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Comparison of the Spray Effects of Air Induction nozzle and Flat Fan nozzle installed on Agricultural Drones

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Abstract: Pest control is essential for increasing agricultural production. Agricultural drones with spraying system for pest control has generated great interest among farmers. However, spraying system installed on unmanned aerial vehicle, like any other sprayer, can cause damage to environment due to drift of agent. Air induction (AI) nozzles are known to produce less drift (e.g., larger spray drops) than other nozzles, but there is a lack of research analyzing their effectiveness in combination with drones. In this study, AI and flat fan nozzles were installed on drones to evaluate their spray and pest control performance. Aerial spraying was conducted on rice and soybeans to measure the coverage and penetration ratio and analyze the crop production as well as the crop damage due to pests and diseases. The drone flight was conducted at an altitude of 3 m and velocity of 2 m/s. Spray droplets were collected using water sensitive paper at two heights above the soil surface. The experiments showed that the crop coverage with the AI nozzle was 130% higher than with the flat fan nozzle. Drift reduction of AI nozzles increased the coverage of spray droplets. But the difference in penetration ratios which is the ratio of agents to be delivered inside the crop was not significant between the nozzles. Also, there was no significant difference in crop yield and pest control efficacy; Although the AI nozzle did not show a significant difference, it performed similarly to the flat fan nozzle and caused less drift, so it should be considered for use in aerial control.

Keywords: Agricultural drones; Air-induction nozzle; Aerial spraying; Control Efficacy; Coverage; Penetration ratio

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1. Introduction

The increasing global population reached 8 billion in November 2022; it is projected to reach 9.7 billion by 2050 [1]. Thus, the demand for food has also increased with the population; therefore, food production will also need to increase by up to 70% [2]. To achieve this food production goal, pests must be controlled because crop yield would substantially decrease without pest control [3]. In particular, pests and insects are becoming increasingly common as a result of global warming, necessitating pest-prevention measures [4]. However, the number of farmers is continuously decreasing, causing a farm labor shortage [5]. Efficient pest control is essential. Many researchers have studied various sprayers for effective and efficient pest control. Moreover, recently considerable attention has been focused on the use of agricultural spraying drones [6-9].

Agricultural spraying drone comprises a system that sprays plant protection products using remote or automatic control tool [10-12]. Plant protection products are sprayed from unmanned aerial vehicles and delivered to crops using gravity and downwash airflow from the rotor. Agricultural drone facilitates convenient operation, high work efficiency for targeted application, and high worker safety; therefore, its use by

farmers is gradually increasing [13-15]. In particular, agricultural drones are widely used in East Asia [16]. For example, China has 106,000 drones for pest control, and their work area is estimated to be 64 million hectares [17]. Xiongkui, et al. [18] analyzed the current pest control status using drones in China, Japan, and South Korea. In Europe, a few studies of the spray drone in mountainous terrain have been conducted in spite of regulation [19]. Several studies focused on improving the usability of agricultural drones have been also conducted [20,21].

With the growth of the agricultural spraying drone market, there is a huge concern about drift of pesticide and drop bounce from agricultural drone spray system [22]. In Europe, aerial spraying is generally not permitted due to the risk of drifts [23]. In South Korea, aerial spraying has also become a problem due to revised pesticide use standards in 2019. The quantity of drift is generally associated with the ratio of fine spray droplets [24]. Depending on the size of the spray droplets, more than 70% of the volume can be drifted [25].

Many factors including flight altitude, additives, and downwash can affect the spraying performance of agricultural drones [26-28]. Various studies have been conducted to analyze droplet downwash from drones [29-31]. The type of nozzle determines the diameter of sprayed droplets and the spray angle and shape, thereby substantially impacting spraying performance [32,33]. Chen, et al. [25] used four flat fan nozzles with different orifice sizes to analyze the effect of droplet size on droplet deposition and drift. They verified that deposition, penetration of droplets, and drift distribution were affected by the droplet size. Guo, et al. [34] used machine learning methods to analyze the droplet diameter and distribution pattern of the nozzles. Among the various nozzles, the flat fan nozzles are widely used for unmanned aerial sprayers [35], because of a high spray efficiency [36]. In contrast to flat fan nozzles, AI nozzles produce large droplets by including air bubbles inside the droplets and reduce drift of droplets [37-41]. However, there is a lack of research that actually uses drones equipped with AI nozzles to conduct control and analyze their effectiveness. Therefore, research is needed to actually perform aerial spraying with AI nozzles and compare performance differences with conventional nozzles when using drones.

