

Article

Performance Evaluation of UAVs in Wheat Disease Control

Qingqing Zhou ^{1,2,†}, Songchao Zhang ^{1,2,†} , Xinyu Xue ^{1,2,*}, Chen Cai ^{1,2} and Baokun Wang ^{1,2}

¹ Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China

² Sino-USA Pesticide Application Technology Cooperative Laboratory, Nanjing 210014, China

* Correspondence: xuexinyu@caas.cn; Tel.: +86-025-8434-6242

† These authors contributed equally to this work.

Abstract: Plant protection unmanned aircraft vehicles (UAVs) were developed rapidly in China. The operation performances of different models of UAVs were different. This paper systematically studied droplet deposition distribution; pesticide-mixture utilization rate; operational efficiency; wheat-disease control efficacy; and a comprehensive score of three types of UAVs, a boom sprayer, and a knapsack sprayer. The results showed the descending order of the droplet penetration rate of the pesticide application equipment (PAE) was boom sprayer; UAVs; and knapsack sprayer. The pesticide-mixture utilization rates of the UAVs and boom sprayer were more than 50% while that of the knapsack electric sprayer was only 27.8%. The UAVs' average labor productivity was 5.75 ha per man-hour, which was slightly less than that of the boom sprayer and 21.3 times that of the knapsack sprayer. The control efficacy of each machine on wheat Fusarium head blight was more than 90%. The average performance comprehensive score of the UAVs was 0.812, which was slightly lower than the score of 0.929 for the 3WPZ-700 self-propelled boom sprayer but much higher than the score of 0.399 for the 3WBD-18 knapsack electric sprayer. The results clearly showed the potential of UAVs for improving the pesticide-mixture utilization rate and operational efficiency, as well as the wheat Fusarium head blight control efficacy.

Keywords: pesticide application equipment; UAV; performance evaluation; droplet penetration rate; pesticide-mixture utilization rate; labor productivity; wheat Fusarium head blight



Citation: Zhou, Q.; Zhang, S.; Xue, X.; Cai, C.; Wang, B. Performance Evaluation of UAVs in Wheat Disease Control. *Agronomy* **2023**, *13*, 2131. <https://doi.org/10.3390/agronomy13082131>

Academic Editor: Peng Fu

Received: 14 July 2023

Revised: 3 August 2023

Accepted: 9 August 2023

Published: 14 August 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Wheat is one of the primary grain crops throughout the world; however, fungal diseases provide a great obstacle to improving wheat yields, now and into the future [1]. Fusarium head blight not only reduces the yield of wheat but also produces toxins harmful to the human body [2]. Wheat powdery mildew is a frequently encountered foliar disease that causes serious yield losses [3]. However, chemical control is still the most effective way to prevent bacteria epidemics [1].

At present, the commonly used pesticide application equipment (PAE) in China mainly includes knapsack sprayers, boom sprayers, and plant protection unmanned aircraft vehicles (UAVs) [4]. On small Asian farms ranging from one to two hectares, boom sprayers, and knapsack sprayers have been widely used due to their simple operation and relatively low price [5,6]. Due to the flexibility, ease of operation, efficiency, accuracy, and penetration advantage of the rotor wind field of UAV [7], agricultural UAVs have developed rapidly [8,9]. Although agricultural UAVs have been used in remote sensing monitoring, seeding, fertilization, auxiliary pollination [10], and other fields, their main usage is pesticide application [11].

The spraying effects of different models of UAVs vary greatly [12,13]. Different brands and product models of UAVs have different sizes, load limits, rotor numbers and shapes, nozzle atomization principles [14], and nozzle layouts [15]. Many scholars have studied the crop-canopy deposition of different types of UAVs in rice, maize, wheat, and trees and

have optimized the operation parameters, such as flight height and flight speed [16–20]. Zhang et al. [21] compared two typical kinds of UAV models based on the first industry standard of China and proved that the decrease of flight speed and flight height in a certain range can increase the effective spray width and droplet penetration rate. Wang et al. [22] tested the spraying coverage and work efficiency of four typical UAV models; the results showed that the UAV models had uneven droplet distribution and low time utilization. Chen et al. [23] studied the deposition of oil-powered single-rotor UAVs and electric single-rotor UAVs in the rice canopy; the results showed that, compared with the knapsack manual sprayer, the UAVs improved the penetration rate. Wang et al. [24] compared the droplet deposition, control efficacy, and working efficiency of a six-rotor UAV with a self-propelled boom sprayer and two conventional knapsack sprayers on wheat crop. It was found that the deposition uniformity and droplet penetrability of the UAVs were poor; however, the UAVs had comparable control efficacy on wheat aphids and had high work efficiency.

