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ASSESSING TWO METHODS FOR AGROCHEMICAL APPLICATION (TRACTOR-BASED AND UAV) IN RICE FIELDS

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Palabras clave: vehículo aéreo no tripulado; spray boom; eficiencia; arroz; regulador de crecimiento.

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ABSTRACT

Introduction. Rice is one of the world's most consumed grains in the world and is the most cultivated annual crop in Costa Rica. During rice's growth, some kernel characteristics can be enhanced by using plant growth regulators (PGR), usually sprayed over the crop with a tractor-based spray boom (SB). Recently, the use of Unmanned aerial vehicle (UAV) sprayers, in PGR applications, has become more common. However, the lack of efficiency compared with conventional methods (as SB) urges research development. **Objective.** To compare spraying efficiency of SB and UAV using a PGR over rice (*Oryza sativa*). **Materials and methods.** Three treatments of different volumes with SB (SB100=100 L ha^{-1}, SB150=150 L ha^{-1} and SB200=200 L ha^{-1}), three treatments with UAV (D10=10 L ha^{-1}, D20=20 L ha^{-1} and D30=30 L ha^{-1}) and one control (no spray application) were conducted in a rice field located in Pavones, Guanacaste, Costa Rica. Five repetitions were carried out in a completely randomized design for all treatments with different PGR rates and considering spraying quality (coverage, uniformity and droplet density), rice yield, and rice milling quality as efficiency parameters. **Results and discussion.** SB and UAV treatments did not present statistical differences in rice milling quality and yield. Considering the spray quality for SB, SB100 complied with the required droplet density (more than 20 drops cm^{-2}), while being the treatment with the lowest water use. As for spray quality in UAV treatments, neither had the minimum droplet density required (7.44 - 17.4 drops cm^{-2}), in addition to a poor uniformity performance with high values of coefficient of variation (48.49 - 57.77%). **Conclusion.** After evaluating the efficiencies of SB and UAV treatments, SB100 is the most efficient method based only on the spray quality parameter, since rice milling quality and yield did not present statistical differences.

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RESUMEN

Evaluación de dos métodos para aplicaciones agroquímicas (spray boom y dron) en el cultivo del arroz. Introducción. El arroz es de los granos más consumidos en el mundo y el cultivo anual más producido en Costa Rica. Durante el crecimiento del arroz, algunas características del grano pueden mejorarse mediante reguladores de crecimiento (PGR), usualmente aplicados con spray boom montado en tractor (SB). Recientemente, ha aumentado el uso de drones para aplicaciones de PGR. Sin embargo, escasez de comparaciones de eficiencia con métodos convencionales (como SB) hace necesario el desarrollo de investigaciones. **Objetivo.** Comparar la eficiencia de aplicación entre un SB y un dron usando un PGR sobre arroz (*Oryza sativa*). **Materiales y métodos.** Tres tratamientos de diferentes volúmenes con SB (SB100=100 L ha^{-1}, SB150=150 L ha^{-1} and SB200=200 L ha^{-1}), con dron (D10=10 L ha^{-1}, D20=20 L ha^{-1} and D30=30 L ha^{-1}) y un control se aplicaron en un campo arrocero en Pavones, Guanacaste, Costa Rica. Se realizaron cinco repeticiones en un diseño completamente aleatorio para todos los tratamientos con diferentes tasas de PGR y tomando como parámetros de eficiencia la calidad de aplicación (cobertura, uniformidad y densidad de gotas), el rendimiento del arroz, y la calidad molinera. **Resultados y discusión.** Los tratamientos con SB y dron no presentaron diferencias estadísticas en calidad molinera y rendimiento del arroz. En cuanto a la calidad de aplicación de SB, SB100 cumplió con los requerimientos de densidad de gotas (mayor a 20 gotas cm^{-2}) siendo el tratamiento con menor uso de agua. Considerando la calidad de aplicación de dron, ningún tratamiento cumplió con densidad de gotas requerida (7,44-17,4 gotas cm^{-2}) sumado a una baja uniformidad (48,49-57,77%). **Conclusión.** Después de evaluar eficiencias de los tratamientos con dron y SB, SB100 resultó en el método más eficiente basado únicamente en el parámetro de calidad de aplicación, ya que no se presentaron diferencias estadísticas en calidad molinera y rendimiento del arroz.

1. INTRODUCTION

Rice, the second most cultivated crop globally after wheat (*Triticum aestivum*), has an annual production of 517.60 million tons (FAO 2023) and represents 53.20% of annual crop production in Costa Rica (INEC 2023). Plant growth regulators (PGR) can be broadly important by improving and helping the growth of the plant (Alcántara *et al.* 2019). Within PGRs highlights abscisic acid (ABA) which is a phytohormone that aids in plant and fruit development by ripening acceleration (Ramírez *et al.* 2019), promotion of grain yield and quality in rice (Chen *et al.* 2019) and response to water stress inducing stomatal closure (Matsuda *et al.* 2016).

Previous studies demonstrate that ABA increases rice yields and improves milling quality. Flores (2019) and Solera (2019) obtained higher rice yields in 28.8% and 8.96%, respectively, with higher percentages of whole kernel yield and fewer percentages of broken kernel yield in treatments with ABA compared to treatments without it. While Chen *et al.* (2019) also indicated an increase in grain yield and milled rice ratio while using ABA plus sucrose in rice, compared to treatments without ABA applied. In addition, Qin et al. (2021) indicated that genes involved in starch synthesis and grain filling in rice were activated by ABA. Therefore, the starch content in rice is higher when ABA is applied (Chen *et al.* 2019).

