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Transversal distribution of a spray drone applying different nozzles and measuring methods

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ABSTRACT

In Switzerland, regulatory requirements mandated that spraying drones undergo a testing procedure, which included assessing their transversal spray distribution using a patternator. Various stakeholders have repeatedly expressed uncertainty as to whether these static measurements correctly reflect the real dynamic spray distribution or whether this type of measurement falsifies the spray pattern. Taking these uncertainties into account, the present study compared the static patternator method with dynamic field measurements using water-sensitive and filter paper. The three methods showed good agreement in the results. In contrast to the other two methods, the measurements on the patternator showed the lowest variability, which shows that hovering at the same point probably causes some compensation in the distribution. Different nozzles (flat fan, hollow cone, air induction nozzles) produce quite similar distribution patterns in all three measurement methods, whereby the injector nozzle with the largest droplets produced the best transverse distribution with a coefficient of variation of less than 10 %.

1. Introduction

Unmanned aerial spray systems (UASS) have seen exponential growth in China from 695 units in 2016 to 106,000 units in 2020 (Zhang et al., 2021). The same is true in Japan, where Umeda et al. (2022) cite an expansion from an area sprayed by drones of 684 ha in 2016 to 119, 500 ha in 2021. DJI, the largest manufacturer of UASS, claims to have 200,000 agricultural drones in use (DJI, 2023), demonstrating the importance of this global market. UASS are mainly used by smallholder farmers in East Asia for paddy rice production. In contrast, drones are rarely used on large fields in countries such as the USA, Latin America, Canada and Australia (Croplife, 2020; Ozkan, 2023). Their limited size results in higher costs compared to ground or conventional aerial spraying (Ozkan, 2023). However, new applications such as spot spraying and sensing are becoming increasingly attractive for larger farms. In Europe, there are only few UASS in use and are not in harmony with the ban of aerial application of plant protection products. However, since 2019, Switzerland has set up a particular procedure for the use of UASS in Agriculture. Companies can apply for an official registration, and each machine needs to pass a sprayer test (Anken, 2020). Switzerland was the first European country demanding a standard sprayer test for UASS in use. Up to now, more than 90 machines have been registered. They are mostly used to spray steep vineyards which are difficult to reach or not accessible by tractor and in addition they replace laborious and exposed manual work.

Vertical patternators with lamellae or discs are commonly used to test airblast sprayers and assess their vertical spray distribution. However, these tools cannot be used to test Unmanned Arial Spray Systems (UASS) due to their vertical orientation. Ismail et al. (2020) conducted a study where they tested a drone fixed in a hall on a rail to measure the distribution of the drones using water-sensitive paper. To do this, they controlled the motors directly. However, nearly all published studies on UASS distribution are done on agricultural fields where water-sensitive papers are fixed on the plant canopy. The review by OECD (2021) provides an overview of the field measurements conducted, and many of them show uneven distributions with coefficients of variance exceeding 50 %. This level of variation is considered unacceptable, as ISO 16122-2 requires field sprayers to have a coefficient of variation lower than 10 %. Therefore, there is a need to address this significant gap and define procedures to accurately measure the distribution of UASS, similar to

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other sprayers.

Since the introduction of UASS in Switzerland, a sprayer test utilizing a modified patternator designed for field sprayers with a groove length of 3 m and a width of 6 m has been employed to assess the transversal distribution of the spray liquid (Anken, 2020). This approach was chosen for its expediency and simplicity. However, a drawback of this method is that the airflow is directed towards an impermeable surface, created by the grooves of the patternator, rather than into an authentic crop canopy. This represents a simplification compared to the complexities of actual plant canopies. Given the differences between this approach and the actual application in the field, some questions are raised regarding its representativeness. If UASS are used to spray crops like rice or wheat in a juvenile stage, nearly bare soil is sprayed. This is comparable to a patternator. For field sprayers, this simplification has proven its performance for decades. In addition, the conditions in vineyards are very different in spring with few leaves compared to the full developed crop in summer. In any case, it is therefore very difficult to define representative conditions for this test procedure. Discussions about the accuracy of different measurement methods for sprayer testing are not new and in fact are well known for airblast sprayers. Vertical test benches consisting of air-permeable lamellae or non-permeable disks have proven to be useful. Allochis et al. (2014) showed that both methods deliver comparable results. It has to keep in mind that airblast sprayers create high air volumes (10–40,000 m^3 air/h) and windspeeds from 4 to 10 m/s (Balsari et al., 2016). In most countries the simplification to use disks collectors is accepted. Encouraged by the first positive results, Agroscope decided to introduce patternators to also test UASS. Today this method is applied by Agroscope in Ettenhausen (CH) and the Agricultural Chamber in Sion (CH). The experiences are positive and over 90 UASS have been tested so far.

