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EDITED BY
Xin Ning,
Institute of Semiconductors (CAS), China

REVIEWED BY
Gabriel Gomes,
State University of Campinas, Brazil
Adebola Abosede Adeyi,
University of Ibadan, Nigeria

*CORRESPONDENCE
Zhen Lin
✉ zhenlin@sanyau.edu.cn

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Research and experiment of electrostatic spraying system for agricultural plant protection unmanned vehicle

Zhen Lin[1]*, Jinye Xie[1], Shuo Tian[2], Xihong Wang[3], Wenfu Sun[1] and Xiaoqin Mo[1]

[1]Institute of Technology, University of Sanya, Sanya, Hainan, China, [2]Sanya Xiaoxiang Technology Co., Ltd., Sanya, Hainan, China, [3]Sanya Institute of Technology, Sanya, Hainan, China

Introduction: The traditional spraying system is not suitable for agricultural plant protection in small plots due to its disadvantages of weak droplet refining ability, small spraying area, large pesticide consumption, and high manual spraying cost. At present, spraying pesticide is the main way to resist crop diseases and insect pests. The utilization rate of pesticide is only 38.8% in China, which leads to serious waste and serious environmental pollution. It is necessary to develop advanced plant protection equipment and pesticide application technology to solve the problem. The combination of agricultural plant protection vehicle and electrostatic spray technology may solve the problems of spraying efficiency, droplet adsorption rate and evenness. It is of great significance to improve the efficiency of plant protection and pesticide utilization.

Methods: In this paper, the principle of droplet charging is described, an electrostatic spraying system is designed and tested, and the effects of charging voltage and pump pressure on the droplet charge ratio and droplet size are analyzed.

Results and discussion: This study has shown that electrostatic spraying systems are suitable for agricultural plant protection unmanned vehicles.

KEYWORDS

plant protection, electrostatic spray, plant protection unmanned vehicle, charge mass ratio, precision agriculture

1. Introduction

If people eat vegetables, fruits, and other agricultural products with pesticide residues for a long time, it is extremely harmful to their health. As people pay more attention to pesticide residues in agricultural products and food safety, higher requirements are also put forward for plant protection machinery. China's plant protection machinery is mainly manual and small motorized medical machinery. This kind of plant protection operation has high labor intensity, low work efficiency, serious environmental pollution, and serious waste of medicinal solution. At present, the effective utilization rate of pesticides in China is only 20–30%, which is far lower than the 60–70% in developed countries. Electrostatic spraying technology is a high-tech technology that can form charged droplets of pesticide liquid, improve the adsorption effect and accuracy, and has the advantages of high deposition efficiency, comprehensive and uniform adhesion, pesticide saving and environmental protection, and is suitable for large-scale orchards. It is different from the traditional plant protection equipment.

The traditional pesticide spraying method is direct spraying, which is easy to cause uneven spraying, incomplete adhesion and a lot of waste, resulting in environmental pollution and low spraying efficiency. With the emphasis on crop safety and the higher demands of farmers on plant protection efficiency and cost, electrostatic spraying technology applied in industry, printing, medicine, and other fields has been improved and applied in agriculture. Electrostatic spray technology belongs to modern agricultural technology. It can make charged droplets when pesticide droplets are ejected, which is different from the traditional washing method. Electrostatic spray is only 40 microns of charged droplets, which can spray the objects evenly and completely adsorb (Manfred et al., 1990; Shuming, 2011). With the agricultural plant protection unmanned vehicle, unmanned electrostatic spraying can be realized, so as to reduce the cost, improve the spraying efficiency, improve the droplet adsorption rate, and make the spraying more uniform and drug-saving (Xiongkui, 2004). In view of the experiment of electrostatic spraying device, explored the effect of electrostatic spray deposition. The results showed that electrostatic spray increased by 162% compared with the sprayed leaf backing. UAV electrostatic spray system experiments of Yu et al. (2015) show that static electricity can effectively increase the deposition density. Yanlun et al. (2018) designed an electrostatic spray device mounted on the UAV. The results show that the classical spray has advantages over the ordinary spray in the uniformity of droplet deposition. Yongliang et al. (2020) analyzed the present situation and prospect of the intelligent development of orchard wind sprayer, and the results showed that the integration of multi technology, the integration of agricultural machinery and agronomy, and the integrated application of high and new technology will become the trend of orchard spraying air mist conveyor. Ziyu et al. (2009) designed the variable spray system of vehicle sprayer, designed to improve the utilization rate of pesticides and reduce pesticide residues and environmental pollution. Bo and Lingwei (2018) explored the droplet deposition distribution under different operating conditions and environments. The results showed that the spray height, walking speed, spray flow, air humidity, temperature, and wind speed were significantly positively correlated with the droplet deposition distribution and pesticide efficacy.