When comparing the performance of two nozzles, the effect of pest reduction when pest control is conducted using agricultural drones must also be investigated [42]. The control efficacy is one of the most important criterion of the spraying system. However, most of previous studies have examined only the deposition of spray droplets using collectors to evaluate the physical spraying performance of agricultural drones. Furthermore, even when pest control is conducted using the same system, the penetration rate of plant protection products may vary depending on the size and shape of the crops, affecting pest control efficacy [25,43,44]. However, only few studies have been conducted to compare the differences in the pest control efficacy of crops when using agricultural drones.

The main objective of this study was to compare spraying performance of the flat fan nozzle and the AI nozzle when using a drone. To compare performance, the deposition, penetration rate, and control efficacy were analyzed. The deposition and penetration rates of sprayed droplets were analyzed and compared while performing aerial pest control using water sensitive paper. To compare the differences between crops, the experiment was performed on soybeans and rice. Crops were collected after pest control to compare control efficacy by investigating the yield and damage caused by pests.

2. Materials and Methods

2.1. Experimental site

The experiments were conducted at an farmland in Gimje, South Korea (Figure 1). The experimental field was where rice and soybeans were cultivated, and the areas for rice and soybean cultivation were 4,000 m² respectively. Rice and soybeans are the main

food crops in South Korea, and recently, soybean cultivation in paddy fields has been increasing, so both were selected as target crops. The rice variety was Sindongjin, which was planted on June 2 with a planting density of 15 plants/m^2. The soybean variety was Daechan, which was planted on May 17 with a planting density of 8.3 plants/m^2. The spraying was conducted around 9 am to minimize the influence of wind. The weather conditions during the experiment were measured using a kestrel 5500 weather meter (KestrelMeters, USA). The temperature during the experiment was 20.9°C ~ 25.3°C, and the wind speed was 1 ~ 2 m/s. There were no significant obstacles that affected pest control around the experimental site.



Figure 1. View of experimental site.

2.2. Equipment

The agricultural drone used in the experiment was a multicopter (SG-10p, Hankooksamgong, Seoul, Korea) with eight rotors (Figure 2). An agricultural drone was equipped with a flight controller (K++, JIYI, Shanghai, China). Maximum thrust of rotor is 5.1 kg. The detialed specifications of the agricultural spraying drone are listed in Table 1. The pump installed on the drone had a rated pressure of 0.8 MPa and a rated flow rate of 5.5 L/min. During the experiment, the chemical solution tank was filled with 10 L of the plant protection product solution before the flight. Only the two front nozzles were used to eliminate the overlapping effect of spraying the front and back nozzles. The nozzles were installed in the pipe located just below the rotor. The horizontal distance between the nozzles was 158 cm and the spray width of the drone is 4 m. The drone was operated by a professional using a remote control (T12 Data link Remote Controller, Skydroid, Quanzhou, China).

Table 1. Specifications of agricultural spraying drone.

Parameter	Value
Dimension (mm)	2075 (W) × 2075 (L) × 700 (H)
Total weight (kg)	14.5
Fligt controller	K++
Maximum Thrust (kg/rotor)	5.1
Maximum takeoff weight (kg)	24.9
Rated pressure (MPa)	0.8
Rated flow (L/min)	5.5
Capacity of solution tank (L)	10
Spray width(m)	4
Number of used nozzles	2



Figure 2. Agricultural spraying drone (SG-10P).

Conventional flat fan nozzles (XR110015VS, Teejet Technologies, Glendale Heights, IL, USA) and AI nozzles were used with drones. The XR110015VS has a flat fan-shaped spray form and the droplet size is classified as fine on a general spraying pressure. In the AI nozzle, the sprayed droplet diameter enlarges via air induction. The AI nozzle is less affected by wind compared with other nozzles. To develop a new AI nozzle for aerial spraying, a research on nozzle design factors was conducted and a new AI nozzle was developed based on it [40]. The developed AI nozzle has a spray rate of 0.6 LPM, an air to liquid mass ratio (ALR) of 0.0005, and an spray angle of 110 degrees. The volume median diameter (VMD) was measured based on the standardized method to identify the characteristics of the droplets sprayed from the two nozzles [45]. The VMD is an important factor in determining the amount of drift because it determines how far the droplets travel horizontally in the wind. If the VMD of the spray droplets is smaller, spray droplets can move further away depending upon the wind speed and air inversion characterisitcs at the time of spraying [46]. The measurement results showed that the VMDs of the flat fan and AI nozzles were 189 and 450 μm, respectively. The specifications of the nozzles are listed in Table 2.