Despite the generally positive experiences obtained during UASS tests in Switzerland, there have been reservations expressed regarding the static patternator's accuracy. These concerns stem from the fact that the drone hovers steadily at a fixed position during patternator measurements, while in a typical dynamic spray operation, the drone maintains a forward speed of approximately 2–3 m/s. This raises questions about whether the two flight modes (static/dynamic) yield similar distribution outcomes. To investigate this issue, this study compares the transversal distribution determined by a patternator with the dynamic ones determined with water sensitive paper or tracer collected with filter paper.

2. Material and methods

The transversal distribution of the spray liquid of a currently used Unmanned Aerial Spray System (UASS) has been tested using three different methods which were patternator (PAT), water sensitive paper (WSP) and filter paper (FP).

2.1. UASS, settings and nozzles

The UASS "Agras T16" (DJI, Shenzen, China) was employed for conducting the tests. The aircraft has a total weight of 39.5 kg and a width of 272 cm (distances between tips of the propellers). It's powered by 6 motors and is equipped with 8 nozzles located in 4 pairs at the external motors (Fig. 1). One nozzle is placed 35 cm below the middle of the motors and the second nozzle is placed at the same height shifted 18 cm towards the centre of the UASS. Notably, the two motors positioned at the front and at the back of the UASS are not equipped with nozzles.

Three different types of nozzles were used (technical indications according to Teejet (2023) and Lechler (2023)).

- Teejet XR 110-015, flat fan, producing "fine" drops (XR)
- Teejet TXA 80-015 cone jet, producing "fine" drops (TXA)
- Lechler IDK 120-015, flat fan with air injection producing "coarse" drops (IDK)

These nozzles were used with a flow rate of 520 ml/min according to a pressure of 2.5 bar.

Our practical experience with the patternator has revealed that an optimal flying height falls within the range of 2.5–3 m (Anken and Waldburger 2020). Lowering the flying height to 1 m resulted in a significant decrease in quality of the transversal distribution. Existing literature supports various flying height recommendations, with reported values of approximately 2 m (Nordin et al., 2021; Zhan et al., 2022), 1.5–2 m (Subramanian et al., 2021), 2.5 m (Fengbo et al., 2018), and 3 m (Zhang et al., 2020). Notably, Chen et al. (2021) demonstrated that increasing the flying height from 1 m to 3 m led to improved uniformity in droplet distribution. Consequently, a flying height of 3 m was selected for all measurements in this study.

Regarding the collecting tests by artificial targets, the optimal flight speed is indicated by many authors to be lesser than 4 m/s. Wen et al. (2019) demonstrated that when the speed exceeds 4 m/s, it leads to the formation of a horseshoe vortex. This vortex causes the stream tube to detach from the ground, no longer efficiently delivering the spray

Fig. 1. UASS hovering over the patternator (left) and UASS flying over the slats fixing the strips of water sensitive and filter paper (middle), UASS DJI T16 with 2 nozzles per propeller on external motors (right).

directly to the ground plane (Coombes et al., 2022). Flying at a speed of 2 m/s directs the airstream vertically toward the soil, as indicated by Zhang et al. (2020), who suggested an optimal flight speed of 3 m/s. To prevent the formation of a vortex, the presented trials were executed with a flight speed of 1.9 m/s for the tests with water sensitive and filter paper.