The application of PGR is usually sprayed. The spraying conventional methods used in Costa Rica are: 1) backpack sprayer for small areas, 2) planes or helicopters for areas with obstacles or heterogeneous and 3) tractor-based spray boom (SB) for large areas (Jiménez Salas 2015). However, soil compaction, destruction of rice fields where the tractor’s tires go through

(Gómez and Rodríguez 2019), high consumption of water and fossil fuels and deposition drifts (Wang *et al.* 2018), are involved during tractor-based SB operations.

While comparisons of conventional methods with new spraying methods focused on parameters such as productive yield and rice quality are rare, research on SB is usually centered on structural changes such as nozzle variations (Matilde *et al.* 2018) or air generators addition (Lamare *et al.* 2022) and their effects on spray cover or uniformity (Foqué *et al.* 2013). Lamare *et al.* (2022) used a SB with an air-assisted mechanism to produce a forced airflow that blows the droplets at different speeds over the crop. Different bar heights and nozzle spacing and their effect on drift and deposition were evaluated. They concluded that a 0.60 m bar height configuration and nozzle spacing derived the highest deposition and drift reduction. Also, the air assistance, which primarily function was to avoid drift, did not significantly affect those parameters.

Typical volumes for agrochemical spraying in arable crops are between 25 and 200 L ha^{-1} (Foqué *et al.* 2013). However, this author used higher volumes in a SB with air assistance to evaluate their off-target deposition. Results showed that the air assistance did not present significant differences in the results, and the higher the volume, the higher the off-target deposition, with the lowest volume being the treatment with less drift among the ones compared (Foqué *et al.* 2013).

In the study of Wang *et al.* (2019), the spray uniformity of a SB, UAV, and two backpack sprayers was analyzed using the coefficient of variation (CV) which lower values indicate better uniformity (Zhang *et al.* 2020). Considering a spraying capacity of 300 L ha^{-1}, 10 L ha^{-1}, and 75 L ha^{-1} for the SB, UAV, and backpack sprayers, respectively, it resulted in a better uniformity for the SB with a CV of 32.1% against the CV of 87.2% for the UAV, and 84.4% and 81.2% for the two backpack sprayers. Conversely, Matilde *et al.* (2018) analyzed the spray coverage of a SB with volumes of 130 L ha^{-1} and 90 L ha^{-1}, resulting in higher coverage for the highest volume with a covered area of 20% against 15%, respectively.

Technological advances might enhance the efficiency of agrochemical spraying, as alternatives have been presented recently with the use of UAVs in this sector. However, in the same way as SB, research is focused on aspects such as the height of application, drifts (Woldt *et al.* 2018), or the influence of meteorological conditions (Wang *et al.* 2018) in UAV operations. While comparisons with other methods are lacking, there is a need to create standards for this equipment.

According to Li *et al.* (2019), flight height above 3.00 m and below 1.50 m contributes to spray drift and, nowadays, the UAV spray capacity is in a range of 11 L ha^{-1} to 30 L ha^{-1}. That agrees with research by Woldt *et al.* (2018), who concluded that the best uniformity was obtained at 2.00 m flight height with a CV of 7.00% for the MG-1 model and 3.00 m height with a CV of 15.50% for the V6A model.

The flight height at which the UAV spraying would not be affected by climate conditions as wind speed (and the spray drift would not be increased) was studied by Wang *et al.* (2018). This resulted in the recommendation of a 2.50 m flight height at wind speeds of around 3 m s^{-1} to reach that purpose. Although, some researchers, such as Zhang *et al.* (2020), concluded superior heights up to 4 m for the highest coverage with 12-15 L ha^{-1} volumes.

Research in UAVs and their comparison with conventional tractor-based spraying methods promotes sustainable agricultural development by reducing water and fossil fuel consumption, reducing workable time in agriculture (Wang *et al.* 2019), and subsequent cost reduction. All while encouraging technological innovation (Ahmad *et al.* 2021).

While studies have been conducted on SB and UAV sprayers, research on these methods focuses mainly on the effect on spray distribution due to changes in the equipment characteristics.

The results from these studies are useful for future research but need to cover other important parameters involved in crop spraying, as intended with the present methodology, which includes the effect of the spraying method on milling quality and rice yield, in addition to spray quality.

These parameters represent the main aspects to consider while performing a rice agricultural activity for commercial purposes. In this sense, rice milling quality and rice yield focus on the grain weight and the kernel quality obtained, and therefore, the profitability of the activity, while spraying quality is centered on the optimization of agrochemical use. Therefore, this research aimed to compare spraying efficiency of SB and a UAV using a PGR over rice (*Oryza sativa*).

The rice importance and need of research on comparison between spraying methods underscores the significance of our study's focused on improving rice cultivation efficiency. The potential benefits of our findings, which could lead to the development of more efficient and sustainable rice cultivation practices, are significant for the rice industry, benefiting both farmers and consumers.

