Static and In-Field Validation of Application Accuracy of Commercial Spray Drones at Varying Flow Rates

Ravi Meena[1], Simerjeet Virk[2], Coleman Byers[1]

[1]College of Engineering, University of Georgia, Athens, GA 30602, USA

[2]Department of Crop and Soil Sciences, University of Georgia, Tifton, GA 31793, USA

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Abstract.

Spray drones are becoming common application technology for pesticide applications, but limited information is currently available regarding their performance. A study was conducted to assess the application accuracy of two commercially available agricultural spray drones (DJI Agras T40 and Pegasus Robotics X100P) at varying flow rates. Two different types of testing and data collection (static and in-field validation) were performed for each spray drone at four different application rates of (18.71, 28.06, 37.41 and 46.77 L ha^{-1}) with each rate applied at 4.5 m s^{-1} speed, based on the target application rate. The static testing consisted of measuring flow rate from the nozzles for different target flow rates while the field validation consisted of measuring the amount of solution in the tank before and after actual application at the selected rates and speed. The data analysis for static testing results shows XAG P100 Pro consistently underdelivered the intended flow rates across the tested range of 1 - 11 L min^{-1}, except at 6 L min^{-1}. In contrast, the DJI Agras T40 generally over-delivered flow rates, except the highest target flow rate of 5.77 L min^{-1}. Furthermore, the DJI T40 exhibited asymmetrical behavior between its atomizers, particularly at lower rates of 0.57 - 1.74 L min^{-1}, with one overapplying and the other underapplying the target flow rate. Field testing data shows that XAG P100 Pro under-applied at lower target rates (18.7 and 28.0 L ha^{-1}) but over-applied at higher rates (37.4 and 46.8 L ha^{-1}). The DJI Agras T40 consistently over-applied across all tested target application rates. As industry and grower interest increases in precision, targeted applications with spray drones, it is important to understand the extent of application errors associated with spray drones and if certain best management practices for proper controller setup and/or selection of application parameters can be followed for effective pesticide applications with spray drones.

Keywords.
Spray drone, pesticide application, unmanned arial vehicle, precision agricultural.

Introduction

The use of pesticides in modern agriculture is crucial for protecting crops from weeds, pests, diseases, and to improve crop yields(Sinha et al., 2022). However, extensive pesticide applications in recent years have raised concerns regarding environmental impacts and human health risks (Gibbs et al., 2021; Hewitt et al., 2009; Langley and Mort, 2012). Globally, the pesticide market is projected to reach $81.3 billion by 2025, driven by the increasing demand for food production and the need to combat pest infestations (Anonymous, 2020). In the United States alone, over 0.5 million metric tons of pesticides are applied annually across various agricultural systems (Atwood and Paisley-Jones, 2017). While pesticides play a vital role in crop protection, their excessive or improper use can lead to environmental contamination, harm to non-target organisms like beneficial insects and wildlife, and potential risks to human health through pesticide residues on food products (Lan et al., 2017; Langley and Mort, 2012).

To address these concerns, there has been a growing emphasis on developing and implementing precision agriculture technologies that enable more targeted and efficient pesticide applications(Castaldi et al., 2017; Christensen et al., 2009). One such technology that has garnered significant attention is the use of unmanned aerial application systems (UAAS), commonly known as spray drones (Qin et al., 2016; Y. Huang et al., 2009). Compared to conventional ground-based sprayers, spray drones offer several advantages including ease of accessing and spraying difficult areas e.g. steep terrain, narrow spaces, or areas with dense vegetation (Huang et al., 2013). In some cases, spray drones can also provide more precise and targeted applications, reducing off-target drift and minimizing pesticide wastage (Hunter et al., 2020; Qin et al., 2016);Qin et al., 2019). Additionally, the use of drones can reduce soil compaction and crop damage associated with heavy ground equipment (Huang et al., 2009). The potential benefits of spray drones in reducing environmental impact and improving application efficiency have driven their rapid adoption in various agricultural sectors(He, 2018). However, their effectiveness relies heavily on accurate pesticide applications. Inefficient pesticide applications can lead to inadequate pest control, crop damage, environmental contamination, and economic losses (Giles and Billing, 2015).