2.2. Trial location and weather conditions

All the measurements were conducted on a meadow in Tänikon (47.481°N, 8.906°E). The average wind speed during the measurements ranged from 0.8 m/s to 1.6 m/s, calculated as an average over 10-min intervals using data from the official weather station "Tänikon" (www.meteoschweiz.ch). No maximum wind gusts exceeding 3 m/s occurred during the measurement period (September 14, 2021, 09:35–12:00). The weather station is situated approximately 150 m away from the measurement site. There were no obstacles in between. The temperature during the measurements ranged between 22.0 and 24.8 °C.

2.3. Description of measuring technologies

A patternator according to ISO 16122-2 (2015) was used to determine the static transverse volume distribution of the sprayed liquid. The width of the patternator was set to 6 m and the groove length was enlarged to 3 m. At the rear and front ends, a vertical board of 20 cm was fixed to collect the fine drops pushed by the wind of the UASS. The liquid deposited in each groove was collected in 500 ml cylinders and manually read after each application. Throughout the measurement process, the drone maintained a hovering position above the center of the patternator at a height of 3 m, a configuration upheld for approximately 75 s. Each measurement was replicated three times.

The measurements of the drone hovering directly over the patternator were compared to those of real dynamic flight situations. To accomplish this, the drone flew over a 6 m long x 25 mm wide band of Water Sensitive Paper (WSP) (Syngenta Crop Protection AG, Basel, Switzerland) and a parallel band of filter paper (FP) 597 (Schleicher & Schuell, Dassel, Germany) showing the same dimensions as WSP. The paper strips were placed on supportive wooden slats 40 cm above the ground. The bands were placed 20 cm apart from each other (Fig. 1). The drone flew 3 m above the target papers (according to the radar of the drone and visual control) with a flying speed of 1.9 m/s over the middle of the slats, simulating a standard spray application of 100 l/ha. The filter paper was used to collect the tracer deposits (Helios SC500, Syngenta Crop Protection AG, Basel, Switzerland) which had been applied during the flights. The water sensitive paper was cut into 20 cm strips and the percentage coverage was determined using ImageJ software (https://imagej.net). The filter paper was cut into 25 cm pieces. The tracer was washed off using 50 ml of Isopropanol and then the concentration was subsequently determined using a portable fluorimeter (Syngenta Crop Protection AG, Basel, Switzerland). Three repetitions were conducted for each flight, and each procedure was iterated three times, yielding a cumulative total of 9 paper strips for each treatment.

Finally, all results were normalized to a measuring width of 20 cm. For the patternator, the readings from two individual grooves (each with a width of 10 cm) were added. Regarding the filter strips, the outcomes from the single 25 cm strips were computed, assigning them the weighting corresponding to the length they covered within the respective 20 cm interval.

To compare the three measuring methods the values of each measurement were linearly normalized by attributing 100 % to the maximum of each single measurement.

2.4. Statistical analysis

From the values measured on the patternator the coefficient of variation was calculated according to ISO 16122-2. In order to determine the ideal overlap to get a minimal coefficient of variation, three working widths were increasingly overlapped in 10 cm steps (Fig. 2). These steps were determined by the groove width of the patternator which was 10 cm. The assumption was, that the left wing of the UASS overlaps with the left wing after a 180° turn at the end of the field and the same was calculated for the right wing. It was assumed that the drone is always spraying in forward direction. For each incremental step of overlap, the coefficient of variation was calculated. For these values the minimal was selected as the final result. This approach was also used to identify the working width that yielded the most consistent distribution.

The relationships between the various nozzles and measuring methods were assessed through the utilization of linear regression models, which were computed using RStudio software, which is an integrated development environment for the R programming language (RStudio, 2024). Raw data are available on https://zenodo.org/.

3. Results

The different methods for the determination of the transversal distribution produced well comparable results. The same was the case for the three tested nozzle types.

3.1. Transversal distribution of the measurement methods

All three measuring methods employed to assess the transversal distribution of the spray liquid yielded comparable results across the board, as illustrated in Fig. 3. Each nozzle is graphed individually with all 3 measurement methods (Fig. 3A – XR, Fig. 3B – TXA and Fig. 3C – IDK). Lastly the standard deviation is considered for all nozzle for the 3 measurement methods (Fig. 3D).

