Journal of Biosystems Engineering
https://doi.org/10.1007/s42853-020-00067-6

Online ISSN 2234-1862
Print ISSN 1738-1266

TECHNICAL ARTICLE

Evaluation of Spray Characteristics of Pesticide Injection System in Agricultural Drones

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Received: 29 July 2020 / Revised: 22 September 2020 / Accepted: 23 September 2020

Abstract

Purpose This study aims to verify that the characteristics of the typical injection pumps and nozzles used in pesticide injection systems in current agricultural drones in Korea are consistent with those presented in the product specifications, and to provide experimental quantitative data for selecting the correct pump and nozzle.

Methods The performances of three types of pumps and 18 types of nozzles currently in use were evaluated in terms of the pressure-flow rate curve, injection flow rate, spray angle, and droplet size.

Results For pesticide injection pumps, the maximum pressure and pressure-flow rate curve should include the nozzle's injection pressure and flow rate range. Most of the 18 nozzles used in the test showed nearly the same results as the flow rates suggested from the manufacturer, but the spray angle showed a difference of up to 10%. The droplet size was slightly smaller than the value suggested by the manufacturer, and the relative span factor ranged from 0.2 to 1.2.

Conclusion The pressure-flow rate curves of the injection pumps and spray angles of the commercial nozzles used for agricultural control drones must be evaluated for official approval/assessment of such agricultural drones to ensure the performance of agricultural drone sprayers.

Keywords Agricultural drone sprayer · Injection nozzle · Pesticide injection system · Precision pesticide control

Introduction

Recently, owing to developments in science and technology, the mechanization and "intelligentization" of agriculture have been rapidly progressing, and farming using unmanned helicopters and drones is emerging as a countermeasure for the aging agricultural labor population. Agricultural drones are being used to observe diseases and pests such as pine wilt, as well as for precision pest control, such as by spraying pesticides. Precision pest control using drones is known to have a high control effect, as the low altitude (3 to 5 m) for spraying pesticides minimizes the exposure to pesticides, and the downward wind from the drone rotor blade allows the pesticides to evenly permeate to the lower parts of crops. Moreover, it is attracting significant attention from farmers, as the average control time is 1/10 that of power sprayers, saving labor. Moreover, it is very economical, with 1/5 of the purchase cost and 1/10 of the operation cost of unmanned helicopters. In addition, it can solve problems related to the usage of burst sprayers and manned helicopters, such as the low pest control efficiency caused by the scattering of the pesticides in the air (Yeom and Jung 2019; Jung et al. 2015).

Although agricultural drones are widely used in pest control, the nozzles for conventional power sprays or unmanned helicopters are still being used in the pesticide injection systems mounted on drones, without sufficient review of the flight characteristics and operating environments. In particular, as the rotor blade downward wind flow of agricultural drones is different from that of unmanned helicopters owing to the characteristics of lift and thrust generated by the

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Published online: 12 October 2020

multirotor blades, it is necessary to optimize the design of the pesticide spray system while considering the downward wind (Choi et al. 2019; Shukla and Komerath 2018; Qing et al. 2017).

An agricultural drone for pest control consists of a flying body and pesticide injection system mounted on the drone (Myint and Kim 2019). The pesticide injection system for an agricultural drone consists of a pesticide tank, controller, pesticide pump, DC motor, spray boom, tube, and nozzle. The variables influencing the pest control effect include the rotor blade downward wind flow characteristics, pesticide injection flow rate, injection pressure, injection speed, number of nozzles, location of installation, nozzle structure, and nozzle spray characteristics (speed and droplet size). Therefore, it is necessary to optimize many variables to improve the application rate through precision pest control, and to improve the pest control efficiency by reducing spray drift potential.

Many studies related to agricultural drones have been conducted, and several research groups are currently conducting research in various fields related to the optimization of pest control systems with drones. However, most studies related to agricultural drones focus on the drone body in the performance of a specific task, such as in-flight attitude control, communication, collision avoidance, or optimization of the path for the pest control mission (Pharne et al. 2018; Reddy et al. 2017; Maguteeswaran and Srinivasan 2016). There are relatively few studies related to the pesticide injection systems in agricultural drones and nozzle optimization technology. In South Korea, studies have been conducted on pest surveillance using drones (Lee et al. 2017) and on the spray drift characteristics in the aerial application (Jin et al. 2008; Park et al. 2007; Kim et al. 2019a, b), but there are not many studies addressing the pesticide spray nozzles in the pest control systems of agricultural drones. In particular, most of the agricultural drone sprayers used in Korea are made by small- and medium-sized businesses that imitate Chinese products, and the significance of this study is that there is no data to be used for reference.

Therefore, this study aims to verify whether the characteristics of typical spray pumps and nozzles for the pesticide spray systems of agricultural drones currently used in South Korea are consistent with those suggested in the product specifications. In addition, it aims to induce the selection of the proper pumps and nozzles by providing experimentally proven quantitative data. To this end, the performances of three types of pumps and 18 types of nozzles currently in use were evaluated in terms of the pressure-flow rate (P-Q) curve, injection flow rate, spray angle, and droplet size all of which affect the efficiency of drone sprayers.