2. MATERIALS AND METHODS

The study was conducted between September and December of 2022 using 1.50 ha of a rice field located in Pavones, Costa Rica (10°0'13,84" N 85°12'24,73" O). Before the rice planting, 2 L ha^{-1} of herbicides were applied over the field, the soil surface was plowed twice, and the soil was fertilized with 135 kg ha^{-1} of fertilizer formula NPK:10-30-10. The rice variety cultivated was a SENUMISA 20 FL sowed with a rice planter in a sandy loam soil with a row spacing of 17 cm.

After rice planting and just before germination, 2-3 L ha^{-1} of herbicide was used as weed prevention. The soil was fertilized again with 135 kg ha^{-1} of fertilizer formula NPK:26-0-26 after 15, 25 and 45 days of germination. Additionally, 45-55 days after germination, two applications of pyrethroid insecticide and copper oxychloride-based fungicide were applied directly to rice ears.

The SB and UAV spray methods were assessed to determine their effect on spray quality, rice yield, and rice milling quality while using a commercial PGR. This PGR is a systemic agrochemical, with a composition of 200 g kg^{-1} of ABA and a 60 g ha^{-1} dose in the liquid mixed. The rice milling quality and rice yield were evaluated since grain weight and the kernel quality are of important consideration in the characterization of the product and the economic benefits of the activity, while spraying quality is centered on the optimization of agrochemical and water use.

There were three treatments per spray method, with five repetitions each, for a total of 35 experimental units in a completely randomized design. Every experimental unit was set to 8 m x 5 m, but the total sprayed area was 9 m x 8 m to avoid any result conditioned by the border effect. Additionally, there was a spacing of approximately 12 m between blocks to prevent drift spraying from affecting neighboring experimental units. Moreover, one control was carried out consisting of five experimental units with the same characteristics of the entire rice field without any spray application.

A Jacto SB (Brazil, Pompéia) (Figure 1) with 12 m width and 600 L capacity mounted in a John Deere 4500 (United States, Illinois) tractor was employed. The treatments comprised three spray volumes, defined as SB100, SB150, and SB200, for 100, 150, and 200 L ha^{-1}, respectively. Each treatment had a PGR dose of 60 g ha^{-1}, which means 600 mg L^{-1} for SB100, 400 mg L^{-1} for SB150 and 300 mg L^{-1} for SB200. Tractor speed during spray studies is recommended to be at 1.50 and 2.50 m s^{-1} (Dou *et al.* 2021), which matches with the 1.70 m s^{-1} set for this research and commonly used by operators in this region (Table 1). A calibration was performed beforehand to reach the volumes selected, and the pressures were set at 70 psi for SB100, 125 psi for S150, and 450 psi for SB200. Moreover, the bar height used was 0.60 m over the crop canopy.

Table 1. Spray methods and their characteristics.

Spray method	Spray Boom (SB)			Unmanned aerial vehicle (UAV)		
Treatment	SB100	SB150	SB200	D10	D20	D30
Volume (L ha^{-1})	100	150	200	10	20	30
PGR rate (mg L^{-1})	600	400	300	6.000	3.000	2.000
Spraying speed (m s^{-1})	1.70	1.70	1.70	6.06	5.33	4.61
Spraying height (m)	0.60	0.60	0.60	2.00	2.00	2.00

Figure 1. Tractor and Spray Boom (SB) used during spraying.

For the UAV method, a 10 L capacity DJI Agras MG-1P UAV (China, Shenzhen) (Figure 2) was used. The treatments comprise three spray volumes, defined as D10, D20, and D30, for 10, 20, and 30 L ha^{-1}, respectively. Each treatment had a PGR dose of 60 g ha^{-1}, which means 6,000 mg L^{-1} for D10, 3,000 mg L^{-1} for D20 and 2,000 mg L^{-1} for D30. The UAV flight height was set at 2.00 m and the speed was 6.06 m s^{-1} for D10, 5.33 m s^{-1} for D20, and 4.61 m s^{-1} for D30 (Table 1).

The spraying was conducted during milky stage. To identify it, approximately 100 panicles were tested resulting in around 24 being in milky stage. The crop harvest was manual, using a structure with wooden support and horizontal bars (Figure 3), especially made for that purpose. The rice grains were separated from the plant by hitting it on the wooden structure three times on each side of the panicle and then recollected in plastic canvas located right below. Ultimately, grains were placed in classified bags according to treatments.

Figure 2. Unmanned aerial vehicle (UAV) used during spraying.

Figure 3. Wooden structure used to separate grains from the panicles.

2.1 Parameters evaluation

All evaluated parameters and measurement procedures were the same for SB and UAV spraying, which are explained below.

2.1.1 Spray quality

Spray quality was measured by considering the percentage and drop count of the covered area and uniformity. The coverage percentage and drop counting were estimated using two water-sensitive papers (WSP) attached to a wooden stick and placed at canopy height on the experimental units treated. Four out of five experimental units for each treatment were used since the amount of WSP available was 50 papers, enough to analyze the coverage percentage and drop count, statistically. After each application, the WPS were photographed, and the software ArcMap 10.8 was used to analyze the image and obtain the percentage of area covered. A subsequent drop count was conducted to determine droplet density in drops cm^{-2} units.

According to FAO, (Portuguez 2019) and Syngenta Crop Protection AG (Zhu *et al.* 2011), droplet density must be at least 20 drops cm^{-2} in the case of any systemic agrochemical (as the PGR used in this study). Finally, the uniformity was measured using the coefficient of variation (CV) which lower CV values indicate better uniformity (Zhang *et al.* 2020).