The different coloured surfaces, indicating the average standard deviation, show strong overlapping areas across the working width. This indicates great similarities of the different measuring methods. Looking at the variability of the different measuring methods, the patternator showed least variations for all three nozzles (blue surfaces in Fig. 3). Both the filter and water sensitive paper showed higher variability across the three nozzles (larger coloured areas). This behaviour is also expressed by the average of the standard deviation of the different methods (Table 1). Specifically, for the three nozzles, the patternator yielded standard deviations ranging from 3.5 % to 5 %, while the two other methods yielded values ranging from 7.3 % to 14.5 %.

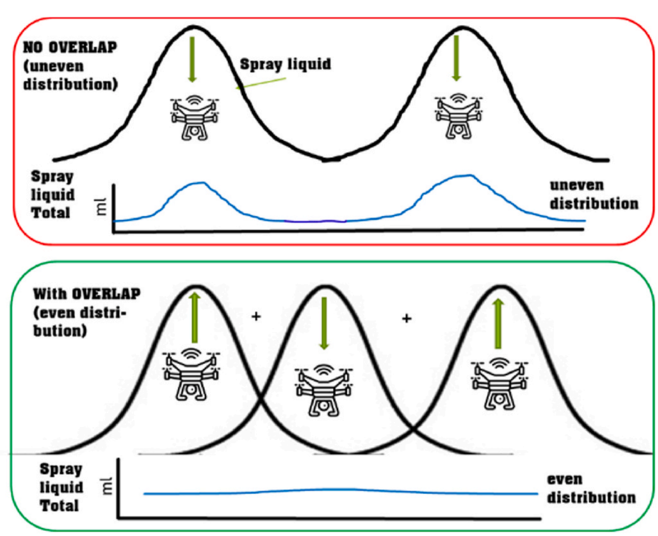

Fig. 2. Transversal distribution without overlap (top) and with optimized overlap (bottom).