Materials and Methods

Test Pump and Nozzles

The Ministry of Agriculture, Food, and Rural Affairs enacted and published the “Inspection Methods and Criteria for Agricultural Spraying Drones” in June 2016 to promote the agricultural use of drones (KS 2016). The criteria for pesticide injection systems installed in agricultural drones are described in detail in “Table 4: Agricultural Machinery Inspection Methods, (77) Agricultural Spraying Drones” and “Table 5: Agricultural Machinery Inspection Criteria, (66) Agricultural Spraying Drones.” One pesticide spray nozzle-related item among the inspection criteria for agricultural drones states that agricultural drones should meet a spray rate of 8 L/ha ± 15% per area. This inspection criterion was prepared from the viewpoint that a pesticide should be applied in the amount required for the target, in terms of the pest control effect. To satisfy this criterion, the pest control speed (according to the number of nozzles mounted on the drone), the injection flow rate per nozzle, and pesticide spraying width must be determined. Based on the 8 L/ha suggestion in the criteria for agricultural drones, the required spraying length changes from 2333 to 1429 m when the spraying width changes from 3 to 7 m. When the spraying speed is set to 2 to 5 m/s, the required spraying time is 28 to 5 min, and the injection flow rate is in the range of 0.29 to 1.68 liters per minute (LPM). Considering the spraying width (5 m) and spraying speed (3 m/s) most commonly used in domestic agricultural drones, the total injection flow rate of the nozzles mounted on an agricultural drone is set as 0.8 L/min, and the average flight time for spraying an area of 1 ha is approximately 10 min. This standard is similar to the Japanese standard (ISO/DIS 16119-5 (2018): Environmental Requirements for Sprayers - Part 5: Aerial Spray Systems), which is defined by an 8 L/ha uniform spraying and 6% error range at a spraying rate of 0.8 L/min (ISO/DIS 16119-5 (2018)). Most of the nozzles used in the pesticide spray systems of domestic agricultural drones are XR series (flat fan) nozzles. Some nozzles are equipped with TP series (cone jet) nozzles, with an injection flow rate in the range of 0.25 to 0.76 LPM (0.068 to 0.2 gallons per minute (GPM)). Table 1 shows the nozzles currently used in agricultural control drones, and similar nozzles for comparison; a total of 18 nozzles from four series (XR, TP, TX, and AI) were used for the performance evaluation.

As it is important for agricultural drones to spray pesticide to as many areas as possible within a limited flight time by using the electric energy charged in the battery, it is efficient to fly with a large battery and as much pesticide as possible. Therefore, a lighter takeoff weight of the flying vehicle allows for a larger load of pesticide, and the capacity of the pesticide injection pump mounted on the drone should be optimized for the injection conditions. The pesticide injection pump

Table 1 List of test nozzles with classified into four groups (XR, TX, TP, AI series)

Nozzle			Flow rate @ 2.76 bar (40 psi)		Spray angle	Operating pressure	
Series	Name	Type	Gallons per minute (GPM)	Liters per minute (LPM)	degree	psi	bar
XR[a)]	XR8001-VS	Flat fan	0.10	0.38	80	15–60	1.03–4.14
	XR80015-VS	Flat fan	0.15	0.57	80	15–60	1.03–4.14
	XR80020-VS	Flat fan	0.20	0.76	110	15–60	1.03–4.14
	XR11001-VS	Flat fan	0.10	0.38	110	15–60	1.03–4.14
	XR110015-VS	Flat fan	0.15	0.57	110	15–60	1.03–4.14
	XR110020-VS	Flat fan	0.20	0.76	110	15–60	1.03–4.14
TX[b)]	TX VK-04	Hollow cone	0.067	0.25	80	30–300	2.07–20
	TX VK-06	Hollow cone	0.10	0.38	80	30–300	2.07–20
	TX VK-08	Hollow cone	0.133	0.50	80	30–300	2.07–20
	TX VK-12	Hollow cone	0.20	0.76	80	30–300	2.07–20
TP[c)]	TP8001-VS	Flat fan	0.10	0.38	80	30–60	2.07–4.14
	TP11001-VS	Flat fan	0.10	0.38	110	30–60	2.07–4.14
	TP8002-VS	Flat fan	0.20	0.76	80	30–60	2.07–4.14
	TP11002-VS	Flat fan	0.20	0.76	110	30–60	2.07–4.14
	TP800067-VS	Flat fan	0.067	0.25	80	30–60	2.07–4.14
	TP1100067-VS	Flat fan	0.067	0.25	110	30–60	2.07–4.14
AI[d)]	AI110015	Flat fan	0.15	0.57	110	30–100	2.07–6.9
	AI11002	Flat fan	0.20	0.76	110	30–100	2.07–6.9

a), b), c), d) series (Spraying system Co. Ltd., Glendale Heights, IL, USA). Schematics and specifications of all nozzle listed in this table can be found in Spraying system Co. Ltd

currently used is equipped with a DC motor and uses the pulse width modulation (PWM) or voltage control to control the number of revolutions. In this study, three models were selected for investigating the performance of the pesticide injection pumps mounted on agricultural drones. The three pumps used in this study were selected by referring to agricultural control drones used in Korea. Table 2 shows the types and specifications of the pumps used in the experiment.