Table 2. Characteristics of flat fan and AI nozzle.

Nozzle	Pressure (MPa)	Spray angle	VMD (μm)
XR110015	0.28	110	189
AI	0.28	110	450

2.3. Evaluation of Spray coverage and penetration

To analyze the effect of nozzle type on coverage and penetration, the agricultural spraying drone was equipped with a flat fan nozzle and an AI nozzle and sprayed with water in September 6 and October 5, 2021. The drone flew at a height of 3 m above the ground and a speed of 2 m/s during the experiment. The flight distance of single spraying was 40m. The pressure of pump was set to 0.28Mpa based on the nozzle recommendation [45]. The flow rate of pump at this pressure was 1.2 L/min. The sprayed droplets were collected using water sensitive paper (76 mm × 52 mm, Teejet Technologies, Glendale Heights, IL, USA) [47]. Since the water sensitive paper is sensitive to moisture, the humidity was controlled below 80% by draining the water in the rice field the day before the experiment. To minimize the effects of humidity, the paper was put out immediately prior to spraying and collected a few seconds after the drone sprayed the plant protection product. Three sampling points were arranged along the perpendicular direction of the agricultural drone flight route symmetrically with three repetitions (Figure 3). The

interval distance between sampling points was 2 m. The total length of the sampling points was designed for the effective spray width. The distance between flight center line was 10 m and while the drone was returning, the spraying stopped. The water sensitive paper was attached to the angle-control label stand (Figure 4). The water sensitive paper was installed at two lelvels: the canopy (h_1 = 80 cm) and middle point (h_2 = 40 cm) of the crop at each sampling point. The collectors were installed at three points on the flight path. After the experiment, the each water sensitive paper was sealed in a zipper bag to block contact with moisture and delivered to the laboratory. The images of the water sensitive paper were obtained using a red, green, and blue camera and analyzed via binarization.