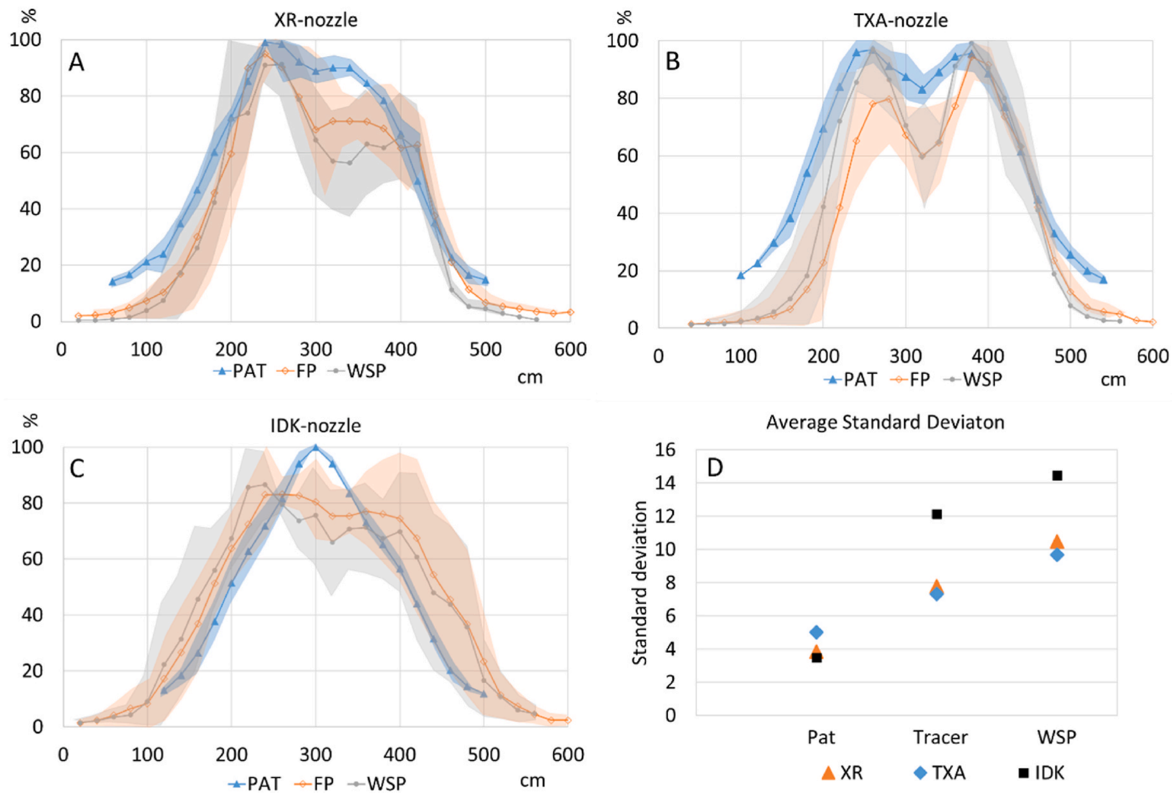

Fig. 3. Transversal distribution (%, maximum of each single measurement = 100) of the three nozzles (XR - A, TXA- B, IDK- C) measured on patternator (PAT), filter paper (FP) and water sensitive paper (WSP). X-axis represents the working width in cm. Each curve represents the average of three repetitions. The coloured surfaces indicate the average ± the standard deviation for each nozzle (A, B and C) and D shows the standard deviation for each treatment for all nozzles.

Table 1
Average standard deviation in % of the transversal distribution representing all width intervals and 3 repetitions.

	Patternator	Filter paper	Water sensitive Paper
XR	3.8	7.8	10.5
TXA	5.0	7.3	9.7
IDK	3.5	12.1	14.5
Average	4.1	9.1	11.5

3.2. *Relation between the different measuring methods*

The relation between patternator and filter paper is marked by a quite large variation (Fig. 4A). If the possible red outliers from the measurement IDK, repetition 1 are removed, then a R-square value (r^2) of 0.72 is achieved. The relation of patternator and water sensitive paper showed a higher variation and resulted in an r^2 of 0.61 (data not shown). The relation between filter paper and water sensitive paper showed a closer relation ($y = 1.00*x - 0.30$, $r^2 = 0.90$) (Fig. 4).

3.3. *Transversal distribution of the three nozzles*

When comparing the averages of three repetitions for the transversal distribution of the three nozzles as measured on the patternator, a relatively consistent distribution pattern is evident (Fig. 5). Specifically, IDK exhibited a tendency toward the smallest working width and displayed the most uniform distribution pattern.

Comparing the different nozzles to each other, measured on patternator, quite closer and significant relationships can be found (Fig. 6). The two flat fan nozzles XR and IDK nozzles showed a close linear

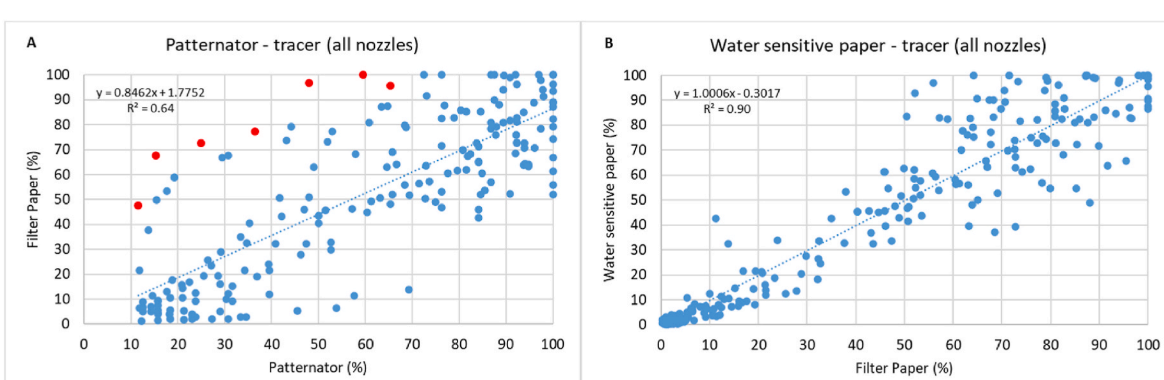

Fig. 4. Relation between filter paper and patternator (A) and the relation between water sensitive paper and filter paper (B) indicated for all 9 flights with three different nozzles.