Electrostatic spraying is a technology that uses high-voltage electrostatic technology to make the atomized liquid particles carry the same charge and break into smaller droplet particles to form a group of charged droplet particles during the process of liquid atomization through nozzles. Electrostatic spraying technology charges the droplets and forms an electrostatic field of mutual adsorption with the crops, which can effectively improve the uniformity of the droplets, the deposition amount of the droplets on the target, the uniformity of the distribution of the droplets, and the adsorption to the crops. At present, electrostatic spraying technology plays an important role in many fields (dust removal, spraying, combustion, pesticide spraying, etc.). Especially in the field of pesticide spraying, its advantages are particularly prominent. The smaller the droplet size of the liquid medicine reaches the target, the more uniform the distribution and the higher the utilization rate of the pesticide are. In this way, raw materials and water resources can be relatively saved, thereby improving resource utilization and reducing environmental pollution.

Electrostatic spray is a spray method that charges the sprayed droplets through high-voltage electrostatic generator. Electrostatic spray technology is an advanced application technology in the world. Electrostatic spraying can be divided into three processes: one is the atomization process of the liquid through the atomizer nozzle, the second is the charging process of the liquid droplets after atomization, and the third is the delivery process of the charged droplets to the target. During the charging process of the deposition process on the target, a negative high-voltage power supply is used to charge, so the charge of the droplets is the same charge, so that the droplets are repelled by the same charge, so that the sprayed area of the droplets is larger. No aggregation and merging of droplets will occur. Under the attraction of the opposite charges on the surface of the target, the droplets are moved to the target along the lines of electric force by the electric field force, and the electric force lines are distributed in various parts of the target object, so that the droplets move to various positions of the target. Therefore, the droplets of electrostatic spray can not only be adsorbed on the front of the target, but also can be adsorbed on the back of the target and other hidden parts, which increases the effective deposition of droplets and increases fog. In the process of electrostatic spraying, when groups of discrete droplets sprayed from the nozzle pass through the charged area, under the action of the electrostatic field generated by the high-voltage electrode, the droplets will be charged and carry the same charge. The electrostatic field generated by the high-voltage electrode strengthens the unstable ripple of the liquid. The instability of the droplet surface is enhanced. When its deformation exceeds the critical value of surface tension, the droplet will be further broken and atomized, the diameter of the droplet will become smaller, the number of droplets will increase, and the surface area per unit mass of the droplet will increase and become larger, thereby increasing the charge on the surface of the droplet, which is conducive to the movement of the droplet to the target. Since the jet droplet carries a charge, there is a certain adsorption capacity between the droplet and the target, which will directly affect the spraying quality of the liquid. The factors that affect the droplet charge include the structure of the electrode, the charging method, the physical properties of the liquid medicine, and environmental factors. These will directly affect the charging effect of the droplets. However, there is no clear relational formula for the influence of these factors on the charging capacity, it can only be analyzed qualitatively or needs to be verified by experiments.

2. Selection of droplet charging mode

2.1. Droplet charging mode

Under the action of the electric field force, the droplets can be quickly adsorbed to the surface of the plant, and the charged droplets can also move backward to the back of the target under the electrostatic field force. In agricultural application, the adsorption rate of droplets is one of the important factors to ensure the effect of plant protection, so it is particularly important to select an appropriate charging method. At present, the commonly used droplet charging methods are contact charging, corona charging and induction charging. The specific principles are as follows. The droplet charging method is used for illustration. This is the method used. I added the droplet charging mode. Compared with the simple droplet impact charging, the new charging mode can increase the output voltage by about 2.3 times, and thus can match the high-voltage electricity environment.

