena, but the variance was far less than the behavior of the droplet on leaf surface of pumpkin (Fig. 2).

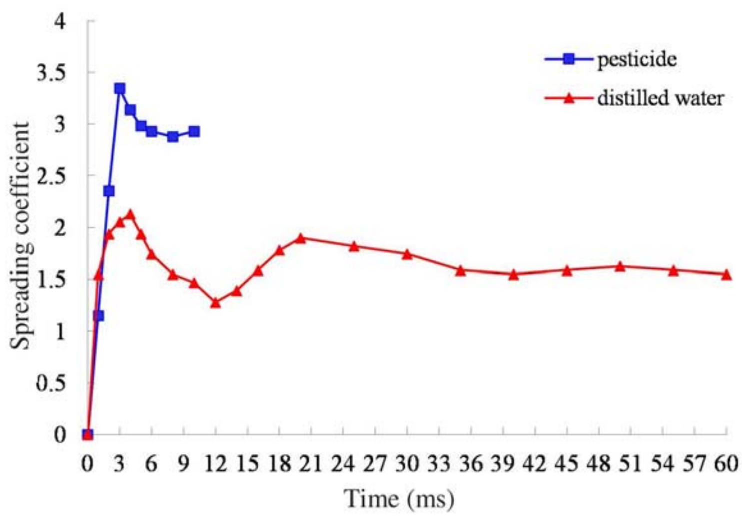

Fig. 5. Spreading coefficient of different droplets impacting onto leaf surface of pumpkin (at a speed of 2.34 m/s, at an angle of 0°).

Under the same condition, spreading speed and coefficient of kresoxim-methyl droplets on leaf surface of pumpkin were obviously greater than those of distilled water (Fig. 5). This may be related to the surface tension of the two liquids, the surfactant in kresoxim-methyl solution decreased the surface tension of the liquid, so that the kresoxim-methyl droplet could be well adhered to leaf surface of pumpkin. The surface tension of distilled water was significantly higher than the critical surface tension of pumpkin leaves, therefore it was not easy to rapidly and completely spread on leaf surface of pumpkin.

The droplet impacted onto the target surface at the speed of 1.87, 2.34 and 2.72 m/s. As shown in Fig. 6, the kresoxim-methyl droplet impacted at the speed of 2.34 m/s onto the leaf surface of corn which was placed at 0°, it gradually spread in 1 ~ 3 ms. Next, the droplet began to splash to the surrounding at 4ms, dispersing into many small droplets and then some of them escaped from the leaf surface. At the end, the droplets did not fully spread.