2.1.2 Rice yield

The rice yield of all treatments and the control were measured based on husked rice with impurities. After harvest, the rice obtained was packed in pouches labeled according to the experimental unit. A digital scale T-Scale MBW-300 model with ± 20 g precision was used. Also, the average yield was compared to the average yield in the Chorotega region and Costa Rica over the last 11 years, being 4,001.25 kg ha^{-1} and 4,210.75 kg ha^{-1}, respectively (CONARROZ 2019, CONARROZ 2023, INEC 2017).

2.1.3 Rice Milling Quality

After rice harvest, a sub-sample of 4 kg of each experimental unit (Figure 4) was separated in paper bags and dried for rice milling quality tests following the technical regulation (Decreto Nº. 34487, 2008). Chalkiness (CH), damaged kernels (DK), stack yield (SY), semolina yield (SeY), small broken yield (sbY), large broken yield (LBY), whole kernel yield (WKY), broken kernel yield (BKY), and commercial rice yield (RY) represented milling quality.

Figure 4. Samples for milling quality tests.

2.2 Statistical analysis

After confirming data normality using the Shapiro-Wilks test, an analysis of variance ANOVA was performed. To compare means, Tukey's test was carried out. If no normality is found by the Shapiro-Wilks test, based on the number of treatments compared, the Kruskal Wallis or Wilcoxon test was performed to identify variances, and the Dunn test was applied to compare means. All statistical analyzes were applied separately for SB and UAV results since, at first, it was desire to define the optimal treatments for each method and after that the statistical analysis was performed on the chosen treatments. The Infostat program 2020 (Di Rienzo *et al.* 2018) was used for the statistical analysis of the results.

2.3 Optimal treatment selection

First, the optimal treatment by spraying method (SB and UAV) was determined by comparing the results of the parameters selected for evaluation (spray quality, rice yield, and rice milling quality). In both methods, if the treatments present high and statistically different rice yield and rice milling quality, high coverage, high uniformity and/or reach the recommended droplet density were considered as optimal.

Water consumption is also considered since is an important part of spraying labor and helped in the decision making. Water consumption resulted from spray volume is a characteristic that not only affects the hydric resource but also affects the activity costs, fuel and energy consumption and working time. In this case, if the parameters results are inconclusive or not enough for optimal treatment selection, the treatments with lower water use were represented with an added positive advantage.

After determining the optimal treatments by method, they were compared according to the parameters (spray quality, rice yield, and rice milling quality) by a statistical analysis, which had been presented previously. Everything was conducted to identify the optimal treatment for SB or UAV applications and select the optimal spray method for this labor, showing at the same time the possible advantages and disadvantages of both.

3. RESULTS AND DISCUSSION

3.1 Optimal spray treatment with SB

3.1.1 SB spray quality

The quality was determined based on the covered area and CV. The covered area was analyzed based on the percentage covered and drops fallen in WSP. The percentage of covered area was also necessary for calculating the CV. The variance analysis was performed, resulting in a p-value of 0.0009, indicating the existence of significant differences between treatments.

The subsequent Tukey test showed that SB100 and SB200 coverage were significantly different. Results in Table 2 demonstrate that as spray volume increases, so does the covered area. This was expected and agreed with the results of authors such as Matilde *et al.* (2018), who indicated greater coverage with greater spray volumes in all crop levels.

The CV results are also presented in Table 2, with SB200 being the lowest with 30.92%. However, according to Wang *et al.* (2019), Holterman *et al.* (2018), and Kluza *et al.* (2019), the desired CV for agrochemical spraying is 10.00% or lower, and none of the three treatments reached this level. With the greatest percentage of covered area and lowest CV (thus resulting in the optimal spray quality) SB200 was a more efficient treatment. However, the drop count performed in all WPS shows that all treatments are helpful for systemic agrochemical spraying, since the minimum droplet density required is 20 drops cm^{-2} (Portuguez 2019).

Table 2. Average coverage and coefficient of variation (CV) of the three Spray Boom (SB) treatments.

Treatment	Average coverage (%)	Standard Deviation (%)	Droplet density (drops cm^{-2})	Standard Deviation (drops cm^{-2})	CV (%)	Tukey*
SB100	21.20	8.79	171.63	85.62	41.46	A
SB150	37.52	14.71	406.81	131.87	39.20	A B
SB200	51.19	15.82	460.20	102.96	30.92	B

*Different letters denote significant differences between treatments.

The low uniformity could be caused by the irregular surface where the tractor advances, resulting in drastic movements and changes in the SB bar and nozzles. Despite that, studies as Wang *et al.* (2019) obtained a similar CV value of 32.1% with a 300 L ha^{-1} volume. In this case, a treatment as SB200 resulted in a lower CV probably due to high nozzle pressure (31 bar) compared to the low nozzle pressure (4 bar) used by Wang *et al.* (2019). Also, the coverage obtained in this research is similar to the results of another study (Borger *et al.* 2013), whose coverage results were 32% using 150 L ha^{-1} volume, 24% with 110 L ha^{-1} volume and 20% with 90 L ha^{-1}.