As the adoption of spray drones in agriculture has increased, various commercial platforms with advanced capabilities such as variable-rate application and precision spot-spraying, are available. However, there is limited information available regarding the accuracy of pesticide applications performed by these systems across a range of operational parameters, such as varying rates, flight speeds and heights (swaths). Previous research has focused on various aspects, including the influence of meteorological conditions (Faical et al., 2014), drone altitude and speed(Martin et al., 2019), and different nozzle configurations (Xue et al., 2016). While these studies have provided valuable information, an investigation into the application accuracy across varying rates is still lacking. Therefore, this study aimed to evaluate the application accuracy (in terms of attaining target flow rate) of two commercially available agricultural spray drones, the DJI Agras T40 and the XAG P100 Pro, across a range of target flow rates - both in controlled settings and under field conditions.

Methodology

Spray Drone Systems

This study evaluated the application accuracy of two commercially available agricultural spray drones: the DJI Agras T40 (SZ DJI Technology Co., Shenzhen, China) and the XAG P100 Pro (XAG Co., Guangzhou, China). These drones represent two of the most commonly used spray drone platforms used by applicators in the US and are equipped with advanced features such as variable-rate application, spot spraying, and advanced navigation and control capabilities.

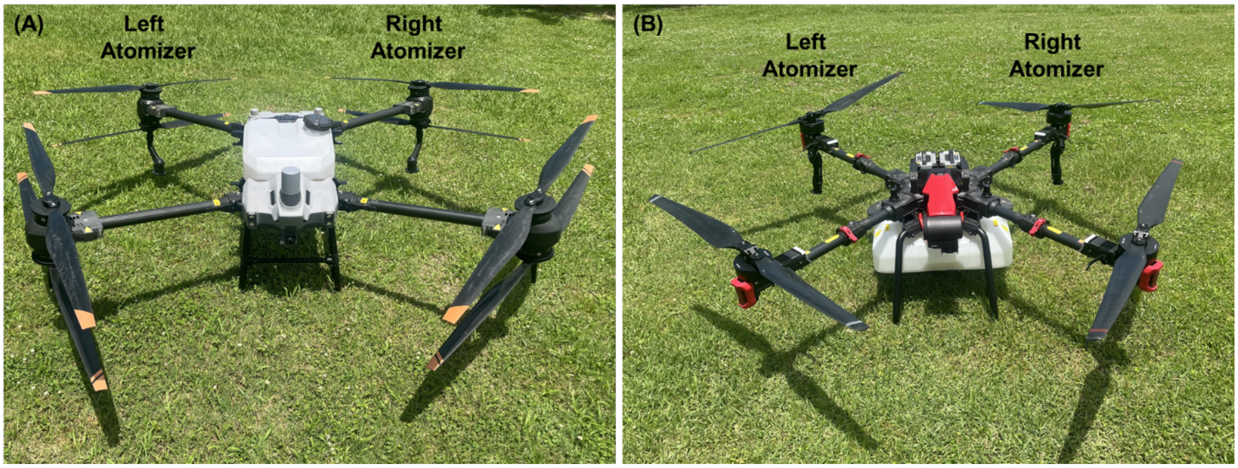

Fig 1. (A) DJI Agras T40. (B) XAG P100 Pro

The DJI Agras T40 and XAG P100 Pro have several differences in their spraying system specifications (Table 1) that may influence their application accuracy and performance. In terms of the spray tank capacity, the XAG P100 Pro has a larger capacity of 50 L compared to the 40 L capacity of the DJI Agras T40. Both drones are equipped with two rotary atomizing nozzles for spraying but differs in the droplet size range they can produce. The DJI Agras T40 can generate droplets ranging from 50 to 300 µm, while the XAG P100 Pro has a broader range of 60 to 400 µm. For maximum effective spray width listed by the manufacturer, the DJI Agras T40 has a wider coverage of up to 11 m, compared to the XAG P100 Pro's spray width range of 5 to 10 m. However, the XAG P100 Pro has a higher maximum pump flow rate of 22 L min^{-1} (combined for two pumps), whereas the DJI Agras T40 has a maximum flow rate of 6 L min^{-1} for each pump. Despite these differences in the spraying systems, both drones share similar hovering precision when utilizing RTK positioning, with a horizontal and vertical accuracy of ±10 cm. However, the XAG P100 Pro has a higher overall weight without payload at 46 kg, compared to the DJI Agras T40's weight of 38 kg without payload.

Table 1. XAG P100 Pro and DJI Agras T40 Specification comparison.