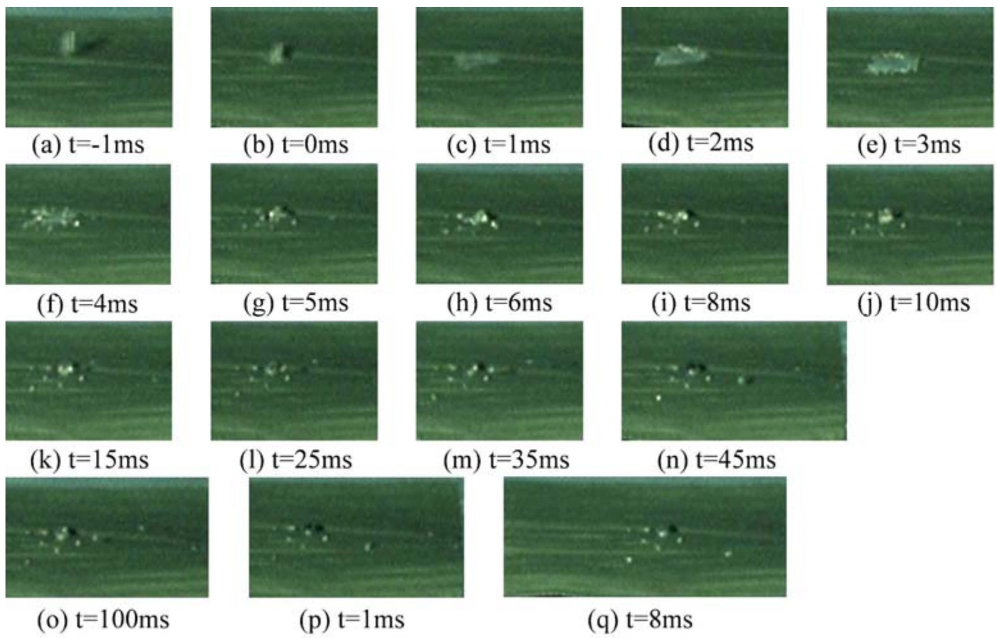

Fig. 6. The spreading process of the kresoxim-methyl droplet impacting onto leaf surface of corn (at a speed of 2.34 m/s, at an angle of 0°).

When the kresoxim-methyl droplet impacted at the speed of 2.72 m/s onto the leaf surface of corn which was placed at 0°, its behavior was similar to that impacted at speed of 2.34 m/s, as shown in Fig. 6. Finally, some small droplets deposited on the leaf surface and did not fully spread.

In Fig. 7, it was found that there were no broken phenomena rather than oscillatory when the kresoxim-methyl droplet impacted onto leaf surface of corn horizontally arranged at the speed of 1.87 m/s. On the contrary, when the impact speed were 2.34 and 2.72 m/s, behavior of the two droplets were similar, both of them spread at first, and then dispersed into many small droplets. Because some little droplets dropped out of the leaf, and some got together, the final spreading coefficient of droplets which impacted at speed of 2.34 and 2.72 m/s decreased a lot.

Impact angle was defined as the angle formed between leaf surface and horizontal plane, here 0, 20, 40 and 60° were taken into account. In this experiment, kresoxim-methyl droplets impacted onto leaf surface of corn placed at different angle at speed of 2.34 m/s.

From Fig. 8, the impact angle was 0°, original spreading diameter was greater than that of impacting onto leaf surface of corn at speed of 1.87 m/s (Fig. 2). The droplet gradually spread, and there were no oscillatory phenomena but broken phenomena.

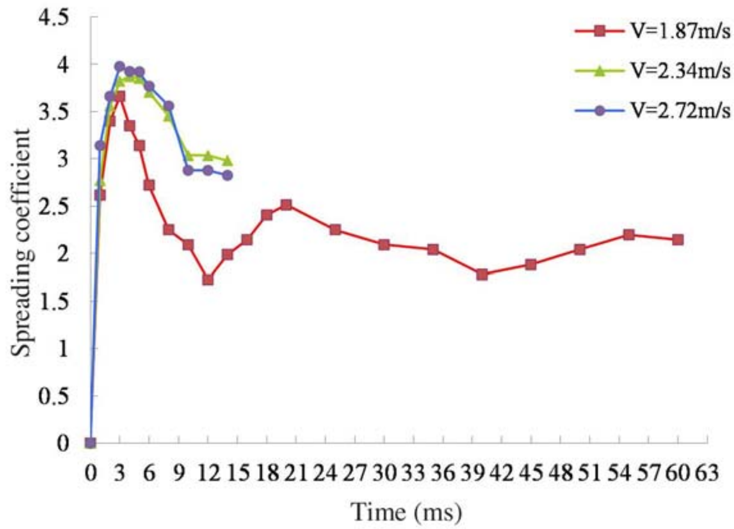

Fig. 7. Spreading coefficient of the kresoxim-methyl droplet impacting onto leaf surface of corn at different speeds (at an angle of 0°).