The above studies mainly focused on the optimization of UAVs' operation parameters. In terms of performance evaluation, on the one hand, the UAVs' model and assessment indicators were not comprehensive; on the other hand, the inconsistent experimental conditions of different kinds of literature, such as moderate meteorological conditions, crop varieties, and disease indexes, resulted in significant differences in the experimental results. With the improvement and upgrading of UAVs [13], the continuous tracking of their operational performance plays a positive role in promoting the benign development of UAVs. In this paper, three typical UAVs were compared with a self-propelled boom sprayer and a knapsack electric sprayer. The droplet coverage and penetration rate, pesticide-mixture utilization rate, labor productivity, and control efficacy of wheat powdery mildew and Fusarium head blight were investigated; based on these indicators, a comprehensive performance evaluation method for PAE was proposed. The differences in droplet deposition and pesticide-mixture utilization rate between UAVs and the ground equipment were analyzed by statistics methods. This study aims to comprehensively evaluate the performance of UAVs in wheat disease control, compared with a boom sprayer and knapsack electric sprayer; this study points out the operational advantages of UAVs and discusses the direction for improvement.

2. Materials and Methods

2.1. Pesticide Application Equipment

The PAE used in the experiment includes an XP2020 electric four-rotor UAV (Ji Fei Technology Co., Ltd., Guangzhou, China), a T16 electric six-rotor UAV (DJI Innovation Technology Co., Ltd., Shenzhen, China), a CE20 electric single-rotor UAV (Wuxi Hanhe Aviation Technology Co., Ltd., Jiangsu, China), a 3WPZ-700 self-propelled boom sprayer (Qingzhou Wolong Pesticide Application Equipment Co., Ltd., Shandong, China), and a 3WBD-18 knapsack electric sprayer (Taizhou Luqiao Minghui Electric Sprayer Co., Ltd., Zhejiang, China).

The main technical parameters of each machine used in this test are shown in Table 1 and the selection of technical parameters was based on the manufacturer's recommendation. The XP2020 electric four-rotor UAV and T16 electric six-rotor UAV were equipped with variable control systems and the flow rate changed with the changes in flight speed and spray width, thus ensuring the stability of the spray volume. However, the CE20 electric single-rotor UAV was not equipped with the variable control system; the tested spray volume fluctuated in the range of 13.5–15 L·ha^{−1}. The operation sites of the different machines are shown in Figure 1.

Table 1. Main technical parameters of each machine.

PAE	Nozzle Type	Number of Nozzles	VMD ⁶ /Pressure	Spray Height above the Crop/m	Forward Speed /(m·s ^{−1})	Spray Width/m	Spray Volume /(L·ha ^{−1})
XP2020 ¹	Rotary atomizing nozzle	2	150 µm	1.5	5	4	15
T16 ²	Teejet Flat fan nozzle F110-01	8	0.3 MPa	1.5	5.5	5	15
CE20 ³	Teejet Flat fan nozzle F110-025	2	0.3 MPa	1.5	5	5.5	13.5~15
3WPZ-700 ⁴	Lanao Flat fan nozzle F110-02	29	0.4 MPa	0.5	1.5	13	240
3WBD-18 ⁵	Conical spray nozzle	2	0.12~0.3 MPa	0~0.5	0.5~1	/	270

¹ XP2020 indicates XP2020 electric four-rotor UAV. ² T16 indicates T16 electric six-rotor UAV. ³ CE20 indicates CE20 electric single-rotor UAV. ⁴ 3WPZ-700 indicates 3WPZ-700 self-propelled boom sprayer. ⁵ 3WBD-18 indicates 3WBD-18 knapsack electric sprayer. ⁶ VMD is an abbreviation for droplet volume medium diameter.

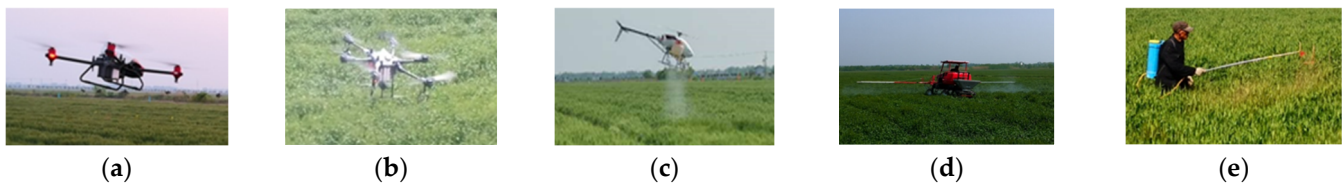


Figure 1. Five test sprayers. (a) XP2020 electric four-rotor UAV; (b) T16 electric six-rotor UAV; (c) CE20 electric single-rotor UAV; (d) 3WPZ-700 self-propelled boom sprayer; (e) 3WBD-18 knapsack electric sprayer.