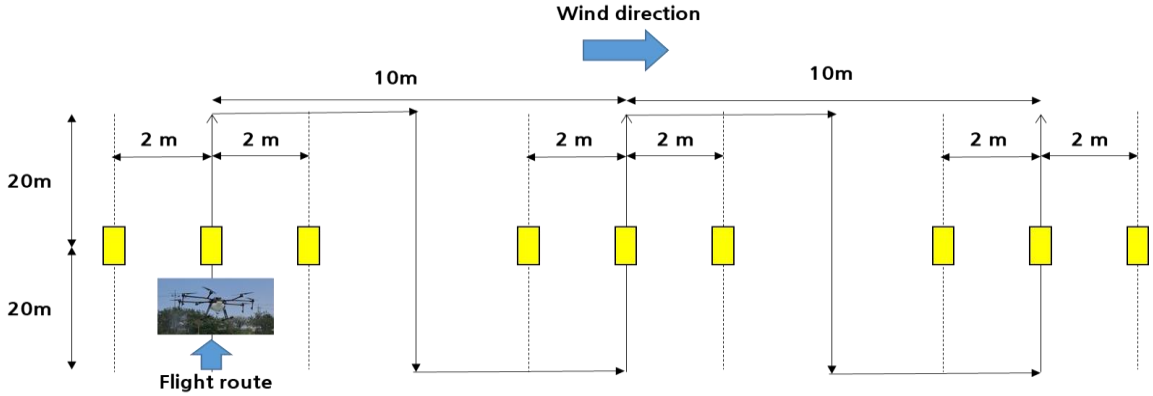


Figure 3. Layout of flight path and collectors

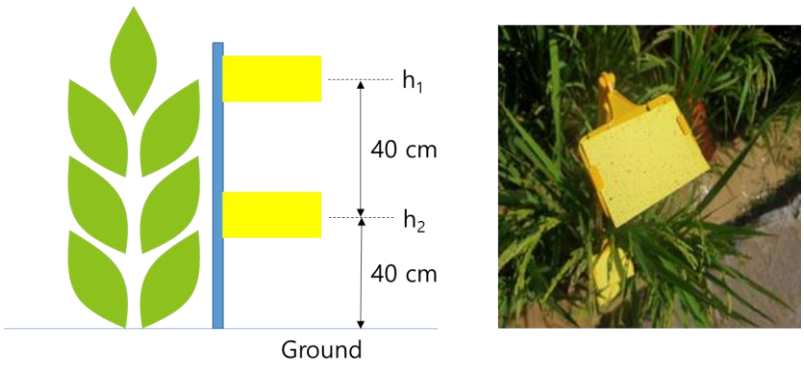


Figure 4. Arrangement of water sensitive paper and angle control label stand

The coverage and penetration ratio (PR) were measured to evaluate the nozzle spray performance because the amount of agent delivered to the surface or inside the crop affects control effectiveness. Coverage refers to the ratio of the droplet deposition area on the collector to the entire collector area. The amount of deposition can be compared based on coverage (Equation 1) [48]. The collector located at the canopy was used to analyze the coverage. The PR was measured to identify the ratio of agents to be delivered inside the crop. PR is important, especially for leafy plants, because it affects the delivery of the agent [49]. The PR was calculated using the ratio of droplet areas attached to the canopy and middle point of crop (Equation 2). R (Version 4.2.2, The R Foundation), a statistical analysis software, was employed to analyze the data. A two-way analysis of variance was conducted to analyze sensitive factors affecting the spray performance.

$$C = \frac{A_D}{A_W} \quad (1)$$

$$PR = \frac{C_2}{C_1} \quad (2)$$

where C is coverage, A_D is total area of droplets deposited, A_W is total area of water sensitive paper, PR is penetration ratio, C_1 is coverage of water sensitive paper at h_1, C_2 is coverage of water sensitive paper at h_2.

2.4. Efficacy analysis

The plant protection product was sprayed three times on rice and soybeans to compare the pest control efficacy based on the nozzle type in July and August 2021. Insecticides and fungicides are shown in Table 3. The plant protection product was diluted with water in a ratio of 1:8. The amount of plant protection product sprayed in each pest control operation for each plot was 0.44 L.

Table 3. Ingredients of plant protection products.

Spraying	Date	Plant Protection Product	Dosage
		Rice	
1	Jul. 16	20 % Ferimzone + 1.5 % Fluxapyroxad + 8 % Etofenprox + 3 % Metaflumizone	0.44L
2	Aug. 5	6% Azoxystrobin + 5 % Validamycin A + 10 % Etofenprox	0.44L
3	Aug. 12	8 % Etofenprox + 3 % Metaflumizone + 30 % Ferimzone + 3 % Thifluzamide	0.44L
		Soybean	
1	Jul. 5	8 % Etofenprox + 3 % Metaflumizone	0.44L
2	Aug. 5	6 % Azoxystrobin + 5 % Validamycin A + 10 % Etofenprox	0.44L
3	Aug. 12	8 % Etofenprox + 3 % Metaflumizone + 13.6 % Boscalid + 8% Pyraclostrobin	0.44L

The rice and soybean field was divided into three areas: the area of pest control using an AI nozzle, the area of pest control using an flat fan nozzle, and the nontreated area (Figure 4). The total area of 4000 m² for each crop was divided into areas of 1600, 1600, and 800 m². To reduce experimental error, the seed variety, soil condition, and cultivation method were the same between treatments. The drone worked across the plot and flew perpendicular to the boundary to minimize the impact on neighboring areas. Based on the treatment, the yield and damaged crop ratio caused by pests and diseases were investigated. In the case of rice, we targeted rice blast and rice stem borer and sheath blight, and in the case of soybeans, we targeted anthracnose, litura and clavatus. For sheath blight, rice stem borer, anthracnose and litura, the percentage of affected stems was examined. For rice blast, the percentage of affected ears was examined. For anthracnose and clavatus, the percentage of affected soybean was examined. Once the plant reached full maturity, a harvest was conducted for pest inspection and production investigation. The three subplots per treatment, area of 3 m × 1.2 m, was selected and investigated by collecting crops for yield and damaged crop ratio data. Duncan's test was conducted to analyze the difference between the experimental results.