Measurement of Flow Rate and Spray Angle

The experimental apparatus shown in Fig. 1 was constructed to evaluate the performance of a pesticide spray system in an agricultural control drone. The experimental apparatus consisted of a liquid supply unit, pesticide spray pump and spray nozzle, spray image acquisition device, droplet size measuring device, and control system. The device for evaluating the P-Q characteristics of the pesticide injection pump and measuring the injection flow rate of the nozzle consisted of a liquid supply device, volumetric flow meter (Model IOG 1/4″, flow range: 0.44–8.3 LPM, Badgermeter, Neuffen, Germany), and pressure measurement sensor (ETM-375-500A, Kulite with 1% accuracy, Kulite Co. Ltd., Leonia, New Jersey, USA) to measure the flow rate, in addition to a test pump and spray nozzle. The electrical signal measured by the flow meter was converted by a flow monitor (KM2 Series, Kyongin Instruments, Seoul, Korea) to LPM, and all measured signals were stored on a computer through a data acquisition system executing in-house LabView code. For the spray image acquisition and droplet size measurement, the liquid

Table 2 List of pesticide injection pumps and their specifications

Pump	Model	Input voltage	Control	Max. flow rate	Max. pressure
Pump 1	Singflo Flo-2203[a)]	DC 12 V	Voltage control	2.6 L/min	4.83 bar
Pump 2	BPP-25 [b)]	DC 22–25 V	Pulse width modulation (PWM) control	3.5 L/min	10 bar
Pump 3	Unbranded/generic [c)]	DC 12 V	Voltage control	5.5 L/min	9 bar

a)YOUME ELECTRIC CO.,LTD., Xiamen, China

b)JMRRC Co. LTD., Guangdong, China

c)ProPumps Co., China

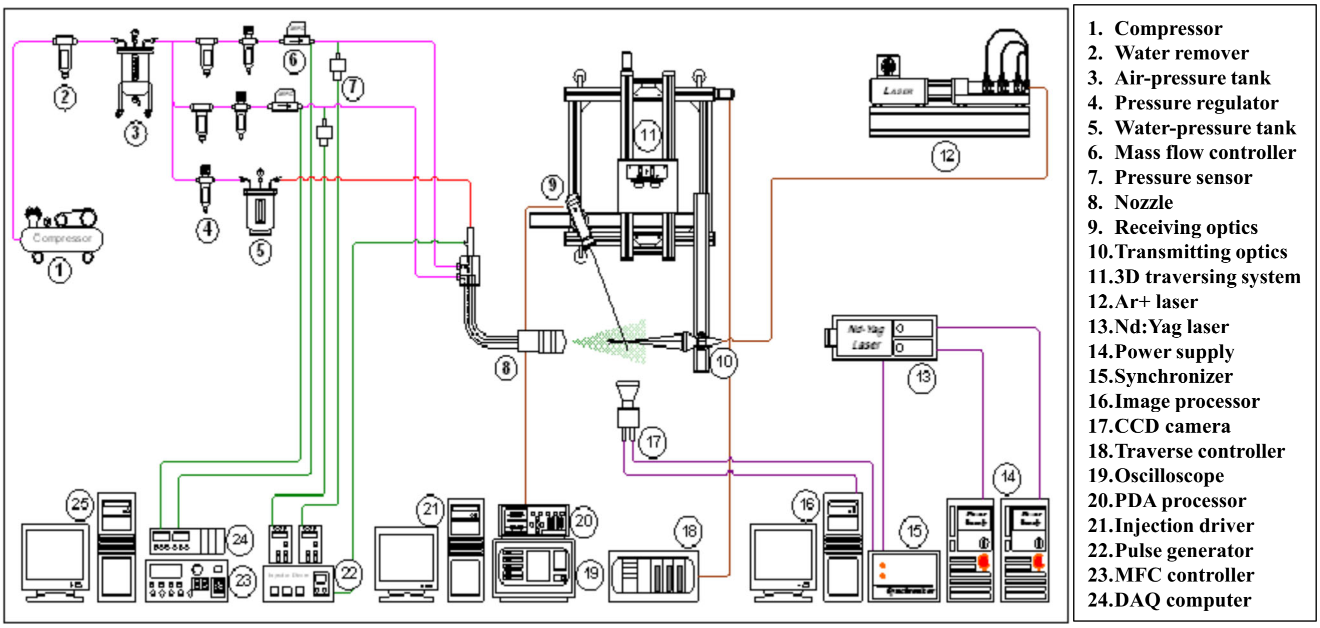


Fig. 1 Drop size and drift potential measurement systems using phase Doppler analyzer (PDA) system for droplet sizing and velocity measurement

was supplied from a compression tank pressurized by compressed nitrogen gas (up to 120 bar) to the nozzle.

The spray images were acquired using a single image acquisition function of a two-dimensional particle image velocimetry (PIV) system (TSI Co., Minnesota, USA), for quantitatively evaluating the spray atomization process in terms of the spray structure, spray development process, and spray angle (Dorr et al. 2013). The PIV system consisted of a laser light source (Dual Nd:YAG Laser, 120 mJ/pulse, 14.5 HZ, Big SKY Laser Co. Ltd., Motana, USA) for irradiating the spray; a charge-coupled device camera (POWERVIEW Plus 2MP, 1600 × 1200, 30f/s, TSI Co., Minnesota, USA) for collecting scattered light from the spray; a synchronizer (Laser Pulse Synchronizer 610034, TSI Co., Minnesota, USA) for synchronizing the camera and laser light source; and, an Insight 3G SOFTWARE (TSI Co., Minnesota, USA) for interpreting the collected image data.