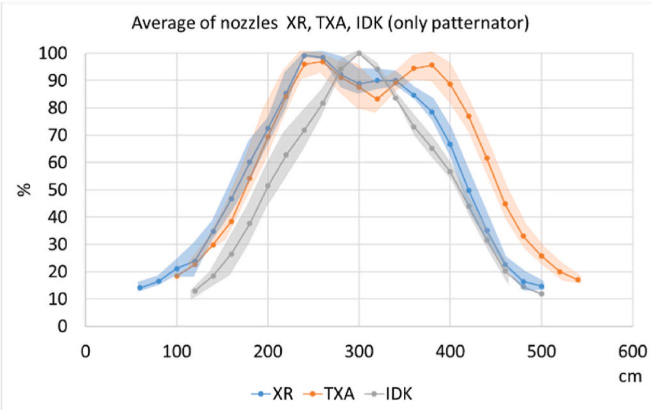

Fig. 5. Transversal distribution of the three nozzles (average of 3 measurements on patternator). The coloured surfaces are indicating the average±the standard deviation.

correlation with an R-square value of 0.89. The nozzles IDK and TXA (hollow cone) showed a relation of $y = 0.959x - 7.448$, $r^2 = 0.90$ (data not shown), whereas the TXA and IDK showed a relation of $y = 0.984x - 14.569$ $r^2 = 0.80$ (data not shown). Taking the measurements for water sensitive and filter paper, similar results can be found, but due to the higher variability the r^2 achieved values between 0.57 and 0.77, excluding the relation between IDK and XR ($r^2 = 0.43$) measured with water sensitive paper.

3.4. *Transversal distribution of different nozzles on patternator*

By calculating the optimal overlap of three working widths using the measurements on patternator, the three nozzles reached minimal coefficients of variation between 5.9 and 15.6 % (see Table 2). The IDK nozzle exhibited the most uniform distribution, with an average coefficient of variation of 7.8 %. In contrast, the XR and TXA nozzles displayed less regular transversal distributions, with coefficients of variation falling within the 10–15 % range. The associated working widths varied between 2.2 m and 3 m.

Comparing the results of the patternator with the two other methods quite similar average working widths can be found (WSP 2.7 m; FP 2.9 m) but the coefficients of variation were much higher (average: WSP 21.1; FP 31.4).

4. Discussion

The results obtained through the various measuring methods are well comparable, with the static patternator demonstrating the least variation in transversal distribution. This can be attributed to the static flight situation over patternator. The superior transversal distribution observed with the air induction flat fan nozzle may be attributed to the higher energy associated with the coarse droplets, resulting in the smallest working width.

4.1. *Determination of the transversal distribution*

Comparing the three methods patternator, filter and water sensitive paper, the following distinctions can be made: the static patternator method showed the lowest variation between the repetitions for all nozzles. The two other dynamic methods generally showed higher variations. This different behaviour could be explained by the fixed position of the drone on the patternator since the drone is hovering steadily at the same position without moving. To keep its position, the multicopter is continuously varying the rotation speed of the different rotors to compensate influences like cross winds. That the airflow of the aircraft changes during the spraying process is described by different authors (Chen et al., 2022; Li et al., 2018) and is an inherent principle of the multicopters. Flying to the right means that the rotation speed of the left propellers has to be increased and vice versa. For the transversal distribution of the spray liquid on the patternator this means that the effects of the different rotation speeds of the propellers are accumulated during

Table 2
Lowest achieved coefficients of variation (CV) with the corresponding working width of the three repetitions (Rep) measured on patternator. "ns" indicates no significant differences according to Tukey (p = 0.05).