Even though SB200 presented the required droplet density and the optimal results in coverage and CV, SB100 also performed the droplet density required for systemic agrochemicals. SB100 has the advantage of reducing water by 100% compared to SB200 and a more concentrated mixture of the water and PGR sprayed. In that sense, it is important to select both treatments and compare them with the optimal UAV treatments to look for differences in all the parameters studied.

3.1.2 SB rice yield

The ANOVA test showed no significant differences in this parameter between treatments and control (p = 0.3634; α = 0.05). In this case, despite SB200 having the greatest value, the average yield does not increase while increasing the spray volume (Figure 5). Moreover, even though the averages in rice yield seem to have differences (with 783 kg ha^{-1} between maximum and minimum values), this is explained by the noticeable differences in standard deviations. For example, while SB200 has the greatest average in rice yield with 3504 kg ha^{-1}, it also has a 929.60 kg ha^{-1} standard deviation. This means that some values are extremely high, increasing the dispersion of data but not enough to make a difference compared to the average of the other treatments and control.

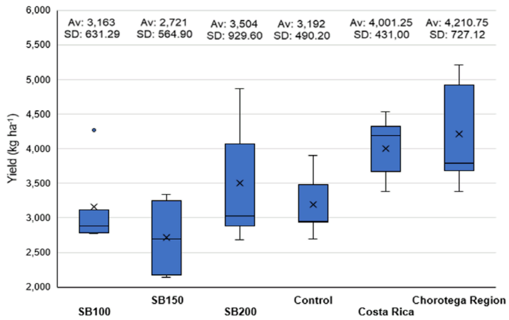

Figure 5. National and regional yields compared to the yield obtained with Spray Boom (SB) treatments (CONARROZ 2019, CONARROZ 2022, CONARROZ 2023, INEC 2017).

Furthermore, comparing the average yield of SB200 (which is the highest among the SB treatments) with the average yield in Costa Rica and the Chorotega region over the last 11 years (CONARROZ 2019, CONARROZ 2023, INEC 2017), resulted in 12.43% and 16.78% less performance, respectively. These results disagree with what was found by Flores (2019), who applied 150 and 300 mg L^{-1} of ABA in rice and obtained a 17.74 and 29.49% higher yield, respectively, compared to the control without ABA. This situation may be due to the use of irrigation in the rice field, the use of a backpack sprayer which the operator could focused on the entire plant since the areas were small, and the application of adjuvants, bio-stimulants and another PGR, which differs from this research.

The previous statement is in accordance with the results obtained by Chen *et al.* (2019), who demonstrated the use of ABA with sucrose addition resulted in an increment of 15.7% of grain yield compared to the control without ABA and sucrose, while treatments with the use of ABA alone did not present a statistically significant difference compared to the control. This may suggest that in order to increase yield in rice with ABA, it is necessary to be accompanied with a complement.

Additionally, the low results compared to the national and regional yields suggested that an external factor may have caused a possible adverse affectation in this parameter. Based on the milling quality results, the damaged kernel parameter had a low value (3.56%), indicating low damaged product due to pests or diseases, which leads to the assumption that a possible negative effect on rice yield results could be caused by environmental factors, like deficient soil conditions.

Rice yield is an important factor in rice production's profitability, and it was demonstrated that the three spray volumes evaluated with SB and the characteristics presented did not enhance this parameter. Considering the rice yield, the lack of significant differences between treatments and control and the low yield obtained compared to national and regional yields, the selection of the optimal treatment for SB was not accomplished.

3.1.3 SB rice milling quality

The variance analysis showed no significant difference in the milling tests between treatments and control (p = 0.6584-0.8908; α = 0.05). Considering that all results had a similar performance, the commercial rice yield (RY) was be used (Table 3). The RY is the amount of whole kernel and large broken rice, which is obtained from a test sample of rice in chaff, without impurities (<1.5%) and dry (<13% moisture). The results showed no trend for RY related to the volumes. Therefore, the yield does not increase while increasing the spray volume (Table 3).

Table 3. Commercial rice yield (RY) average values obtained in the milling test of rice sprayed with three Spray Boom (SB) treatments and the control (C).

Treatment	Average (%)	Standard Deviation (%)	Min (%)	Max (%)
SB100	65.28	2.31	62.00	67.80
SB150	64.12	3.05	58.90	66.50
SB200	65.04	2.28	63.40	69.00
C	65.88	3.14	61.30	69.20

Besides not having a significant difference in RY between treatments, the average values were similar, with a maximum difference of just 1.80%. Moreover, the lack of differences is evident when the standard deviations are similar and low, with an average of just 2.70%.

The average percentages of the three treatments of each milling quality parameter were compared to the results of a previous study in Costa Rica who used the same technical regulation for rice milling quality test (Rojas 2012). As shown in Table 4, the results for damaged kernels (DK), stack yield (SY), semolina yield (SeY), whole kernel yield (WKY), and broken kernel yield (BKY) were similar to those found by Rojas (2012), with a range of difference between -2.41% and 2.62%, while chalkiness (CH) was the parameter with the most difference being 7.97% higher in this research, followed by small broken yield (sbY) with 5.32% less than Rojas (2012).

Table 4. Milling quality comparison between Spray Boom (SB) treatments and other studies.