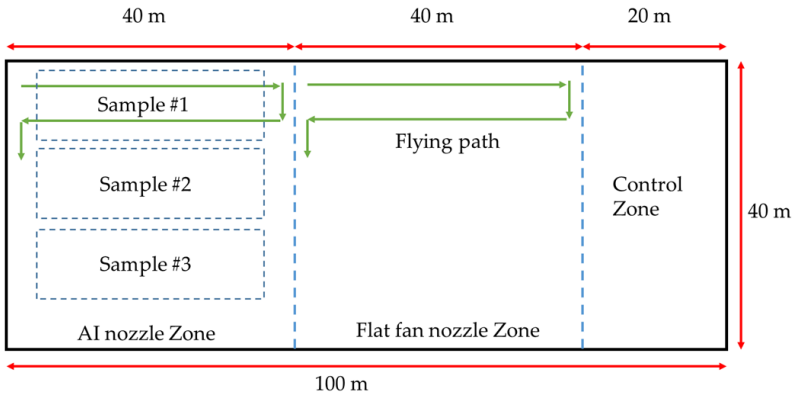


Figure 4. Layout of field for experiment treatment.

3. Results and Discussion

3.1. Coverage and penetration ratio of spray

The analysis of the coverage of droplet deposition by plants and nozzles showed that the coverage of experiment with AI nozzle (5.05 and 3.35 %) was 2.5 times higher than that of experiment with the flat fan nozzle (2.11 and 1.44 %) in both plants (Figure 5). When the same amount of spray is applied using both nozzles, an increase in deposition indicates a decrease in drift. This means that in drone aerial sprayers, just like in ground-based sprayers, the use of AI nozzles reduces drift compared to the use of flat fan nozzles. The larger diameter of the droplets sprayed from the AI nozzle resulted in less drift, consistent with previous research [25]. However, Hunter, et al. [50] showed that coverage decreases as the size of the droplet increases. This appears to be caused by downwash from the drone affecting the behavior of the spray droplets. For more accurate analysis, a downwash analysis of the drone should also be performed. According to two-way analysis of variance, there is significant difference only in the effect of the nozzle type ($p < 0.05$) (Table 4). This means that it is useful to use AI nozzles to deliver more spray droplets to the crop during spraying operations. Although the average deposition of rice was higher than that of soybeans, there was no significant difference by plant [51,52]. Deposition of droplets is affected by the height of the crop, size of the spray drops and wind speed, but in this study the crops were of similar height, so there does not seem to be a difference in coverage [53].

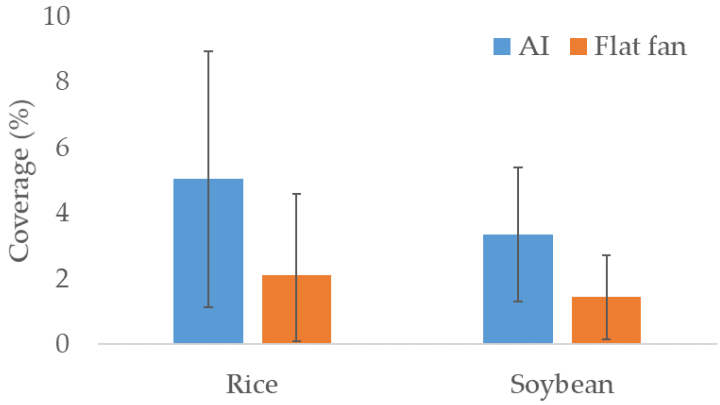


Figure 5. Coverage of droplet deposition by plants and nozzles.

Table 4. Two-way analysis of variance of droplet deposition.

Factor	Degree of freedom	Sum of Squares	F	*p*-value
Plant	1	6.15	0.764	0.3904
Nozzle	1	43.9	5.450	0.0279
Plant × Nozzle	1	1.92	0.238	0.6300

C_2 of AI nozzle were 1.68% in rice and 1.12% in soybean. And C_2 of flat fan nozzle were 0.27% in rice and 0.73% in soybean. The PR averages of the AI nozzle were (27.4 and 33.3 %) and those of the flat fan nozzle (19.0 and 31.5 %) respectively (Figure 6). To analyze the effect of plant and nozzle on PR, a two-way analysis of variance was performed and it was found that there was no significant difference in the treatment (Table 5). According to previous research, it is expected that larger size spray droplets have a greater PR [25]. However, in this study, spray droplets applied to soybeans using the flat fan nozzle resulted in higher than expected C_2. After checking the experimental data, the C_2 value was measured to be higher in the downwind direction in two out of three iterations. This

may have been caused by a temporary strong wind at the time of the experiment, and we believe that it needs to be improved through additional experiments in the future.