2.1.1. Contact type

The contact charging method is to make the discharge electrode directly contact with the liquid medicine and form a circuit with the ground wire (as shown in Figure 1), so as to charge the liquid medicine and form charged droplets after atomization through the nozzle. The charging effect of contact charging method is very good, but in the working process, due to the direct contact between the nozzle and the discharge electrode, it is easy to cause leakage, endanger the operator or other electronic equipment, and have very high requirements for insulation.

2.1.2. Corona type

At present, corona charging is one of the most widely used methods in electret charging. It is composed of a needle-shaped electric level, a flat electric level and a metal grid. The corona charging method is to install the discharge electrode near the nozzle. When the high-voltage static electricity is released, the tip discharge phenomenon will be generated, so as to ionize the air near the nozzle (as shown in Figure 2) and generate charged particles. When the ejected droplets pass through the ionized area, they will collide with the charged particles and take charge. The voltage of corona charging mode is usually above 20 kV to achieve better charging effect, and has high requirements for voltage.

2.1.3. Inductive

Inductive charging is to connect the electrostatic power supply with the inductive electrode to form an inductive electric field, as shown in Figure 3. Under the action of the induced electric field, the charge distribution of the ejected droplet will change, and the charge with the same polarity as the induced electrode will be introduced into the earth, so the droplet will carry the charge with the opposite polarity to the induced electrode. Inductive charging has low voltage requirements and is widely used.

2.2. Charging mode selection

The principles of the above three charging modes are quite different, so the most suitable charging mode should be found out in the design (Chen, 2014). In terms of charging effect, the effect of contact charging is much better than corona charging and induction charging (Wumei and Chaozhen, 2009), but in practical application, the insulation is difficult to ensure. Corona charging has the characteristics of good insulation, but the required voltage is high (Fangli, 2012). The voltage required for inductive charging is about 10 kV, the structure is relatively simple and the cost is low, so inductive charging is used as droplet charging in this study.

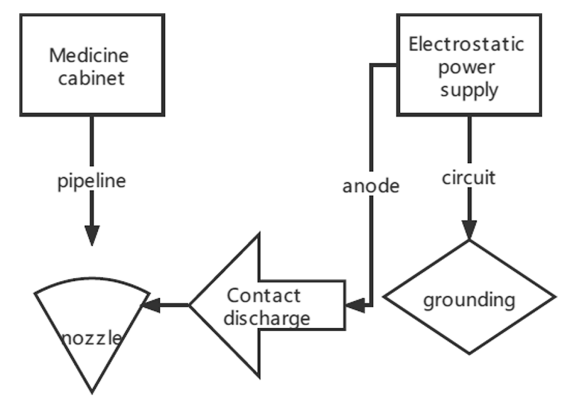

FIGURE 1
Contact charge schematic diagram.

2.3. Principle of inductive droplet charging

The study uses inductive charging to charge the droplet. After the inductive electrode is energized, the induced electric field can be generated. When the droplet passes through, the same charge in the droplet and the electrode will be repelled, so the droplet with heteroelectricity will be formed. The two ends of the DC (direct-current, DC) power supply are, respectively, connected with the sprayer grounding and the inductive electrode. During the working process, the induction electrode and the droplet can be compared to the polar plate of the capacitor, and the air between them is the insulating medium of the capacitor (Figure 4 is an equivalent circuit diagram. The number 1 is the induction electrode, and the number 2 is the spray liquid film).

The equivalent capacitance calculation formula is:

$$C = \frac{\varepsilon s}{d} \tag{1}$$

Where: ε is the air dielectric constant between capacitor plates, s is the positive area of capacitor plates, and D is the distance between capacitor plates. The capacitance value is directly proportional to the area of the capacitor plate, and the distance between the capacitor plate and the liquid film is inversely proportional (Liqin et al., 2008).

3. Electrostatic spray system design

3.1. System composition

Figure 5 is a schematic diagram of the system. The system consists of a medicine box, a water pump, a pressure gauge, a pressure regulating valve, a DC power supply, an electrostatic power supply, and an electrostatic sprinkler. The working process is as follows: turn on the power supply of the water pump, the water pump will pump the liquid medicine in the medicine box into the nozzle through the pressure regulating valve, turn on the electrostatic power supply at the same time, and the charged droplets will be ejected.