Specification	XAG P100 Pro	DJI Agras T40
Max Payload (kg)	50	40
Hovering Accuracy (RTK) (cm)	±10 (horizontal/vertical)	±10 (horizontal/vertical)
Spray Tank Capacity (L)	50	40
Max Flow Rate (L min^{-1})	22 (dual pumps)	12 (dual pumps)
Droplet Size (µm)	60-400	50-300

Testing Procedures

To evaluate the application accuracy of the DJI Agras T40 and XAG P100 Pro, the study employed two different types of testing: static testing and in-field validation. Static testing was conducted under controlled conditions to assess the application rate accuracy of both drone models at various target flow rates. This testing was conducted to collect and establish baseline performance data for each drone model across different flow rate ranges without influence of any other factors. Field testing was conducted to assess the accuracy of the XAG P100 Pro and DJI Agras T40 under field conditions. This testing involved evaluation of the application rate accuracy across a range of target flow rates, capturing the inherent variability and potential challenges associated with field operations.

Static Testing

For the static testing, the methodology was slightly different between the two drone systems due to variations in their operating systems and rate-setting features. For the XAG P100 Pro, the target application rate can be entered into the controller in liters per minute (L min^{-1}) for each of the two atomizers separately. The rates tested ranged from 1 to 11 L min^{-1} in increments of 1 L min^{-1} per atomizer. This corresponded to a total system flow rate range of 2 to 22 L min^{-1}. In contrast, for the DJI Agras T40, the target application rates can be entered in gallons per acre (GPA), which is a more common unit for agricultural applications in the US. Based on the target application rate and speed, the controller computed a flow rate (in gallons per acre) to meet the desired application rate. By entering the different target rates and speeds, the flow rates tested ranged from 0.5 to 5 GPA (47.8 L ha^{-1}) in increments of 0.5 GPA (4.7 L ha^{-1}). The results for both drones are presented in L min^{-1} for ease of comparison and to present all results in metric units.

To measure real-time flow during static testing, compact turbine flow meters (Model BV2000TRN050B, Omega Engineering Inc., Norwalk, CT) were installed in-line with both atomizers on each spray drone as shown in figure 2. A custom data acquisition system (NI USB 6210 DAQ, National Instruments, Austin, TX) and a LabVIEW program (National Instruments, Austin, TX) were used to record and log the real-time atomizer flow rates at a sampling frequency of 10 Hz (Fig. 2). This allowed for precise monitoring and recording of the flow rates from each atomizer during the static tests. For both drones, the flow rate from each atomizer was recorded over the range of the flow rates that can be attained by each drone. This was accomplished by inputting different combinations of target application rate (L ha^{-1}) and speed (m s^{-1}). The measured flow rates were then compared to the expected values based on the rate entered in the controller.

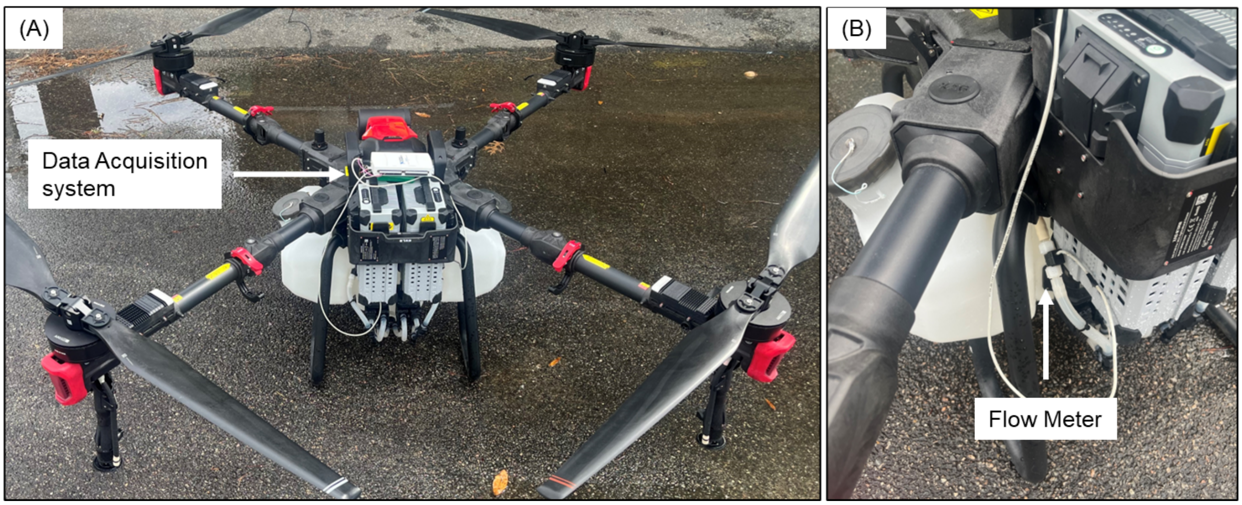

Fig 1. (A) NI USB-6210 DAQ. (B) A Flow meter was installed to measure flow rate.