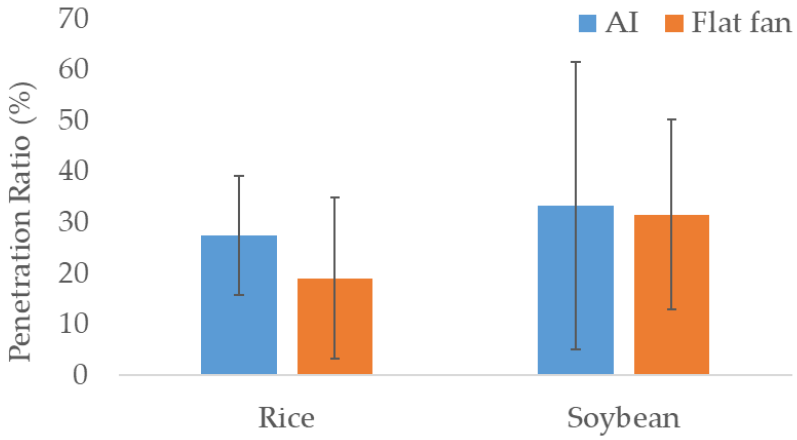


Figure 6. Coverage of droplet deposition by plants and nozzles.

Table 5. Two-way analysis of variance of penetration ratio.

Factor	Degree of freedom	Sum of Squares	F	*p*-value
Plant	1	1104	2.668	0.117
Nozzle	1	398	0.962	0.337
Plant × Nozzle	1	2	0.005	0.947

3.2. Control efficacy

The crop productions at sprayed areas were higher than that of non sprayed area for both crops (Table 6). To compare the difference caused by the nozzle, Duncan's test was conducted to determine whether there was a difference in crop production. As a result, no significant difference was found between the experimental groups using AI and flat fan nozzles for both crops ($p < 0.05$). Based on the coverage measurements in 3.1, the amount of spray droplets delivered to the crop canopy was higher with the AI nozzle, but there was no difference in the PR, so there was no difference in yield. And, it is considered that this is the result of trying to minimize the impact of various factors on crop yields, but not being able to fully control them. Also, the increased size of the spray droplets resulted in increased deposition with less drift, but the decreased surface area seems to have reduced the effectiveness. Further research is needed to determine the optimal spray droplets size.

Table 6. Crop production rate by treatment.

	Rice (g/m²)	Soybean (g/m²)
AI nozzle	465a	324a
flat fan nozzle	449a	309a
Control	322b	240b

* Duncan's test, $p<0.05$

To compare direct pest control efficacy, the damage ratio of rice caused by pests and diseases was investigated. The investigation results showed that in case of AI nozzle treatment, the damage ratios of rice blast, rice stem borer, and sheath blight were 39.3%, 1.0%, and 6.5%, respectively; in case of flat fan nozzle treatment, these values were 42.0%, 2.9%, and 8.0%, respectively; and for the control group, these values were 71.1%, 7.6%,

and 35.0%, respectively. The damage ratios caused by three pests and diseases were reduced by 6.4%, 65.5%, and 18.7% when using AI nozzles compared with those when using flat fan nozzles. Therefore, the AI nozzle is shown to have better control efficacy, giving some indication of smaller drop drift using the conventinoal nozzles.

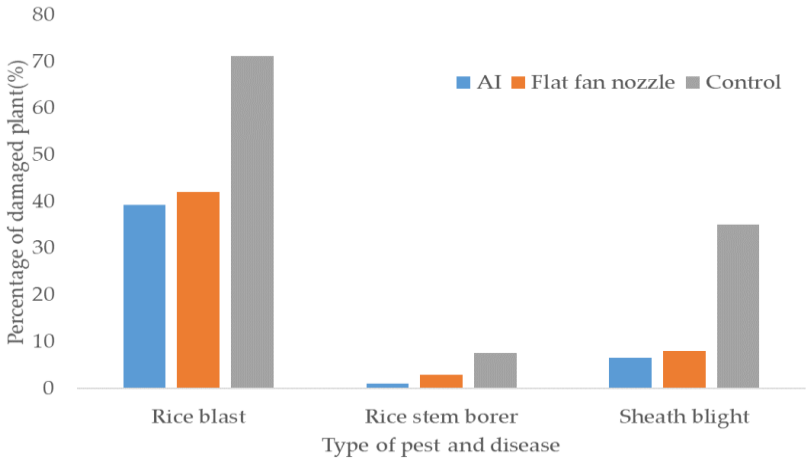


Figure 7. Control efficacy of rice after spraying.