3.2. Selection of main devices

Polyethylene is a thermoplastic resin prepared by polymerization of ethylene. In industry, it also includes ethylene and a small amount of α-Copolymers of olefins. The main purpose of the medicine box is to store the medicine liquid, which must have good corrosion resistance. In this study, polyethylene material is selected to make the medicine box (with a capacity of 300 L), which can achieve the purpose of high

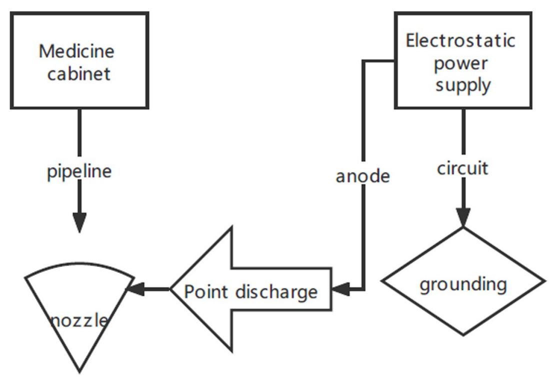

FIGURE 2
Corona charging schematic diagram.

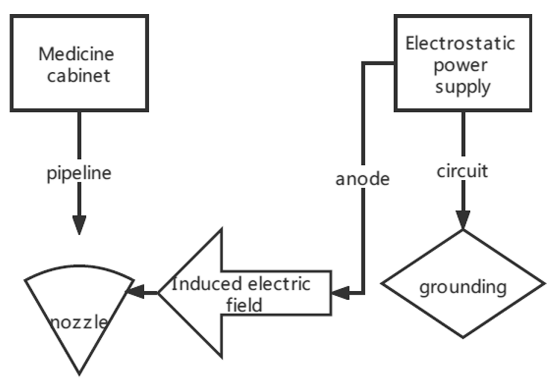

FIGURE 3
Inductive charging schematic diagram.

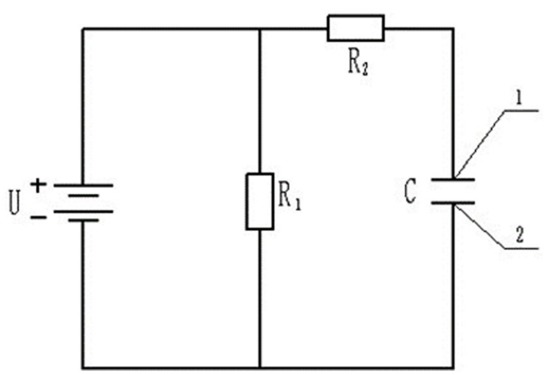

FIGURE 4
Equivalent circuit diagram.

temperature resistance and corrosion resistance. The main purpose of the water pump is to provide water pressure. The DC diaphragm water pump with 12 V input power supply and 0.6 MPa output pressure is selected. The main purpose of the pressure gauge is to provide real-time water pressure display. The pressure gauge with a range of 0-1 MPa is selected according to the output pressure of the water pump. The main purpose of high voltage electrostatic power supply is to transform the input 12 V DC power to more than 10 kV and then output it to the electrostatic nozzle. In order to ensure the charging effect, 0–20 kv adjustable electrostatic power supply is selected. The main purpose of DC power supply is to convert 220 V AC to 12 V DC. Water supply pump and electrostatic power supply are used. In order to ensure stable power supply, 2,000 W switching power supply is selected. Induction electrostatic nozzle is selected for electrostatic nozzle.

4. Experimental method

In order to accurately measure the charging effect of electrostatic nozzle on droplets and analyze the charging law, the ratio of droplet mass to carried charge, i.e., charge mass ratio, is taken as the research index. In this study, ym342l Faraday cylinder and fbs-1076 laser particle size analyzer were used to measure the effects of charging voltage and pump pressure on droplet charge mass ratio and droplet particle size.