The static testing was conducted in a controlled environment to minimize external factors that could influence the flow rate measurements. Each treatment (application rate and speed setting) was replicated four times to account for potential variability. The data collected during the static testing included the measured flow rates from each atomizer, the target application rates set in the drone controllers, and the real-time flow rate data logged by the data acquisition system, along with any relevant operational information or observations.

In-Field Validation

The field testing involved conducting actual spray applications with the drones under real-world conditions. The application rates tested for both the DJI Agras T40 and XAG P100 Pro drones were 18.7, 28.1, 37.4, and 46.8 L ha^{-1}, with three replications for each rate. All spray applications were applied at the constant speed of 4.4 m s^{-1} flight speed for both drones. A field with a known and exact area of 0.40 ha (1 ac) was mapped and used to design the flight plans for both drones. To achieve higher precision in the spray applications, Real-Time Kinematic (RTK) positioning was utilized by installing a base station (D-RTK mobile station for the DJI Agras T40 and an XAG RTK mobile station for the XAG P100 Pro) adjacent to the test area (Fig. 3). These RTK stations provided enhanced positioning accuracy, crucial for precise and consistent spray applications.

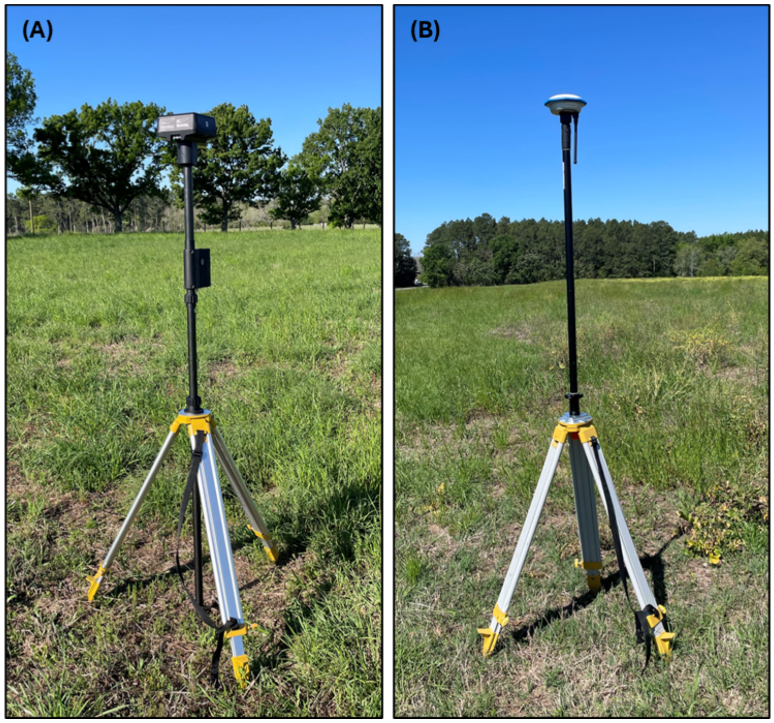

Fig 3. (A) D-RTK 2 High Precision GNSS Mobile Station and (B) XAG RTK Mobile Station

Before each application, the spray tank of each drone was filled with a known volume of water, and the initial weight of the drone, including the solution in the spray tank was recorded using a high-precision weighing machine (Dickey Scales, Model 8510, Mettler-Toledo, Inc. Ohio, USA) with an accuracy of ±10 g . After each application, the remaining volume in the tank was measured by weighing the drone plus the remaining solution again as shown in figure 4(B) and 4(C). The difference between the initial and final values was used to determine the actual volume of liquid applied during the planned operation. The actual applied rate was calculated by determining the volume of liquid dispensed over the known area (0.40 ha), using the difference in weight before and after each spraying operation.

Throughout both static and field-testing phases, the drone controllers logged as-applied information such as the applied rate and the flight speed. These parameters were compared with the target application rates and the measured values obtained from weighing the drones to assess the accuracy and performance of each drone model under varying conditions.