Nozzle	Rep.	CV In %	Work. width in m	Tukey CV
Teejet XR	1	15.0	2.6	ns
Teejet XR	2	9.9	3.0	
Teejet XR	3	10.0	2.7	
Teejet TXA	1	10.1	3.0	ns
Teejet TXA	2	15.6	3.1	
Teejet TXA	3	9.7	3.0	
Lechler IDK	1	8.8	2.4	ns
Lechler IDK	2	8.7	2.2	
Lechler IDK	3	5.9	2.2	
Average		10.4	2.7	

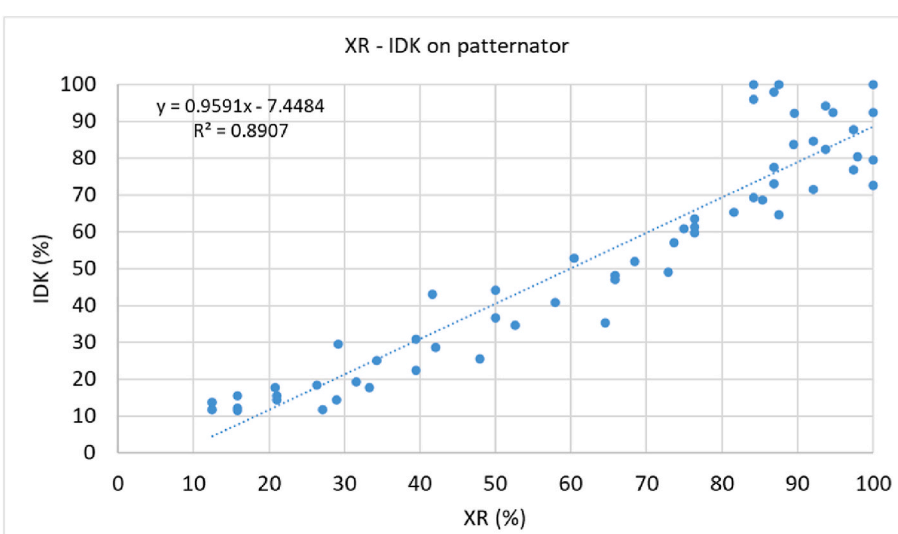

Fig. 6. Relation of the transversal distribution (patternator) between the two nozzles XR and IDK.

the entire measuring period.

In the literature only few results gained on patternator are published. Coombes et al. (2022) successfully used a patternator to measure the distribution below a single rotor. Chojnacki and Pachuta (2021) describe that during their trials they observed that an important part of the droplet stream flew off the reception surface. In our trials this has been addressed by enlarging the patternator and placing boards in front and back, catching small droplets pushed over the table (Fig. 1). On the other hand, the visual observations during the trial showed, that only very fine droplets are carried away by the air which represent only a small part of the whole spray liquid. This was confirmed by the fact that the surroundings of the patternator remained dry during the measurements.

However, when flying over small paper strips of 2.5 cm width for the dynamic methods filter and water sensitive paper, the situation is different. The theoretical duration of the flight over such a strip with a speed of 1.9 m/s is only 0.02 s. This very short duration will thus only represent the status of the air and droplet flow at this particular moment. That means that the next paper strip will show a different status of the droplet flow, representing the status at this particular time. Therefore, it seems that the narrow paper strips are well suited to measure the variability of the droplet streams while the patternator is levelling out this variability. This is confirmed by the fact, that the correlation between water sensitive paper and filter paper was very high. The two slats carrying water sensitive paper and filter paper were placed at a distance of 20 cm apart and thus depict the same flight situation. In addition, this close correlation shows, that the variation is not caused by the measuring methods but by the changing droplet stream.

Beyond merely highlighting the distinctions between these measurement methods, the relatively strong relationship among all three methods indicates their suitability for assessing the transversal distribution of spray liquid. While the patternator provides an average perspective, water sensitive and filter paper methods offer a more detailed view of the variability stemming from variations in propeller speeds.