4.1. Experimental method of charge mass ratio

The charge/mass ratio measuring device is self-made, and the charge to mass ratio of droplets is measured and the spray time is recorded by the charge/mass ratio measuring device. The current value of the spray time is measured by ampereme, and the quality of droplets collected in the spray time is also described. In order to ensure reliable data, the average value is taken as the effective value after three experiments in each group. The calculation of charge mass ratio is shown in formula (2):

$$R_{cm} = \frac{Q}{m} = \frac{IT}{m} \tag{2}$$

Where: Rcm is the droplet charge mass ratio. Q is the droplet charge. m is the mass of internal spray droplets between units. I is the current per unit time. T is the test time.

4.2. Experimental method of droplet size

The experiment uses ordinary water source simulation liquid medicine and laser particle size analyzer to place 40 cm below the classical nozzle. After opening the spray equipment, the droplet size data are analyzed by the laser particle size analyzer. In order to ensure the reliable data, the average value is taken as the effective value after three experiments in each group. The flowmeter is used to detect the flow and under different water pressures. The average value is taken as the effective value after three experiments in each group.

5. Results and analysis

In order to accurately measure the charging effect of electrostatic nozzle on droplets and analyze the charging law, the ratio of droplet mass to carried charge, i.e., charge mass ratio, is taken as the research index. The combination of Faraday cylinder with higher precision and

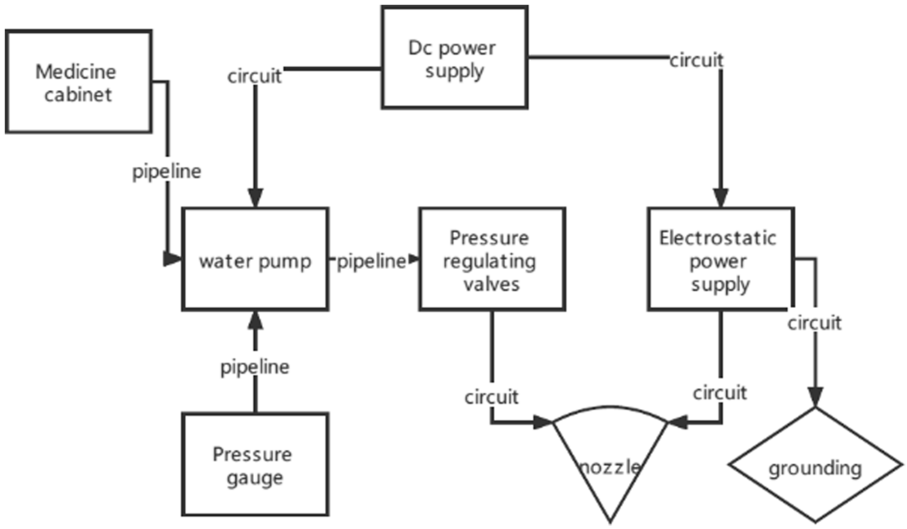

FIGURE 5
Schematic diagram of electrostatic spray system.

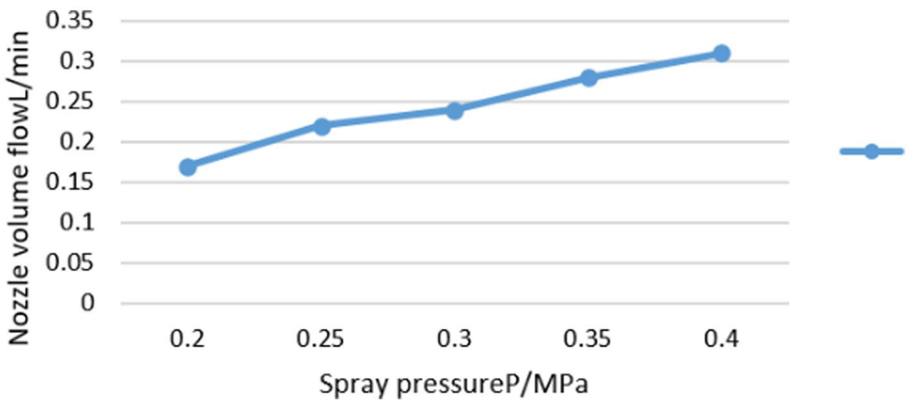

FIGURE 6
Relationship between spray pressure and volume of nozzle.

more accurate results and laser particle size analyzer is used to measure, and the effects of charging voltage and pump pressure on droplet charge mass ratio and droplet particle size are studied. The relationship between spray pressure and nozzle volume flow is shown in Figure 6.