Milling test	SB treatments results (%)	(Rojas 2012) results (%)	(Reyes *et al*. 2020) results (%)	(Flores 2019) results (%)	(Solera 2019) results (%)	(Chen *et al*. 2019) results (%)
CH	12.47	4.50	-	-	-	11.40
DK	3.56	2.48	-	-	-	-
SY	68.17	65.55	68.70	71.72	-	≈67.00
SeY	11.06	13.47	9.34	-	-	-
sbY	3.35	8.67	-	-	-	-
LBY	18.07	-	-	-	-	-
WKY	46.65	44.90	61.45	63.91	61.50	≈60.00
BKY	21.43	22.84	7.27	7.81	7.29	-

CH = Chalkiness, DK = damaged kernels, SY = stack yield, SeY = semolina yield, sbY= small broken yield, LBY = large broken kernel yield, WKY = whole kernel yield and BKY = broken kernel yield.

Similar results in SY have been shown by other studies with differences of 0.53% (Reyes *et al*. 2020), 3.55% (Flores 2019), and around 1.17% (Chen *et al*. 2019) compared to this study. However, BKY, in studies where ABA is involved, is around 7.00-8.00% which is about 14.00-13.00% lower than the BKY obtained with the SB treatments of this study and the study by Rojas (2012).

This situation may be caused by different practices during rice production. Flores (2019) obtained improvement in rice milling quality while using ABA in comparison with the control, but they applied bio-stimulants and other PGR to the rice, which was not the case for this research. Chen *et al*. (2019) used around 30 g L^{-1} of ABA and analyzed the effect of ABA plus sucrose and showed an increase in SY and WKY with statistical differences compared to the treatments using only sucrose or ABA and compared to the control.

The rice milling quality is quite importance in the presentation and characterization of the rice distribution. However, the three spray volumes and the characteristics presented in the methodology did not enhance kernel quality. The lack of significant differences between treatments and control and the similarities with other studies do not allow the selection of the optimal treatment for SB based on rice milling quality.

3.2 Optimal spray treatment with UAV

3.2.1 UAV spray quality

A Kruskal Wallis test was performed, providing a *p*-value of 0.0152, indicating significant differences between treatments. After that, the Dunn test indicated no significant differences between D20 and D30 (p = 0.1884) and significant differences between D10 and D30 (p = 0.0259) and D10 and D20 (p = 0.0023).

When comparing those pairs (Table 5), D20 shows a greater covered area with 6.11% and, in the same way, it has the lowest CV (48.49%), indicating the best uniformity among the three treatments. Even though it was the lowest CV (as explained before) this CV value is higher than the 10.00% or lower required.

Table 5. Average coverage and coefficient of variation (CV) of the three unmanned aerial vehicle (UAV) treatments.

Treatment	Average coverage (%)	Standard Deviation (%)	Droplet density (drops cm^{-2})	Standard Deviation (drops cm^{-2})	CV (%)
D10	2.35	1.33	7.44	4.25	56.64
D20	6.11	2.96	15.38	7.42	48.49
D30	4.41	2.55	17.4	15.53	57.77

The CV values obtained in all treatments were better than the ones obtained by Wang *et al.* (2019), who used a 10 L ha^{-1} volume and obtained a 2.20% of covered area and 87.20% of CV. The possible cause of the differences is the flight height set at 1.0 m by Wang *et al.* (2019), which differs from this research and according to Li *et al.* (2019) a flight height below 1.5 m may contribute to spray drift in UAV. Despite that, the CV was too high in both cases, demonstrating that UAVs present low spraying uniformity.

Finally, the drop count performed in the WPS confirmed the lack of spray quality with this UAV, resulting in a droplet density below 20 drops cm^{-2}, as recommended for systemic agrochemicals in all UAV treatments. Also, according to Jeevan et al. (2023), higher spray volumes result in better coverage and droplet density while spraying, which was not the case for these results. Cedeño et al. (2020) state that air flux produced by UAV propellers can affect and distribute the agrochemicals to different depths lower than canopy levels. In this case, different spray volumes produce different drop sizes, and this air flux could affect the drop distribution.

Although all treatments had poor performance, D20 is considered the most efficient due to its higher uniformity compared to D10 and D30. Because it had the highest coverage percentage with significant differences with D10 and, as with all UAV treatments, it has low water consumption. D20 will be considered in the final comparison with SB treatments.

3.2.2 UAV rice yield

The average results in Figure 6 tend to increase yield while decreasing spray volumes, with D10 being the treatment with the highest yield. However, the variance analysis showed no significant differences between the treatments and the control ($p = 0.2415$; $\alpha = 0.05$).

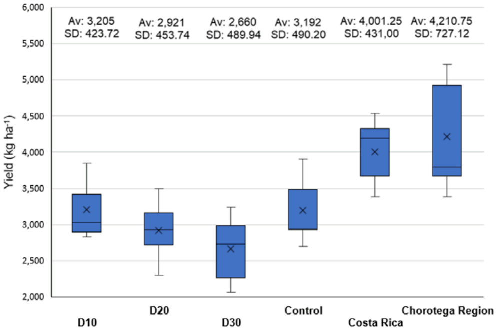

Figure 6. National and regional yields compared to the yield obtained with unmanned aerial vehicle (UAV) treatments (CONARROZ 2019, CONARROZ 2022, CONARROZ 2023, INEC 2017).

The maximum difference in average yield between D10 and D30 is 545 kg ha^{-1}, but the average standard deviation is 464.40 kg ha^{-1}. Some results with high yield values made the D10 average higher, increasing the dispersion, but not enough to make the average significantly different than other treatments.