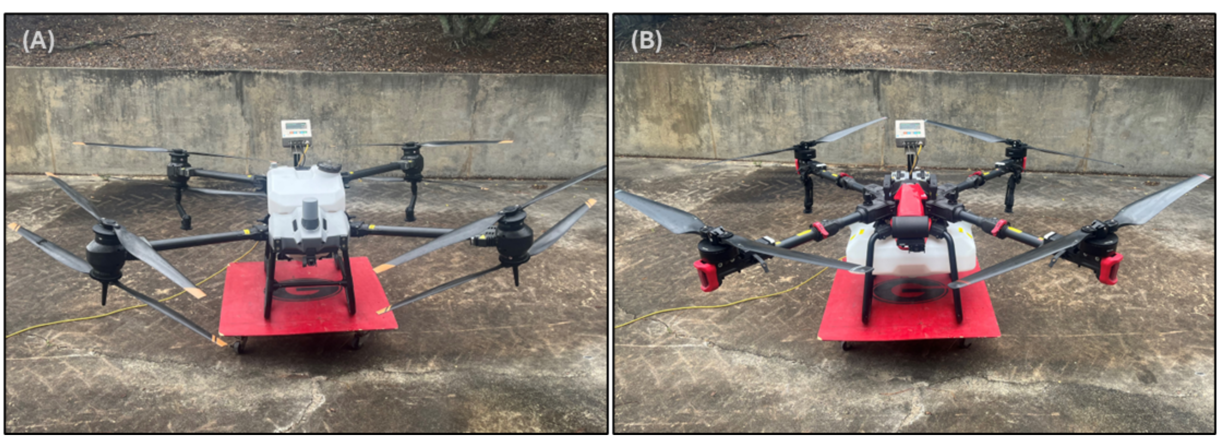

Fig 4. Illustration of weight measurement using a precision scale for the (A) DJI Agras T40 and (B) XAG P100 Pro.

Data Analysis

Both static and in-field data were analyzed to evaluate the application accuracy of the spray drones. The analysis focused on determining the extent of under- and over-application associated with each system at different application rates. For the static testing, the measured flow rates from each atomizer were compared to the expected flow rates based on the target application rates input into the drone controller. The percentage deviation between the measured and expected flow rates was calculated for each test run. For the in-field validation, the applied volumes calculated from the weight differences before and after each application were compared to the target volumes. Again, the percentage deviations between the applied and target rates were determined. The errors in application were categorized into three categories: within ±5%, within ±10%, and >±10% of the target application rate. These categories represent the percentage deviation from the target application rate or volume, with errors within ±5% considered acceptable, errors between ±5% and ±10% considered marginal, and errors greater than ±10% considered unacceptable.

Results

Static Testing Results:

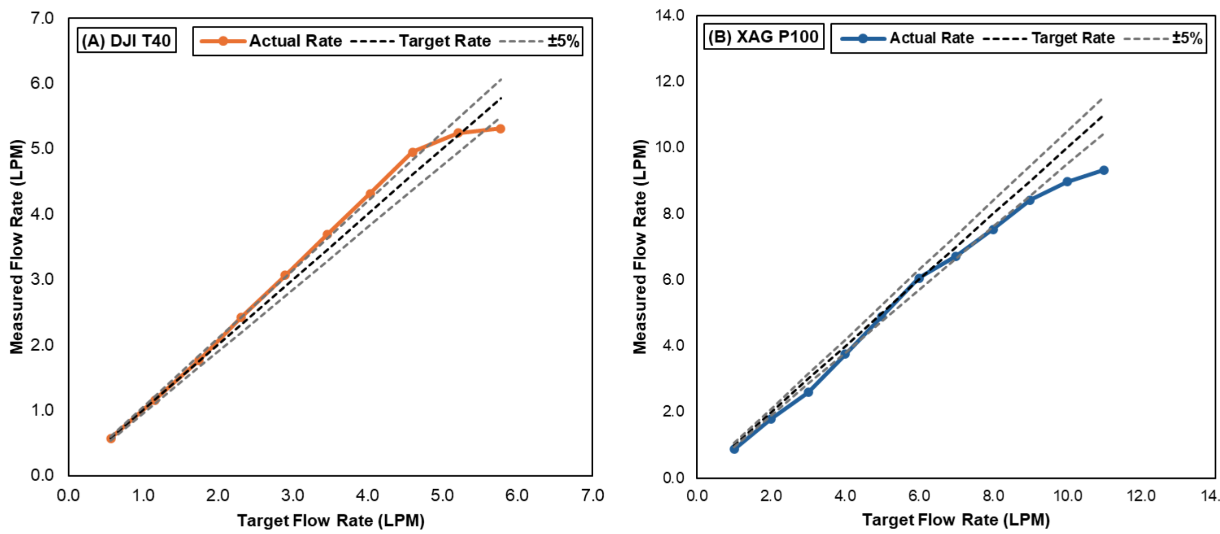

Fig 5. Graphical representation of the actual rate (dark solid lines) versus the target flow rate (black dashed line) during static testing.