5.1. Effect of charge voltage on charge mass ratio

As shown in Figure 7, when the water pressure remains unchanged and the voltage is less than 8 Kv, the charge mass ratio increases with the increase of voltage; when the voltage is greater than 8Kv, the charge mass ratio increases rapidly with the increase of voltage, then tends to be flat, and then decreases gradually. This is because it is in the ohmic conduction stage during the rapid increase in the early stage, and enters the saturation stage during the gentle period. During the decrease period, the charge mass ratio decreases due to the impact of a large number of negative ions and fog droplets.

5.2. Effect of spray pressure on charge mass ratio

As shown in Figure 8, when the voltage is constant, the charge mass ratio increases with the increase of water pressure, and the increase of charge mass ratio becomes gradually flat with the increase of pressure. This is because increasing the water pressure reduces the droplet particle size and increases the total surface area and current of droplets (Toljic et al., 2008). Then the charge mass ratio increases gradually, because with the increase of water pressure, the spray velocity increases and it is difficult to charge.

5.3. Effect of charging voltage on droplet size

As shown in Figure 9, when the water pressure remains unchanged and the voltage is less than 8 Kv, the droplet size

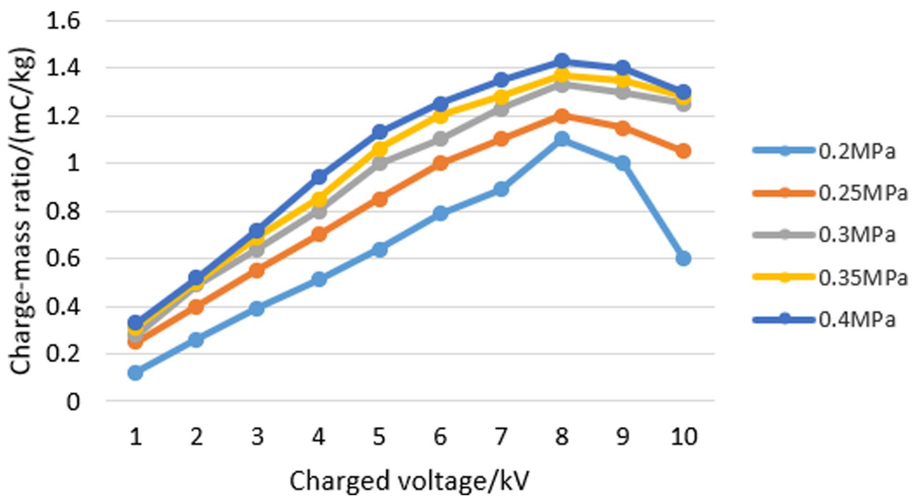

FIGURE 7
Experimental results of the effect of charging voltage on charge mass ratio.

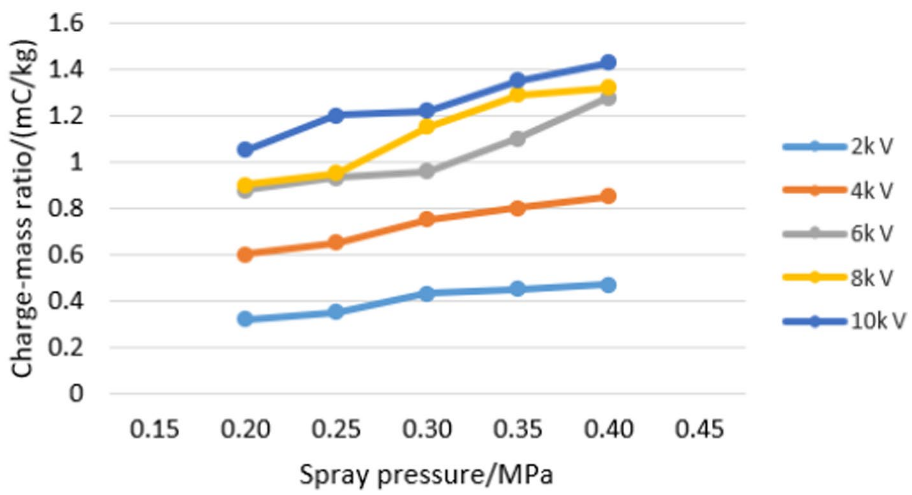

FIGURE 8
Experimental results of the effect of spray pressure on charge mass ratio.