When the average rice yield of D10 (which is the highest among the UAV treatments) was compared to the average rice yield in the Costa Rican and Chorotega regions (CONARROZ 2019, CONARROZ 2023, INEC 2017) over the past 11 years (Figure 6), it is shown that the rice produced were lower by 19.90% and 23.89%, respectively. These results differed from Flores (2019), who applied ABA in rice and obtained a 17.74 and 29.49% higher yield, respectively, compared to the control without ABA. The difference in results may be influenced by the conditions of each experiment, since Flores (2019) implemented a different spray method (backpack sprayer), an irrigation system and adjuvants, bio-stimulants and other PGR. Moreover, UAV treatments had PGR rates up to 6,000 mg L^{-1}, while Flores (2019) applied 150 and 300 mg L^{-1} in the experimentation.

The need to apply ABA with a complement was recommended by Solera (2019), who indicated that it is important to include other nutrients, especially phosphorus. Moreover, Chen *et al.* (2019) showed that ABA can enhance, with significant statistical differences, the grain yield when use together with sucrose.

Furthermore, the averages rice yield indicated poor production in comparison with the national and regional yields and suggest that external factors caused possible negative effects on the rice studied. In the same way as the SB rice yield analysis, the low damaged kernel (3.97%) suggests that pests, microorganisms, or diseases did not play a big part in the low values obtained. It is possible that low availability of nutrients in the soil affected the grain filling in the last rice production stage or either other environmental factors avoided a higher rice yield.

Due to the lack of significant differences between treatments and control and the poor yield results compared to the National and Regional average, it is concluded that the three spray volumes used with UAV, and the characteristics presented did not improve rice yield. Then, it was not possible to choose the optimal UAV treatment based on this parameter.

3.2.3 UAV rice milling quality

The ANOVA test and Kruskal Wallis test (for those data sets with no normality) reported no significant differences between treatments and control in all milling quality parameters (ANOVA: $p = 0.5928-0.9968$; F = 0.02-0.65; KW: $p = 0.8792-0.9583$; H = 0.31; $\alpha = 0.05$). Considering that all results had a similar performance, RY will be used (Table 6). When analyzing RY, it was noted that the treatment averages were similar, with maximum differences as low as 0.7%, and presented an average standard deviation of 2.44%, which clarifies the few disparities between treatments.

Table 6. Commercial rice yield (RY) average values obtained in the milling test of rice sprayed with three unmanned aerial vehicle (UAV) treatments and the control (C).

Treatment	Average (%)	Standard Deviation (%)	Min (%)	Max (%)
D10	65.72	2.26	62.10	67.70
D20	65.18	2.64	62.80	69.10
D30	65.60	1.73	63.60	67.70
C	65.88	3.14	61.30	69.20

The average percentages of the three treatments of each milling quality parameter were compared to the results of a previous study conducted by Rojas (2012), who used the same technical regulation for rice milling tests. As shown in Table 7, the results for damaged kernels (DK), stack yield (SY), semolina yield (SeY), whole kernel yield (WKY), and broken kernel yield (BKY) were similar to those found by Rojas (2012), with a range of difference between -2.86% and 3.75%. Chalkiness (CH) was the parameter with the most difference being 6.96% higher in this research, followed by small broken yield (sbY) with 5.48% less than Rojas (2012).

Table 7. Milling quality comparison between unmanned aerial vehicle (UAV) treatments and other studies results.

Milling test	UAV treatments results (%)	(Rojas 2012) results (%)	(Reyes *et al*. 2020) results (%)	(Flores 2019) results (%)	(Solera 2019) results (%)	(Chen *et al.* 2019) results (%)
CH	11.46	4.50	-	-	-	11.40
DK	3.97	2.48	-	-	-	-
SY	68.69	65.55	68.70	71.72	-	≈67.00
SeY	10.70	13.47	9,34	-	-	-
sbY	3.19	8.67	-	-	-	-
LBY	16.79	-	-	-	-	-
WKY	48.65	44.90	-	63.91	61.50	≈60.00
BKY	19.98	22.84	7.27	7.81	7.29	-

CH = Chalkiness, DK = damaged kernels, SY = stack yield, SeY = semolina yield, sbY= small broken yield, LBY = large broken kernel yield, WKY = whole kernel yield and BKY = broken kernel yield.

The comparison with other studies suggests similarities with that found in present research for SY, having differences of 0.01% (Reyes *et al.* 2020), 3.03% (Flores 2019), and around 1.69% (Chen *et al.* 2019). However, BKY, in studies where ABA is involved, was around 7.00-8.00% which is about 13.00-12.00% lower than the BKY obtained with the UAV treatments. The differences in BKY and WKY may be due to the use of sucrose by Chen *et al.* (2019) and the use of bio-stimulants and another PGR by Flores (2019). Both studies indicated an enhancement in the rice milling quality test carried out, compared to the treatments without the application of ABA.

The lack of significant differences between treatments and control, the similarities with results reported by Rojas (2012) and the poor milling quality compared to other studies with ABA involved concluded that the three spray volumes and the characteristics presented did not improve rice quality. Therefore, it was not possible to choose the optimal UAV treatment based on rice milling quality parameters.