2.2. Test Material

The plant protection operation quality evaluation system, with a horizontal positioning accuracy of 1.1 cm and elevation positioning accuracy of 1 cm (Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs of China), was used to collect the flight trajectory of the UAVs and locate sampling points. Meteorological conditions were observed via the Watchdog 2900ET ground weather station, with a minimum sampling interval of 1 min (Spectrum Technologies, Inc., Aurora, IL, USA). Canopy density was tested by the LAI-2200C Canopy Analyzer (Beijing Ligotai Technology Co., Ltd., Beijing, China). The spray deposition amount was measured by the 722N Visible Light Spectrophotometer (Shanghai Yidian Analytical Instrument Co., Ltd., Shanghai, China); polyester card (ϕ 9 cm), 0.22 µm syringe driven filter (Jinteng PES filter, Tianjin, China); allure red AC, purity 85%, (Beijing Solarbio Technology Co., Ltd., Beijing, China). The sampling equipment for droplet deposition included a 9000F mark ii Scanner (Canon, Tokyo, Japan) and water-sensitive paper, size 76 mm × 26 mm, (Syngenta, Basel, Switzerland). Other test materials included universal clamps for clamping water-sensitive paper and polyester cards, plastic bags for collecting water-sensitive paper and polyester cards, scissors for cutting off wheat plants, and electronic balance, precision 0.01 g, range 200 g, electronic balance, precision 0.1 g, range 30 kg.

2.3. Wheat Growth Condition and Meteorological Conditions

The test was conducted in a national modern agriculture demonstration zone in Jianhu County, Jiangsu Province, China. The wheat variety was Xumai 33. The wheat growth and meteorological conditions regarding the two experiments are shown in Table 2.

Table 2. Wheat growth and meteorological conditions.

Application Time	Growth Period	Wheat Height/cm	Average Leaf-Area Index	Average Wheat Plant Mass per Unit Area/(g·m ⁻²)	Temperature/°C	Humidity/%	Wind Speed/(m·s ⁻¹)
28–29 April 2021	Heading and flowering period	64 ± 6	5.74	3661.7	19.8 ± 0.8	77 ± 2	0.2–0.4
14 May 2021	Filling period	72 ± 5	5.93	3896.5	20.5 ± 0.5	79 ± 2	0.3–0.5

The LAI-2200C canopy analyzer was used to measure the leaf-area index. Three randomly selected sites of wheat plants with a 0.09 m² area were cut off and weighed and the average plant mass per unit area was obtained.

The two tests were conducted from 4 pm to 6 pm, the wind speed was within 0.5 m·s⁻¹, the wind direction was perpendicular to the UAV flight path, the temperature was 19–21 °C, and the humidity was 75–81%. The meteorological conditions were very favorable for aerial spraying.

2.4. Spray Pesticides and Reagents

The spray pesticides were suspended agents, including tebuconazole (a prochloraz compound pesticide), difenoconazole (an azoxystrobin compound pesticide), and imidacloprid; they were applied to control wheat powdery mildew, Fusarium head blight, and aphids. The spraying agent was prepared according to the spray area and the spray volume of equipment applied. A certain amount of allure red AC was added to prepare the tracer solution [25] with a concentration of 5 g·L⁻¹. Approximately 20 mL of spray solution was taken back to the laboratory to analyze the concentration of the allure red AC. After the spray solution was diluted to a certain multiple, the diluted spray liquid was filtered by a 0.22 µm syringe-driven filter. We tested the absorbance of the liquid before and after filtration in the laboratory and verified that the 0.22 µm syringe-driven filter could effectively block suspended pesticides and dust particles but had no effect on the concentration of allure red AC. The absorbance was determined by a visible light spectrophotometer at a wavelength of 504 nm and the concentration of allure red AC in the spray solution was analyzed.

2.5. Experiment Design

2.5.1. Data Sampling

The sampling method for the droplet deposition test in the canopy is shown in Figure 2. One piece of water-sensitive paper and one piece of polyester card were placed on the top of the canopy to acquire the droplet deposition. Another piece of water-sensitive paper was placed in the middle layer to test droplet penetration and another polyester card was placed on the bottom layer to capture the pesticide loss rate [26]. After the placement of the sampling materials was completed, we stirred the wheat plant to restore its normal state to ensure the accuracy of the sampling.