decreases with the increase of voltage; when the voltage is greater than 8 Kv, the charge mass ratio increases rapidly with the increase of voltage, then tends to be flat, and then decreases gradually. This is because it is in the ohmic conduction stage during the rapid increase in the early stage, and enters the saturation stage during the gentle period. During the decrease period, the charge mass ratio decreases due to the impact of a large number of negative ions and fog droplets.

5.4. Effect of spray pressure on particle size

As shown in Figure 10, when the voltage is constant, the droplet size decreases with the increase of water pressure. This is because the increase of water pressure brings more kinetic energy to the liquid medicine (Hui et al., 2009), which promotes the liquid medicine to form a large number of smaller droplets (Jianming, 2013).

6. Farmland experiment

In 2022, our team will conduct field pest control comparative experiments with different application methods at the planting base in Sanya City, Hainan Province. The test day was sunny, with no continuous wind direction, wind power level 3, field temperature 32°, and relative humidity 62%. The test prototypes used Dongfeng Jingguan 3WP-500 boom sprayer (conventional nozzle) and an improved spray nozzle with electrostatic nozzle. Replacing the rod sprayer with the electrostatic nozzle on the original Jingguan 3WP500 boom sprayer, add a high-voltage electrostatic generator (Dongwen high-voltage power supply) and 220 V mobile power supply (Shurui 220 V power supply,

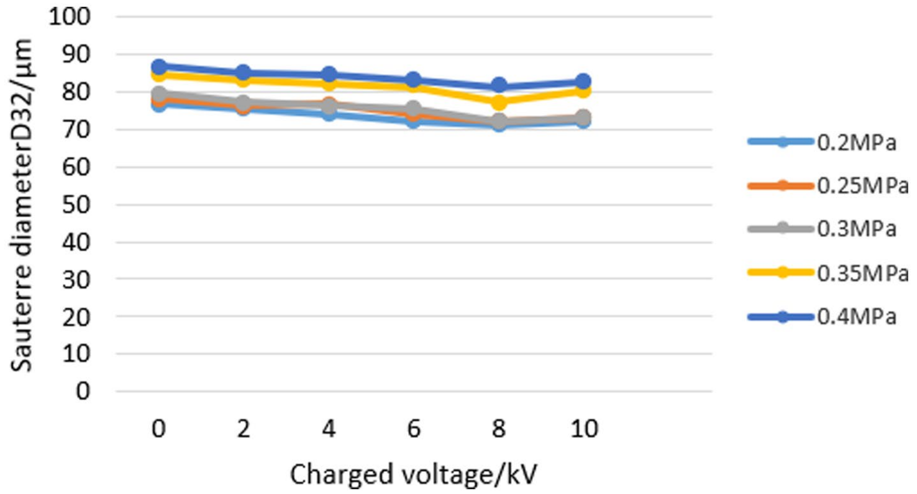

FIGURE 9
Effect of charged voltage on droplet size.

300 W pure sine wave), the working parameter is the charging voltage 6 kV, spray water pressure 0.4 MPa, and nozzle spacing 250 mm.

The experimental pesticides are comprehensive control of multiple pesticides. Two different concentrations of pesticides are prepared according to the principle of the same amount of pesticides used in the same area. Long 48 g, chlorpyrifos 300 L, mixed with water to make 300 L liquid, and used in Dongfeng Jingguan 3WP-500 boom sprayer (conventional nozzle) for non-electrostatic application test. The second type is benzyl propiconazole 200 L, Pymetrozine 150 g, Beta-Cypermethrin 500 mL, Syngenta Fulong 80 g, Chlorpyrifos 500 L, add water to make 200 L liquid medicine, and used for electrostatic spraying method test on the modified boom sprayer with electrostatic nozzle. In addition, an untreated paddy field of 0.40 m^2 was set as a blank control.