Spray Droplet Sizing

The average droplet size was measured using a phase Doppler analyzer system (PDA, Dantec Dynamics Co. Ltd., Skovlunde, Denmark) to investigate the microscopic properties of the spray (Nuyttens et al. 2007). The PDA system consisted of a manipulator including a prism for spectralizing light emitted from a continuous Ar-ion laser (air-cooled, 750 mW), used as a light source for liquid spray irradiation to green (532 nm) and blue (488 nm), and a Bragg cell (40 MHz) for frequency shift, as required for negative velocity measurement; a transmitting optic for integrating the spectroscopic and frequency-modulated lights into a measured volume; a receiving optic for collecting light scattered by the droplets; a photomultiplier tube for converting the collected light into an electrical signal; a shutter width adjuster for evaluating the phases difference from the signals; and, a signal processor for calculating the droplet size using the input signal based on its dedicated SOFTWARE, SizeWare. The droplet size was measured 200 mm from the nozzle tip, according to ANSI/ASAE S572.1 guidelines (2009) (200–500 mm), and the average droplet diameters such as Dv0.1, Dv0.5, and Dv0.9 were measured ((ANSI/ASAE S572.1(2009); ASTM E799-03(2003).

Results and Discussion

Performance Evaluation of Injection Pumps

Most of the pumps used in agricultural drones in South Korea are made in China; the maximum flow rate is in the range of 2 to 5 LPM (0.53–1.32 GPM), and the maximum pressure is in the range of 4 to 9 bar (58 to 130 psi). These flow and pressure ranges satisfy the performance required by the nozzles: 15 to 60 psi (1 to 4.2 bar) for the XR series, and 15 to 100 psi (1 to 6.9 bar) for the AI series. Most pumps made in China are not provided with a performance curve, so it is difficult to understand the performance of the pump, making it difficult to set the optimum injection pressure required by the nozzle for adjusting the droplet size. Fig. 2 shows the results for the pumps 1, 2, and 3 used in the experiment; it also shows P-Q curves for each, for confirming the basic performance of the pump and the injection flow rate with a nozzle installed.

In the performance evaluation results of pump 1 (widely used in domestic agricultural drones), the maximum flow rate

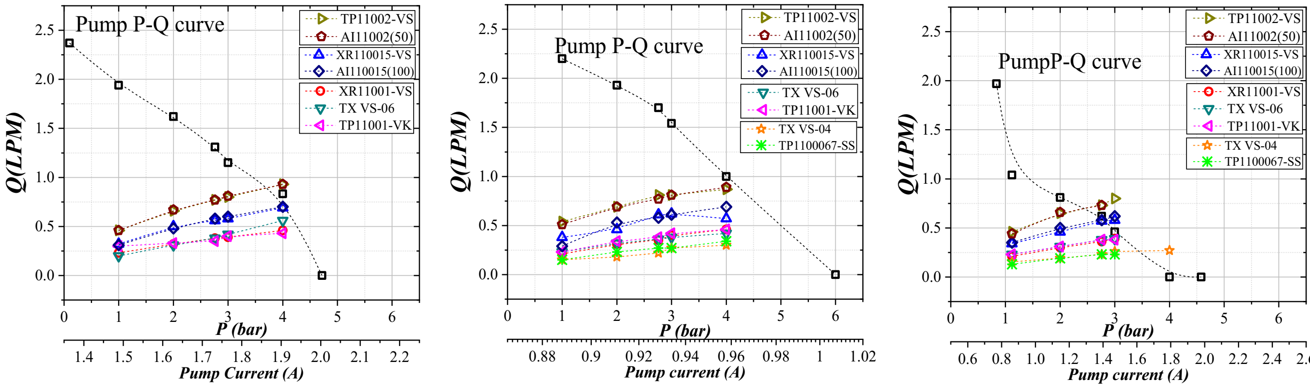


Fig. 2 P-Q performance curves of pump-motor assembly applied in agricultural drones

is 2.37 LPM, i.e., 9% lower than the value given in the technical specifications; the maximum pressure is similar to the value given in the specifications. Looking at the P-Q curve for pump 1 when a nozzle is installed, each nozzle shows a value close to the required flow rate at a reference pressure of 2.76 bar (40 psi). As shown in the P-Q curve, the limit for this pump is 4 bar (60 psi) for a 0.57 LPM (0.15 GPM) nozzle and 3.5 bar (50 psi) for a 0.76 LPM (0.2 GPM) nozzle, and this pump seems suitable for the low flow rate (Nozzle Tip Color code: Orange and Green) spraying of XR and TP series nozzles. In regards to the performance evaluation results of pump 2, it satisfies the capacity range of most of the nozzles used in South Korea, and the P-Q performance curve is ideally distributed, showing the best performance among the three pumps used in the test. In the performance evaluation results of pump 3, not only is there a significant shortage in the maximum flow rate and pressure as compared to the values presented in the specifications but also the P-Q performance curve is abnormal. In particular, the limit for this pump is 2.76 bar (40 psi) for a 0.57 LPM (0.15 GPM) nozzle, and 2.0 bar (30 psi) for a 0.76 LPM (0.2 GPM) nozzle; thus, it would be difficult to use this pump in agricultural drones. These results indicate that if the performance of a pump in the pesticide injection system of a drone does not meet the specification requirements, the pesticide injection flow rate and expected droplet size cannot be achieved. Therefore, the performance curve of a pesticide injection pump mounted on an agricultural drone must be inspected in advance.