The static testing performed on the XAG P100 Pro and DJI Agras T40 agricultural drones showed distinct patterns in their application accuracy across a range of target flow rates tested in this study. Before conducting the tests, both drones were calibrated using the procedure provided by the respective manufacturers to ensure optimal performance. In Table 2 and 3, the results are presented as percent difference between the target and measured rates for both left and right atomizers (left and right identified as front of the drone facing the user/operator).

For the DJI Agras T40, when considering the combined flow rate of both atomizers, it consistently delivered more than the intended application rate in most tests, except for the highest target rate of 5.77 L min^{-1}. For lower target flow rates (0.57 – 2.31 L min^{-1}), the application error was in the range of ±5%, with increase in targeted flow rate (2.90 – 5.77 L min^{-1}) the application error increased to ±10%, except for the target rate of 5.20 L min^{-1} the application error was in the range of ±5% (Fig. 5(A)). However, when considering both atomizers separately the DJI Agras T40 drone, at target flow rates from 0.57 to 2.31 L min^{-1}, most errors were within the ±5% to ±10% range for both atomizers, except at 0.57 L min^{-1} where the left atomizer exhibited an error greater than +10% while the right atomizer was greater than -10%. From 2.90 to 4.60 L min^{-1} target flow rates, the left atomizer consistently had errors greater than +10%, while the right atomizer remained in the ±5% to ±10% range (Table 2). An exception was at 3.46 L min^{-1}, where the left atomizer exceeded greater than +10%. At 5.20 L min^{-1} target flow rate, the left atomizer was in the ±5% range, while the right atomizer fell in the ±5% to ±10% range. At the highest target flow rate of 5.77 L min^{-1}, the left atomizer error was in the ±5% to ±10% range, but the right atomizer had an error greater than -10%. However, differences were consistently observed between the performance of the left and right atomizers across various target flow rates. At the lower and higher flow rate extremes, the errors tended to be greater, with some falling outside the ±10% range, especially for the right atomizer. For DJI Agras T40, these results indicate variations between the flow rates among the two atomizers for different target flow rates.

Table 2. Measured flow rates and percent difference between the target and measured rates for the DJI Agras T40 agricultural drone across different flow rates.

Target Flow Rate (L min^{-1})	Measured Flow Rate (L min^{-1})		% Difference	
	Left Atomizer	Right Atomizer	Left Atomizer	Right Atomizer
0.57	0.61	0.53	6.67	-6.67
1.15	1.21	1.10	4.92	-4.92
1.74	1.82	1.70	4.35	-2.17
2.31	2.50	2.35	8.20	1.64
2.90	3.14	2.98	8.50	2.94
3.46	3.79	3.60	9.29	3.83
4.03	4.43	4.20	9.86	4.23
4.60	5.07	4.83	10.29	4.94
5.20	5.36	5.13	2.91	-1.45
5.77	5.38	5.24	-6.89	-9.18

The combined flow rate of both atomizers of XAG P100 Pro exhibited significant under-application errors across most of the tested target flow rates, with a substantial number of errors falling in the greater than ±10% range. For two lowest (1 and 2 L min^{-1}) and highest (10 – 11 L min^{-1}) target flow rates, XAG P100 Pro applied less than target with the error range of >±10%, and as we move to middle range of tested target flow rates (3 – 9 L min^{-1}), application error get in marginal range of less than ±10%, and further for middle three rates (5, 6 and 7 L min^{-1}) application error get reduced to the range of less than ±5% (Fig. 5(B)).