Before the start of application, five sampling areas were selected in the field according to the five-point sampling method. 80 cm, each sampling layer was distributed with two sampling points, front and back, and the deposition amount of droplets under different spraying methods was counted. Before spraying, the number of insect populations in the field was measured. Seven days after the spraying test, according to the GB/T17980.4-2000 Pesticide Field Test Standard, the different spraying areas and control areas were measured respectively, and the field pests (rice planthopper and chiloquat) were calculated.

The conventional sprinkler application requires a large amount of water, and most of the liquid is deposited on the front of the upper leaves of rice, and the deposition amount is very small in the middle and lower layers and the back of the leaves; the water requirement of the improved electrostatic sprinkler application is 60% lower than that of the conventional sprinkler application but the deposition amount of the liquid medicine on the middle and lower layers of rice and the back of the leaves increased, and the droplet attachment rates on the back of the upper, middle, and lower sampling layers increased from 8, 0, and 0 cm to 34, 14, and 6 cm. The pest control effect of the improved electrostatic sprayer spraying was 92.1%, slightly lower than 95.0% of the conventional sprayer spraying method, but the difference

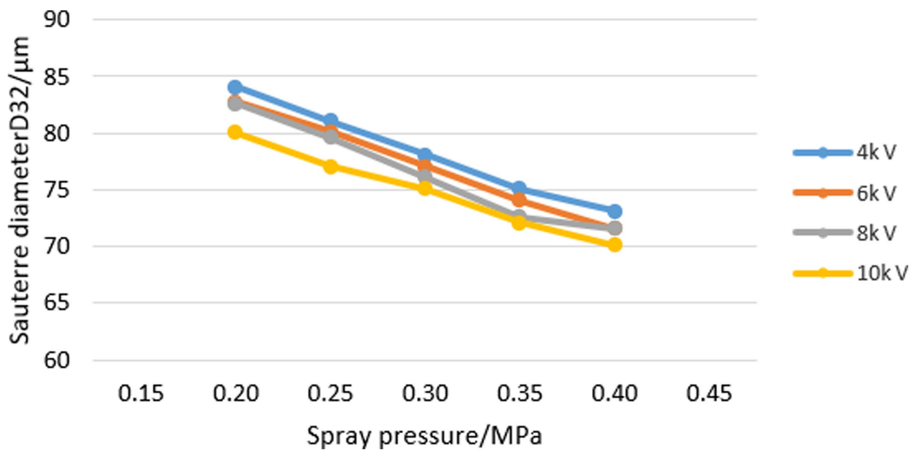

FIGURE 10
Experimental results of spray pressure on particle size.

was not significant, meeting the requirements of the control effect. The full-load (500 L) operation area is increased by 1.5 times, which is beneficial to reduce the number of times of dispensing in field operations and improve the operation efficiency.

7. Conclusion

Electrostatic spray technology is an advanced application technology in the world. A small electrostatic spraying machine produced in the United Kingdom has been popularized in some African countries. In the research and experiment of electrostatic spraying system for agricultural plant protection vehicle, when the water pressure is constant and the voltage is less than 8 kV, the charge/mass ratio increases with the increase of voltage, and droplet size decreases with the increase of voltage. When the voltage is greater than 8 Kv, the charge mass ratio increases rapidly with the increase of voltage, then tends to be flat, and then decreases gradually. When the voltage is constant, the charge mass ratio increases with the increase of water pressure, and the droplet size decreases with the increase of water pressure. With the increase of pressure, the increase of charge mass ratio becomes gradually flat. In this experiment, the charge voltage 8 kV is the best voltage, and the spray pressure 0.4 Mpa is the best water pressure.

The results of farm experiments show that electrostatic spraying can increase the deposition of droplets in the middle and lower layers of rice and the back of leaves. The pest control effects of electrostatic sprayers and conventional sprayers are 92.1 and 95.0%, respectively, and the control effects are basically the same. The water requirement of the medicine is reduced by 60%, and the working area when fully loaded is increased by 1.5 times, which significantly improves the field work efficiency.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZL: experiment designing and editing. JX: experiment process implementing. ST: data collecting. XW: data analysis. WS: put forward research ideas. XM: design research scheme. All authors contributed to the article and approved the submitted version.

Conflict of interest

ST was employed by Sanya Xiaxiang Technology Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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