3.3 Selection of the most efficient spraying treatment and method

To determine if either SB or UAV is the optimal agrochemical spray method, all parameters are compared between the most efficient treatments of each method. Table 8 summarizes the parameters results of the most efficient UAV and SB treatments. In this case, a trend to increase rice yield while increasing the spray volume was absorved with SB200 having the greatest rice yield. However, differences in average yield were not enough to be considered significant, confirmed statistically. Rice milling quality was also compared statistically, and there were no significant differences between treatments in this parameter.

Table 8. Summary of the parameters studied in agrochemical spraying for SB100, SB200, and D20 treatments.

Parameter	Characteristics	Treatments		
		D20	SB100	SB200
Spray quality	Average coverage (%)	6.11	21.20	51.19
	Droplet density (drops cm^{-2})	15.39	171.64	460.20
	CV (%)	48.49	41.46	30.92
Rice yield	Average yield (kg ha^{-1})	2.921	3.163	3.504
Milling quality	RY average (%)	65.18	65.28	65.04

The most efficient method and treatment selection were based on the spray quality parameter. As presented before, SB200 and SB100 have significant differences in coverage percentage. After performing the Wilcoxon test, significant differences were found between treatments ($W = 40$; $p = 0.0019$ for D20:SB100 and $W = 36$; $p = 0.0002$ for D20:SB200).

It was concluded that SB200 is the optimal treatment for agrochemical spraying. As shown in Table 8, SB200 has the lowest CV, confirming this treatment as the most efficient in uniformity. However, its CV = 30.92%, was not nearly as close as required for international standards (CV ≤ 10.00%). In the case of the percentage of coverage and droplet density, SB200 was also the treatment with better results. It presented a CV lower in 10.54% and 17.57% compared to SB100 and D20, respectively, and the droplet density exceeded what is required (460.20 drops cm^{-2}). Additionally, it is important to point out that D20 did not present the droplet density necessary for systemic agrochemicals (> 20 drops cm^{-2}).

As for SB100, the drop density surpassed what is required (171.64 drops cm^{-2}) and, despite having inferior uniformity (CV = 41.46%) compared with SB200 (CV = 30.92%), it advantages SB200 in water consumption, which is beneficial for the environment and people's basic needs, especially in drought prone areas where rice is grown. Reduction in water consumption, also represents a reduction in working hours, lower financial expenses, decrease of fuel consumption, lower tractor driving on rice, and a higher concentration of the agrochemicals in the water sprayed.

The SB100 uniformity weakness could be reduced with some changes and research in aspects like dosing nozzles, bar height, and tractor trajectory. Some research indicate that low uniformity could be the result of the effect of irregularities in the field, which causes abrupt movements in the tractor, changing the bar and nozzles height. This negative effect could be countered with the use of SB with suspensions or with the addition of suspensions to the existing equipment (Cui *et al.* 2019).

Even though it is possible to reach maximum water savings and avoid total crop damage with UAV, the low coverage makes its use difficult due to the lack of reliability with systemic and non-systemic agrochemicals. The use of the latest UAVs or the search for coverage improvement in the currently used UAVs would be beneficial since this equipment is cheaper and incurs fewer financial expenses than mounted sprayers.

The fact that rice yield seemed to have been negatively affected by some factors beyond this research scope, does not allow the linkage between parameters. Thus, it is important to continue the study of spraying with different variables or ranges, different locations, wider areas to facilitate equipment maneuverability and the use of adjuvants in the agrochemical mixture.

4. CONCLUSIONS

This research made possible to study the performance of a conventional (SB) and a modern method (UAV) for agrochemical spraying according to spray quality, rice yield, and rice milling quality parameters. The results are useful not only for PGR or systemic agrochemicals, but they can be considered for any kind of agrochemical to be sprayed.

With the methodology implemented and the rice field characteristics, significant differences in rice yield and rice milling quality were not found for UAV and SB. Thus, the selection of the most efficient spraying method was based entirely on spray quality parameter.

SB200 was selected as the most efficient treatment for agrochemical spraying since it presented the best results in all spray quality terms, compared to SB100 and D20, with a coverage 30.00% higher than SB100 and 45.08% higher than D20, an adequate droplet density of 460.20 drops cm^{-2} and being the treatment with the greatest uniformity (CV=30.92%) between the treatments compared.

SB100 exceeds the droplet density required (171.64 drops cm^{-2}) and has a water consumption of 100% less than SB200. However, having a CV 10.55% higher than SB200 and lower coverage with significant differences resulted in a poor performance in the spray quality parameter. Therefore, it is necessary to improve the characteristics of the equipment that affects negatively the spraying.

The D20 treatment has considerable advantages over any SB treatment, such as low water consumption with 80 L ha^{-1} less than SB100, low storage space needed, fuel consumption is not necessary, the UAV operator has minimum exposure to agrochemicals, and there is no damage to the field contrary to what happens with a SB mounted on a tractor. However, the low uniformity (CV=48.49%) and low coverage (6.11% and 15.39 drops cm^{-2}) in the spraying indicate that D20 does not comply with the necessary characteristics of agrochemical spraying of 20 drops cm^{-2} for systemic agrochemical and a 10.00% or lower CV ruling out D20 as the most efficient treatment. Nevertheless, working on UAV spraying improvement could lead to an advancement in the search of implementation of new technologies for the increase in agriculture efficiency.

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