At lower target flow rates from 1.0 to 3.0 L min^{-1}, both the left and right atomizers had unacceptable errors, with under-application exceeding ±10%. When the target flow rate increased to 4.0 L min^{-1}, the left atomizer's exhibited under-application within ±10%. The 5.0 and 6.0 L min^{-1} target rates were the only instance where both atomizers exhibited rate accuracy within ±95% (Table 3). However, as the target flow rates increased beyond 6.0 L min^{-1}, the errors again exceeded to less than ±10% for most target flow rates. Both atomizers had marginal under-application errors, less than ±10%, for the target flow rates between 7.0 and 10.0 L min^{-1} as presented in table 3 (Table 3). At the 10.0 L min^{-1} target flow rate, the left atomizer's error was less than ±10% under-application range, while the right atomizer exceeded ±10%. The most significant errors occurred at the highest target rate of 11.0 L min^{-1}, where both atomizers demonstrated under-application greater than 10%. Overall, the XAG P100 Pro struggled to maintain application rates within acceptable limits across most of the tested flow rates, with a predominance of unacceptable under-application errors, particularly at the lower and higher flow rate extremes. The 5.0 and 6.0 L min^{-1} target flow rate appeared to be the only values where the drone exhibited relatively better accuracy.

Table 3. Measured flow rates and percent difference between the target and measured rates for the XAG P100 Pro agricultural drone across different flow rates.

Target Flow Rate (L min^{-1})	Measured Flow Rate (L min^{-1})		% Difference	
	Left Atomizer	Right Atomizer	Left Atomizer	Left Atomizer
1.0	0.9	0.9	-12.9	-12.9
2.0	1.8	1.8	-9.2	-11.0
3.0	2.6	2.5	-11.7	-15.5
4.0	3.8	3.7	-4.4	-8.0
5.0	4.9	4.9	-1.8	-2.3
6.0	6.0	6.1	0.3	1.6
7.0	6.6	6.8	-5.5	-2.7
8.0	7.5	7.5	-6.1	-5.7
9.0	8.5	8.4	-6.0	-7.0
10.0	9.0	8.9	-9.7	-10.8
11.0	9.3	9.3	-15.0	-15.5

The tendency of the XAG P100 Pro to consistently undershoot the flow rate and the DJI Agras T40 to overshoot could be influenced by various factors, including hardware configurations, software algorithms, and/or calibration procedures. Regardless of the underlying cause(s), the observed errors, particularly the unacceptable deviations, are concerning as they can lead to significant under- or over-application of pesticides and other agricultural inputs. Maintaining accurate flow rates aligned with label recommendations is crucial for effective pest control and minimizing any potential yield losses.

Field Testing Results:

The field testing evaluated the application rate accuracy of the XAG P100 Pro and DJI Agras T40 agricultural drones under real-world application conditions. For the XAG P100 Pro, at the highest tested target application rate of 46.79 L ha^{-1}, it over-applied as compared to the intended target with a marginal error of ±10% (Table 4). When the target rate was lowered to 37.41 and 28.05 L ha^{-1}, the XAG P100 Pro's accuracy improved, with over-application within acceptable range ±5% error as shown in figure 6. However, as the target rate decreased to 18.71 L ha^{-1}, the under-application increased to 10% error below the target rate. This suggests that the P100 Pro's accuracy may be influenced by the target rate, with a tendency to over-apply at higher rates and under-apply at lower rates. In contrast, the DJI Agras T40 demonstrated a consistent trend of over-application across all tested target rates as presented in table 4. The measured rate for the Agras T40 was consistently greater than the target rate, though mostly within an acceptable ±5% range (Fig. 6). At the highest tested rate, it over-applied slightly above the 5% error.

While both drones exhibited varying degrees of under or over application of intended application rates, the DJI Agras T40 demonstrated a more consistent trend with actual rates mostly within an acceptable ±5% range, while the XAG P100 Pro's accuracy varied based on the target rate, shifting from over-application at the higher rates to under-application as the target rate decreased. These field-testing results highlight the importance of understanding and accounting for the unique characteristics and tendencies of each drone model when optimizing application parameters to ensure accurate delivery and dosage of pesticide to the fields/crops. Appropriate adjustments and calibrations may be necessary to achieve the desired application rates, considering the inherent tendencies observed during field testing. Furthermore, understanding the factors influencing the accuracy of spray drone applications, such as hardware and software configurations, operational settings, and environmental conditions, is crucial for developing best management practices and optimizing the use of this technology.

Table 4. Measured flow rates and percent difference between the target and measured rates for the DJI Agras T40 and XAG P100 Pro agricultural drones across different flow rates in field conditions.