Flow Rate Measurement of Nozzles

To evaluate the performances of the nozzles used in agricultural drones, 18 nozzles were tested, for verifying the difference between the injection flow rate provided by the manufacturer and the actual injection flow rate. The results are shown in Fig. 3.

For agricultural nozzles, as suggested in ANSI/ASAE S572.1 (2009), the injection flow rate at an injection pressure of 2.76 bar (40 psi) is provided in the form of a nozzle tip color code. Among the nozzles tested, the TX VS-04, TP800067, and TP1100067 nozzles showed a slightly smaller injection flow rate than the expected injection flow rate of 0.25 LPM (0.067 GPM). The remaining nozzles showed values similar to the expected injection flow rate (within ± 3.5%) regardless of the nozzle shape, and the injection flow rate increased in proportion to the 0.5th power ($Q = \Delta p^{0.5}$) of the injection pressure. Therefore, if the capacity of a pesticide injection pump is within a range that satisfies the nozzle operating range, the flow rate range indicated by the nozzle color code is reliable to use for selecting a nozzle.

Evaluation of Spray Structure and Spray Angle

Fig. 4 shows the results for an injection pressure of 2.76 bar among the images obtained using the PIV system at injection pressures of 1.03, 2.07, 2.76, 4.14, and 5.17 bar (15, 30, 40, 60, and 75 psi), for evaluating the spray atomization characteristics of the nozzles used in the experiment. The processes of spray development are illustrated. The spray structures of the XF, TP, and AI nozzles (flat fan nozzles) and TX nozzles (hollow cone nozzles) are all symmetrical, with a relatively high droplet number density observed in the center of the spray near the nozzle tip. For the AI nozzle, a low number density of relatively large droplets is observed, unlike in the other three nozzles.

The spray angle was measured based on the spray image according to the change in injection pressure, and the results are shown in Fig. 5. The spray angle of agricultural nozzles is a very important variable in nozzle design, as it determines the spraying area and, for boom sprayers, has a great influence on the distribution of the injection flow rate according to the nozzle spacing. As the spray angle increases, the droplet diameter becomes smaller while the spatial distribution becomes wider; thus, the spray angle is particularly important for agricultural drones equipped with one to four nozzles. Looking at the spray angles of the XR series nozzles, the XR80 (80° spray angle as suggested by the manufacturer) has a spray angle of 95 to 100° at 2.76 bar (40 psi), and the XR110 (110° spray angle as suggested by the manufacturer) has a spray angle of

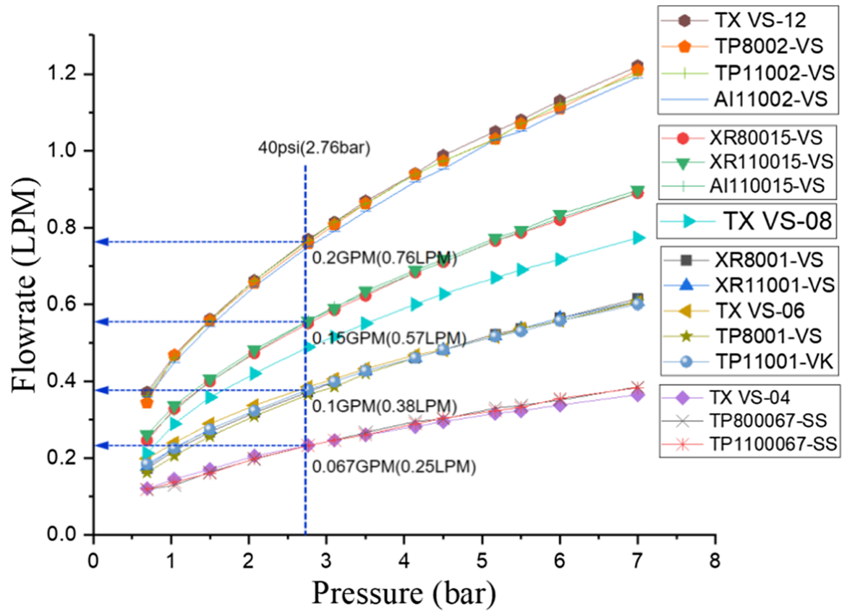


Fig. 3 Injection flow rate (liters per minute (LPM)) with injection pressure (bar) and nominal flow rate at 2.76 bar (40 psi)