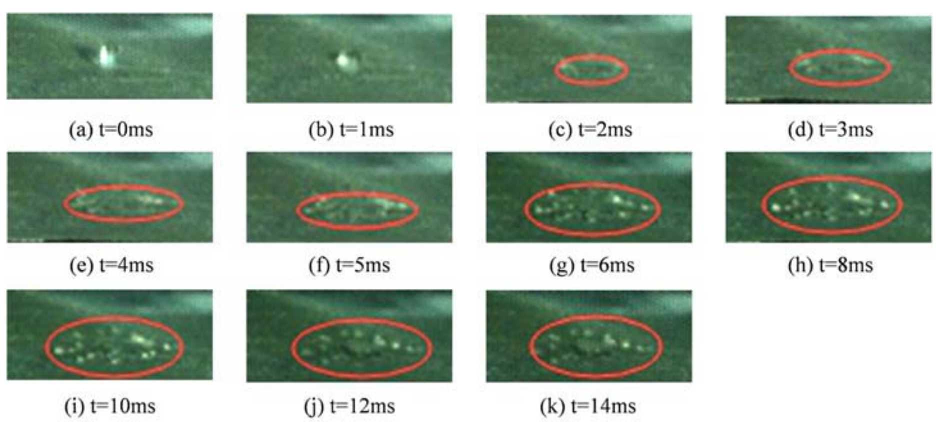

Fig. 8. The spreading process of the kresoxim-methyl droplet impacting onto leaf surface of corn (at a speed of 2.34 m/s, at an angle of 0°).

When the impact angle was 20°, there was no retraction phenomena, the droplet broke into some little droplets and did not get together. The spreading diameter constantly increased with the time until the spreading was achieved, and no rebound phenomena was found.

When the impact angle was 40°, the droplet spreads fast. But some droplets flowed down along the inclined plane. Be different from that of 20 and 40°, rebound phenomena were found when the impact angle was 60°. Also some droplets flow down along the inclined plane, therefore some pesticides were wasted.

Fig. 9 showed that when kresoxim-methyl droplets impacted at speed of 2.34 m/s onto leaf surface of corn placed at 0, 20, 40 and 60°, the spreading coefficient of the droplet at angle of 60° was the maximum, followed by those at angle of 40, 20 and 0° in descending order. That is to say, within a certain range the greater the impact angle, the greater the spreading coefficient.

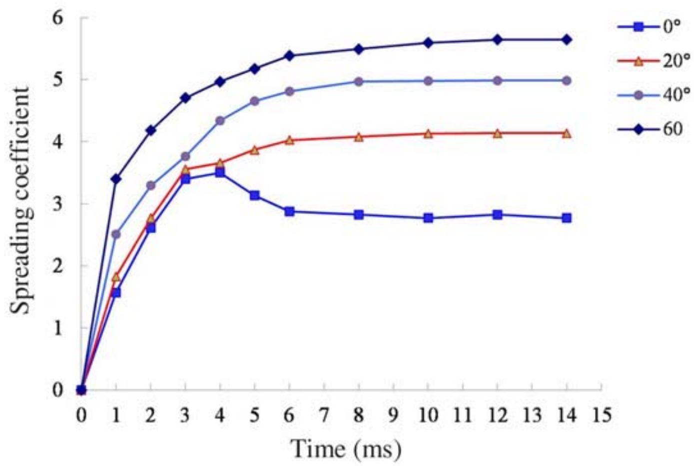

Fig. 9. The spreading process of the kresoxim-methyl droplet impacting onto leaf surface of corn (at a speed of 2.34 m/s, at an angle of 0, 20, 40 and 60°).

The spreading processes of pesticide droplets impacting onto different target surfaces horizontally arranged at speed of 1.87 m/s were observed, the result showed spreading process and spreading coefficient of pesticide droplets on different target leaf surfaces with different physicochemical properties were various. Besides, spreading speed and spreading coefficient of kresoxim-methyl droplets were obviously greater than those of distilled water droplets, indicating that the properties of droplets had a great effect on spreading process of droplets. Therefore, surfactants could apply to pesticides for improving the usage performance of pesticides. Moreover, the variation trend of the spreading coefficient of droplets was in accordance with the impact speed, which potentially guided for the manufacturing of sprayers to a certain extent. At last, spreading coefficient increased with impact angle and rebound phenomena began to appear at angle of 60°. To improve the spreading process of pesticide droplets on target leaf surfaces, the different angles of leaves should be considered.

Therefore, it is of important significance for further research on dynamic trend, spreading process and kinetics of pesticide droplets impacting onto target surfaces. After further investigating the spreading process of pesticide droplets on leaf surfaces, it contributes to decrease the loss of pesticides and maximize utilization efficiency of pesticides.

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