The damage ratios of soybeans caused by pests and diseases were also investigated (Table 7). The pest that causes damage to the leaves was anthracnose and the insect was litura. And the pest that damages grain was anthracnose, and the insect was clavatus. It was shown that the damage caused by pests outweighed the damage caused by diseases and that the leaf damage was more severe than grain damage. For more detailed analysis, Duncan's test was conducted to determine whether there was a difference in damage ratios. However, no significant difference was found between the experimental groups using AI and flat fan nozzles for both crops ($p < 0.05$). Similar to the results of the production investigation, there was no significant difference in the PR values between treatments, so it seems that there is no difference in control efficacy. When analyzing the effects of aerial control in the future, it is considered more accurate to examine PR values rather than canopy coverage. Wang, et al. [54] conducted a study using four different types of sprayers and found that control efficacy varied depending on the type of sprayer. Further analysis is needed to determine if the no significant difference is caused by a small difference from the nozzle or other factors (e.g. wind speed).

Table 7. Control efficacy of soybean after spraying.

	Damaged Leaf Ratio		Damaged Grain Ratio	
	Disease (%)	**Pest (%)**	**Disease (%)**	**Pest (%)**
AI nozzle	0.5a	11.8a	2.2a	3.6a
flat fan nozzle	0.7a	15.9a	2.4a	4.7a
Control	2.3b	49.7b	8.0b	18.4b

* Duncan's test, $p<0.05$

4. Conclusions

The number of farmers using spraying drones is increasing owing to its various advantages. However, spray drift has been a challenge in aerial spraying system. To address this issue, AI nozzle with an effective drift reduction capacity was used. However, there is few research that installed AI nozzles to drone and analyze their effectiveness. In this study, AI and flat fan nozzles were installed on drones to evaluate their spray performance. Moreover, the pest control performance was also evaluated. The deposition and penetration ratios were measured using flat fan nozzle and AI nozzle. Pest control

efficacy was analyzed based on the type of target crops (rice and soybean). The crops used were rice and soybean. The study results are listed as follows:

1. For both crops, coverage was more than 2.3 times higher when using AI nozzles compared with that when using flat fan nozzles. The larger size droplets of the AI nozzle apparently reduced drift, which was attributed to increased deposition of sprayed droplets. A two-way analysis of variance showed that the effect of the nozzle on the coverage was significant ($p < 0.05$). For the effect of the plant on coverages, there was no significant difference.
2. The penetration ratios of both nozzles were analyzed. A two-way analysis of variance showed no significant difference due to the treatment method. It seems that weather conditions may have affected the results of the experiment. Previous studies of vertically growing maize, which has a similar morphology to rice, have yielded different results than this study, and additional analysis is required.
3. The crop production rate was investigated. Duncan's test showed no significant difference between the experimental groups. Environmental and genetic factors seem to have influenced production. Also, it seemed that the decreased surface area reduced the effectiveness.
4. For the control efficacy, Duncan's test showed no significant difference between the experimental groups. As the results of the production investigation, similar PR values between treatments made no difference in control efficacy.
5. When measuring aerial spray performance, penetration rates must be measured in the same time.

The analysis of the aforementioned results showed that using AI nozzles instead of flat fan nozzles for aerial pest control increased droplet deposition of sprayed droplets. However, there was no significant difference in production and control efficacy. Thus, this study showed that aerial control with AI nozzles delivers more spray droplets to the field and the effect on control efficacy needs further study.

In this study, a single flight condition (2 m/s forward speed at 3 m height) was used to compare the effect of nozzle type on control performance. In the future, it is necessary to conduct experiments under various flight conditions, and/or to compare UAV loadings over time to drift. However, since it is difficult to control various conditions in the field, the primary analysis is performed through Computational Fluid Dynamics (CFD) simulation and supplemented by field experiments.

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