Target Flow Rate (L ha^{-1})	Measured Flow Rate (L ha^{-1})		% Difference	
	DJI Agras T40	XAG P100 Pro	DJI Agras T40	XAG P100 Pro
18.7	19.1	17.3	2.1	-7.6
28.0	28.8	26.7	2.6	-4.7
37.4	38.6	38.2	3.2	2.0
46.8	49.1	50.0	5.1	6.8

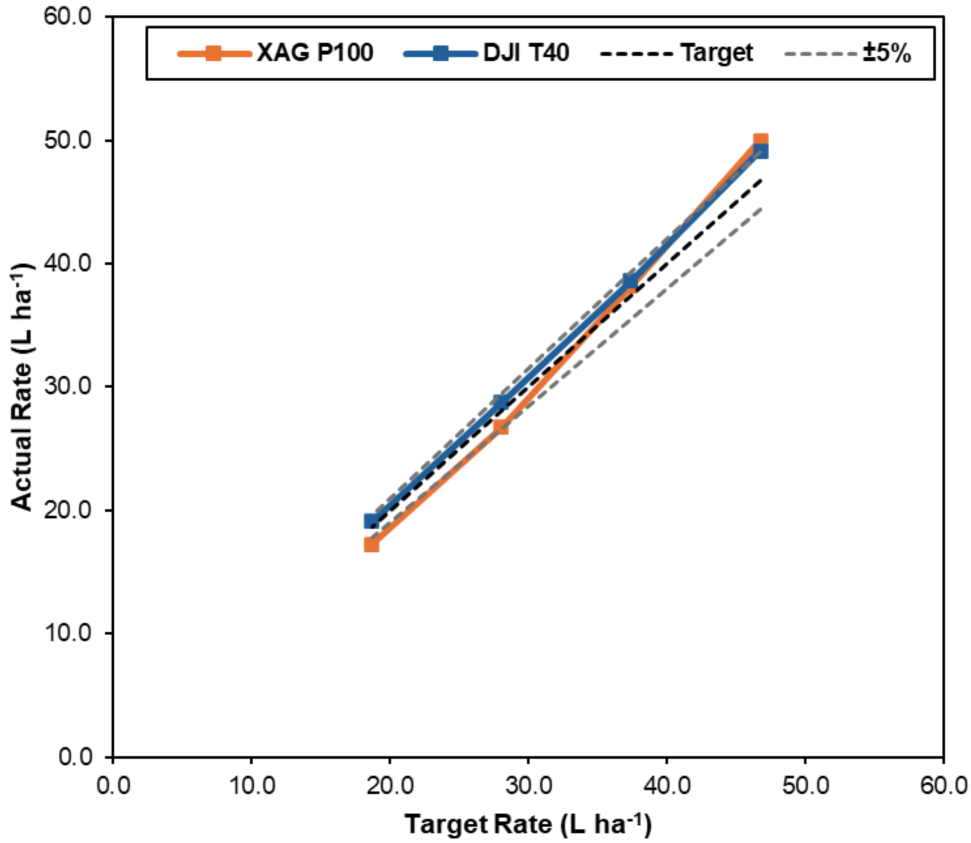

Fig 6. Graphical representation of the actual rate (dark solid lines) versus the target application rate (black dashed line) during field testing.

Conclusion

The objective of this study was to evaluate the application rate accuracy of the XAG P100 Pro and DJI Agras T40 agricultural drones under both controlled static conditions and field conditions. The following conclusions can be drawn from the testing conducted in this study:

Static Testing:

- The XAG P100 Pro applied less than the intended targeted flow rate across the whole range of tested flow rates from 1 – 11 L min^{-1}, except for the target flow rate of 6 L min^{-1}.
- The DJI Agras T40 consistently delivered more than the intended application rate in most tests, except for the highest target rate of 5.77 L min^{-1}.
- The DJI Agras T40 displayed asymmetrical behavior between atomizers across the range

of tested target flow rates (0.57 – 5.77 L min^{-1}), but specifically at the lower rates (0.57 – 1.74 L min^{-1}) with one delivering more and the other delivering less than the target amount.

Field Testing:

- The XAG P100 Pro showed variable performance, with accuracy dependent on the target rate. For lower target flow rates of 18.7 and 28.0 L ha^{-1} drone applied less than the target flow rate, and for the higher target flow rates of 37.4 and 46.8 L ha^{-1}, it over-applied as compared to the target rate.
- The DJI Agras T40 consistently over-applied as compared to the intended target flow rate, maintaining this trend across all target application rates.

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