4.2. Accuracy of the spray and working width

The transversal distribution over the whole working width shows the form of bell-shaped curves for all methods, what is confirmed by Coombes et al. (2022). To reach an even distribution, overlapping the single swathes is necessary. Optimal results with a minimal coefficient of variation below 15 % are achieved with working widths of 2.2–3.1 m (see Table 1). DJI (2019) indicates the working width of the used UASS as 4–6.5 m what is not in harmony with the presented results. Taking into account that the propellers of the UASS are creating downwash with cylindrical forms with a radius corresponding to the one of the propellers (Fengbo et al., 2018; Wen et al., 2019; Xuesong et al., 2019), it becomes evident, that the working width cannot exceed the width of the UASS very much. This is confirmed that about 1 m above the soil and higher, no droplets can be observed outside of the vertical airflow. A certain lateral dispersion is caused by the turbulences near the soil and the crop. But these turbulences are not allowing an important increase of the working width. Especially coarse drops are driven vertically downwards (Coombes et al., 2022) while small drops are prone to be driven more outside the principal airflow by the turbulences formed on the ground. That means that the width of the drone very much determines it's working width.

4.3. Transversal distribution of different nozzles

Our study revealed that the various nozzles generated fairly similar transversal distribution patterns, but the IDK nozzles delivered the most favorable outcomes with coefficients of variation below 10 %. The nozzles had different spray angles of XR 110° (flat fan), TXA 80° (hollow cone), IDK 120° (flat fan). According to the indications of the manufacturers the two nozzles XR and TXA created "fine" drops while IDK created "coarse" drops. Beside the different spray angles, droplet size has probably influenced the distribution on the patternator. The coarser drops of the IDK resulted in a smaller working width than the fine drops of the XR and TXA nozzle, which might be an indication, that coarse drops are following a vertical flight route while smaller drops can be carried laterally by wind turbulences. This might indicate, that using nozzles with a large spray angle of 120° and coarse droplets can improve the transversal distribution with the present setting of the UASS "DJI T16".

As mentioned above, several papers modelled the airstream and showed that it has a cylindric form with a similar diameter of the propeller. At the outside, around this air tube the air speed is very low. As the nozzles are placed underneath of the propellers, no droplets can be observed at the outside of this air stream. Xuesong et al. (2019) showed that within this cylinder the airstream is decreasing towards the centre, due to the lower radial speed of the propellers. These differences of the air speed cause turbulences what is influencing the droplet flow. Shouji et al. (2021) described a spiral rotational flow with low axial velocity inside the downwash flow, which is probably caused by these turbulences and the interferences between the air flows of the different propellers. All these different results show, that the vertical airflow determines the droplet flow, but the occurring turbulences and their influence on droplet transport and transversal distribution are not yet fully understood. The efforts of the drone manufacturers confirm this state of the art as many different nozzle placements can be found. Yu et al. (2021) showed that the inclination angle of the nozzles has a big impact on the distribution which confirms that the airflows are not homogeneous and finding an optimal position for the nozzles is challenging. However, the achieved good results show that actual UASS achieve good transversal distributions. Air induction nozzles with a spray angle of 120° producing coarse drops achieved the best transversal distribution and allow to reduce the risk of pesticide drift when in spraying occasions.

5. Conclusions

The results presented here demonstrate a strong alignment among the static patternator and the dynamic water sensitive and filter paper methods for assessing the transversal distribution of spray liquid. The patternator stands out by delivering the best average with the lowest variation, making it well-suited for standard sprayer tests. Water-sensitive and filter paper methods exhibited a high degree of correlation and are effective in depicting the variability within the droplet stream during flight. By utilizing an air induction, flat fan nozzle with a 120° spray angle that produces coarse droplets, it was possible to achieve a coefficient of variation below 10 %. This underscores the impressive uniformity in the distribution achieved by UASS. Such consistent distribution is attainable only by overlapping working widths, which, in our case, resulted in a final working width roughly similar in size to the UASS itself.

CRediT authorship contribution statement

Thomas Anken: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Gomathi Saravanan:** Writing – original draft. **Thainna Waldburger:** Conceptualization, Data curation, Investigation, Writing – original draft. **Jan Werthmüller:** Investigation, Methodology. **Ronald Wohlhauser:** Conceptualization, Investigation. **Graham Sanderson:** Conceptualization, Data curation, Supervision, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be published on zenodo.org

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