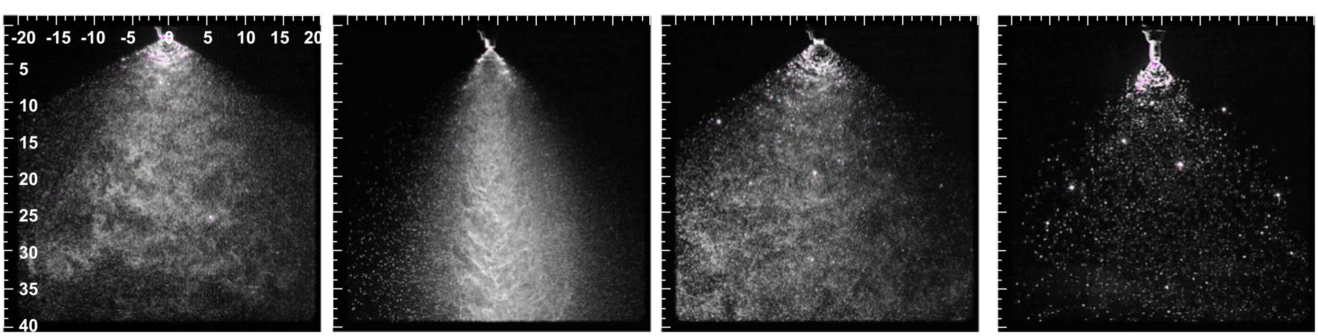
120° or larger; these results are approximately 10% larger than the spray angles suggested by the nozzle manufacturer. For the TX series nozzles, the spray angle presented by the manufacturer is 80° at 7 bar (100 psi). However, the TXVS-04 and TX VS-08 have spray angles exceeding 80°, and the TXVS-06 and TX VS-12 have spray angles near 80°, but lower. This indicates a very large spray change among the TX series nozzles with a hollow cone spray structure.

The spray angles of the TP series nozzles match best with the spray angles (80° and 110° at 2.76 bar (40 psi)) presented by the manufacturer, even with some deviations. The spray angles of the AI series nozzles are different depending on the injection flow rate; the spray angle of the AI11002-VS nozzle matches very well with the spray angle of 110° presented by the manufacturer.

As there is a difference (maximum of 10%) between the spray angle suggested by the nozzle manufacturer and actual spray angle, depending on the nozzle, the results of the spray angle measurement must be referred to when setting the nozzle spacing and overlap of spray patterns. In addition, as the spray angle increases almost linearly as the injection pressure increases, the pre-set injection pressure must be observed when spraying using a drone.

Droplet Sizing of Sprays

The atomization characteristics (average droplet size, size distribution, uniformity) and flow characteristics (velocity distribution) of the nozzle are factors directly affecting the adhesion rate and drift characteristics of the spray droplets. Therefore, a droplet size evaluation must precede sprays under very complicated flow field (downwind and sidewind) conditions, such as sprays using agricultural control drones. In addition, the nozzles should form a droplet size distribution that can reduce or minimize spray drift. Many studies related to spray drift potential have suggested that the drift potential can be reduced when the average droplet size (volume median diameter (VMD) or Dv0.5) is at least 200 μm (Czaczyk et al. 2012; Fritz et al. 2012).



a) XR8001-V (b) TX VS-06 (c) TP8001-VS (d) AI110015

Fig. 4 Spray images at injection pressure of 2.76 bar (40 psi) (**a** XR8001-VS (Q = 0.38 LPM), **b** TX VS-06 (Q = 0.38 LPM), **c** TP8001-VS (Q = 0.38 LPM), **d** AI110015 (Q = 0.57 LPM))

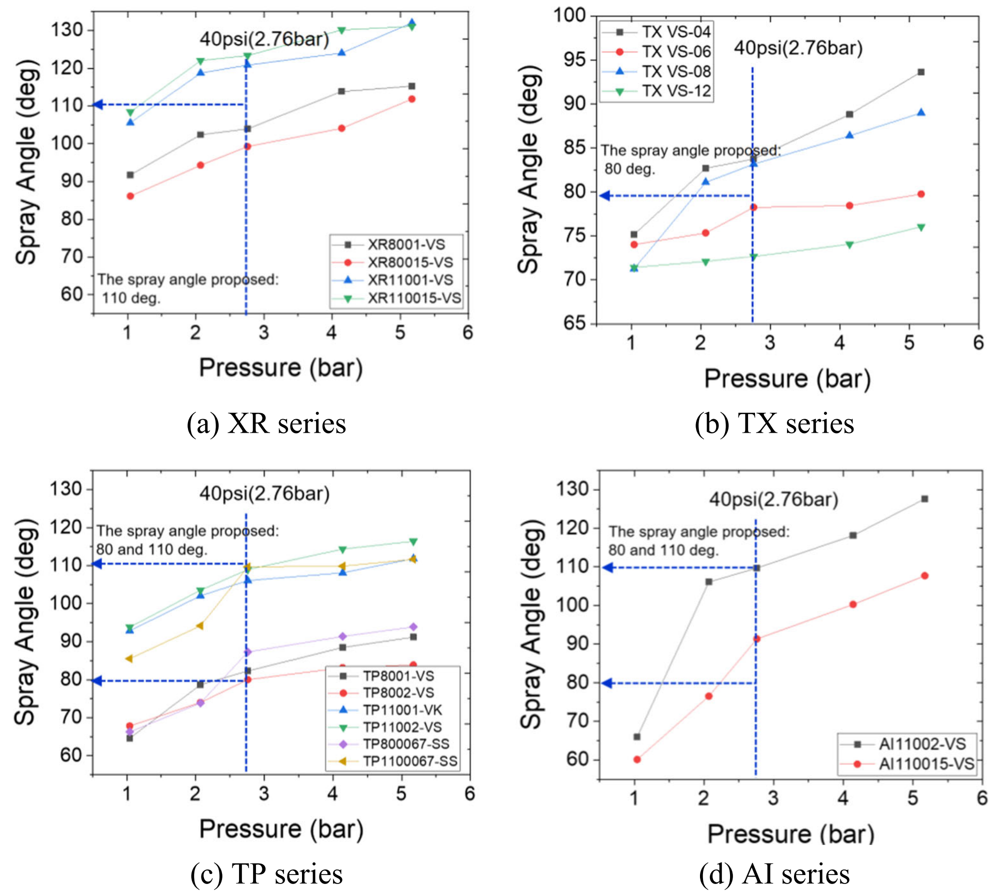


Fig. 5 Spray angles with injection pressures and nominal spray angle at an injection pressure of 2.76 bar for XR, TX, TP, and AI series. **a** XR series. **b** TX series. **c** TP series. **d** AI series

Fig. 6 shows the VMD (Dv0.5) and relative span factor (RSF) together, for evaluating the atomization characteristics of the nozzles used in the test. As mentioned above, VMD is the volume medial diameter, and RSF is a dimensionless index indicating the degree of dispersion of the droplet size distribution. It is defined by RSF = (Dv0.1–Dv0.9)/Dv0.5. The XR series nozzles have droplet size ranges suggested by the manufacturer in the ranges of fine (orange, 144 to 235 μm) and very fine (VF) (61 to 144 μm, at 4.14 bar (60 psi)), but the experimental results are in the range of 80 to 120 μm, indicating a droplet size distribution close to VF (red, 61 to 144 μm) (color code: Fritz et al. 2012). In particular, many small droplets of approximately 80 μm are present in the center of the spray with a high number density, and thus the spray is very vulnerable to spray drift characteristics. These droplets decrease as the injection pressure increases. The TX series nozzles are manufactured to have a droplet size range of VF (red, 61 to 144 μm), and the experimental results show a droplet size range of approximately 50 μm in the center of the spray and 120 μm in the outer area of the spray. The TP series nozzles have a droplet size range suggested by the manufacturer in the range of fine (orange, 144 to 235 μm), but the experimental results are in the range of 90 to 120 μm, indicating a smaller droplet size distribution, i.e., closer to VF (red, 61 to 144 μm). The RSF is in the range of 0.2 to 1.1 for the XR series nozzles, 0.3 to 1.0 for the TP series nozzles, and 0.2 to 1.2 for the TX series nozzles, indicating that the uniformity of the XR and TP series nozzles is better than that of the TX nozzle. The outer area of the spray shows a low RSF while the central area of the spray shows a high RSF, indicating that the central area is composed of large and small droplets.

Fig. 7 shows the weighted mean VMD (WMDv0.5) of DV0.5 (see Fig. 6) as measured along the radial direction at 200 mm below the nozzle tip, considering the droplet density at each measurement point. The WMD v0.5 tends to decrease with increasing injection pressure, regardless of the spray angle. Among the nozzles with a spray angle of 80°, TP8001 shows the largest droplet size, followed by XR and TX. The nozzles with a spray angle of 110° show a droplet size slightly smaller than that of the nozzles with a spray angle of 80°. This is because the initial droplet size is reduced, owing to the decrease in the thickness of the liquid film as the spray angle increases. These results are obtained by converting the droplet size range suggested by the manufacturer into the mean value after considering the weight for the number density, which may be used as a more quantitative value when selecting a nozzle.

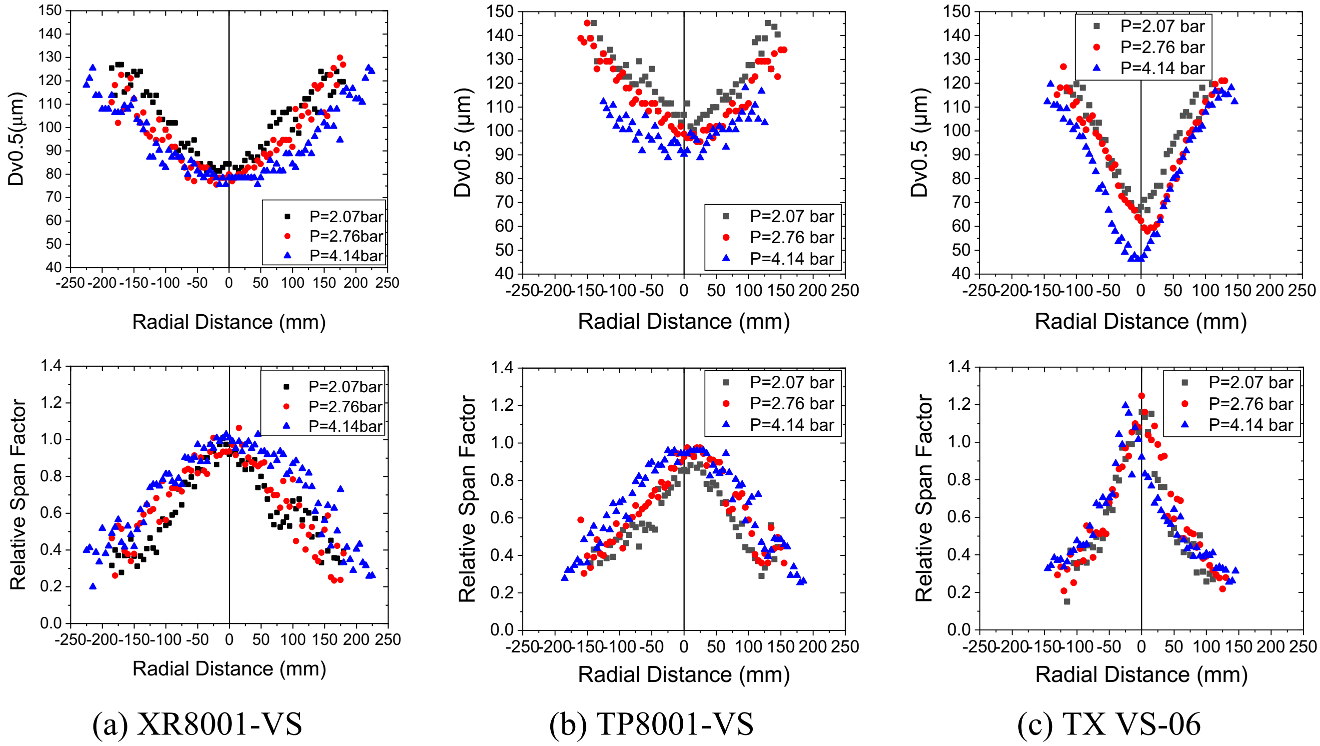


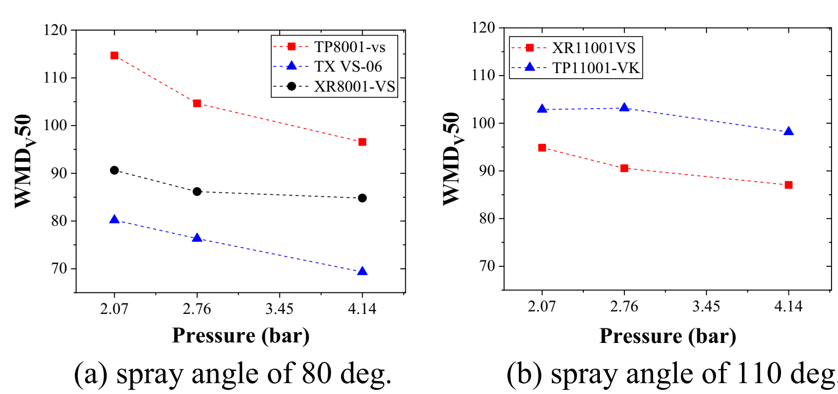
Fig. 6 Volume medial diameter (VMD, Dv0.5) and relative span factor distribution at an axial distance of 200 mm from the nozzle tip. **a** XR8001-VS. **b** TP8001-VS. **c** TX VS-06

Conclusions

This study was conducted to verify whether the characteristics of typical spray pumps and nozzles for the pesticide spray systems of agricultural drones currently used in South Korea are consistent with those suggested in the product specifications, and to induce the selection of proper pumps and nozzles by providing experimentally proven quantitative data. To this end, the performances of three types of pumps and 18 types of nozzles currently in use were evaluated in terms of the pressure-flow rate (P-Q) curve, injection flow rate, spray angle, and droplet size. The results are summarized as follows.

For a pesticide injection pump, the maximum pressure and P-Q curve must include the ranges of the injection pressure and the injection flow rate of the nozzle. As the pesticide spray characteristics are a function of the injection pressure, verification is required prior to mounting an injection pump to a drone to ensure the performance of the nozzle. While most of the 18 types of nozzles used in the test showed results matching the flow rates suggested by their manufacturers, the spray angles of the XR series and TX series nozzles showed differences of up to 10% and 7%, respectively; the flow rates of the TP and AI series nozzles were measured to be close to the values suggested by the manufacturer. Therefore, when installing nozzles using a boom on a drone, it is necessary to determine the spraying range while considering the spray angle error. The droplet size of the XR, TX, and TP series nozzles (as measured at 200 mm below the tip of the

Fig. 7 Mean VMD (Dv0.5) at an axial distance of 200 mm from the nozzle tip. **a** Spray angle of 80°. **b** Spray angle of 110°



nozzle) was slightly smaller than the droplet size suggested by the manufacturer. The RSF was in the range of 0.2 to 1.1 for the XR nozzles, 0.3 to 1.0 for the TP nozzles, and 0.2 to 1.2 for the TX nozzles. In addition, it was confirmed that the WMDv0.5 can be used as a useful quantitative index for selecting a nozzle.

Funding This work was carried out with the support of "Research Program for Agriculture Science and Technology Development (Project No. PJ013819)," National Institute of Agricultural Science, Rural Development Administration, Republic of Korea.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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