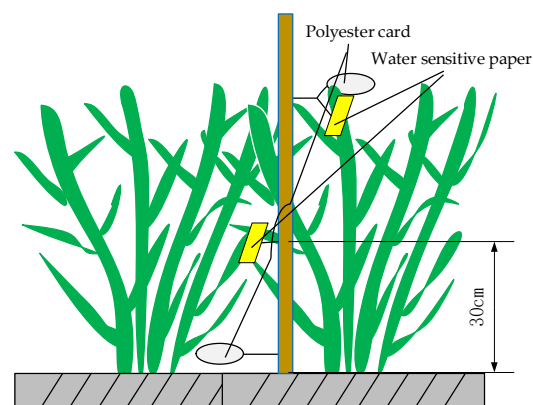


Figure 2. Sampling method.

The flight path and sampling point position of the XP2020 electric four-rotor UAV is shown in Figure 3. The droplet deposition test of the UAV was repeated four times while the droplet deposition test of the self-propelled boom sprayer and the knapsack electric sprayer was sampled once. Each test area was set with 9 sampling points. The GPS information of the 9 sampling points was recorded by the plant protection operation quality evaluation system. The plant protection operation quality evaluation system was installed on the top of the UAV with less interference to keep the antenna transmission signal stable. When the spray operated normally, the plant protection operation quality evaluation system tracked the GPS information of the sprayer's operation track in real-time and reflected it directly on the mobile terminal through the 4G module. The status information was collected and uploaded synchronously and the data were exported after the completion of the operation [27]. According to the GPS information collected by the plant protection operation quality evaluation system, the operation time and the actual operation area of the sprayer were obtained through the software [28]. After spraying, the actual spraying amount and spray area were recorded.

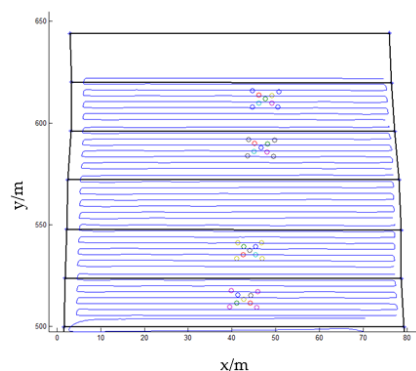


Figure 3. XP2020 UAV flight path and sampling point position. Note: The circles are the GPS information of the 9 sampling points.

2.5.2. Droplet Deposition and Penetration

The deposition amount and penetration of the droplets in the canopy reflect the operation quality of the spray. For the prevention and control of plant diseases and insect pests in the middle and lower parts of plants, the droplets were required to have high penetration. Droplet deposition data were collected by water-sensitive paper and then processed by image analysis software. Water-sensitive papers were scanned and saved as a picture with a resolution of no less than 600 dpi. The droplet coverage rate was analyzed with Deposit Scan software [29]. The penetration rate was the ratio of the middle-layer coverage rate to the upper-layer coverage rate.

2.5.3. Pesticide-Mixture Utilization Rate

The pesticide-mixture utilization rate refers to the ratio of the amount of pesticides deposited per unit area and the spray amount per unit area. The higher the pesticide-mixture utilization rate, the less droplet loss there was in the air or on the ground. Crop deposition was measured by using tracers and manual collection cards or plant sampling. Allure red AC was used as a tracer due to its high recovery rate and strong light stability. Polyester card was used as a manual collection card due to its high elution rate.

The polyester cards were taken back and sealed to be stored separately after spraying. About 15 wheat plants around the sampling site were clipped, sealed, and light-shielded for storage [30]. The polyester cards were eluted with 15 mL of water and the wheat plant was timely weighed and eluted with 100 mL of water. The eluent of the polyester card, eluent of the sample wheat plant, and eluent of the blank wheat plant were filtered by a 0.22 μm syringe-driven filter. The absorbance was determined by the visible light spectrophotometer and the concentration of allure red AC in the eluent was analyzed.

The spray deposition amount per unit area of the polyester card was calculated according to Equation (1) [31]; the spray deposition amount per unit area of the wheat plant was calculated according to Equation (2):

$$\beta_{dep} = \frac{(\rho_{smp} - \rho_{blk}) \times V_{dii}}{\rho_{spray} \times A_{col}}, \quad (1)$$

$$\beta_{dep} = \frac{(\rho_{smp} - \rho_{blk}) \times V_{dii}}{\rho_{spray} \times m / S_m}, \quad (2)$$

where, β_{dep} is the spray deposition amount per unit area, $\text{mL} \cdot \text{cm}^{-2}$; ρ_{smp} is the sample eluent concentration, $\text{mg} \cdot \text{L}^{-1}$; ρ_{blk} is the blank sample eluent concentration, $\text{mg} \cdot \text{L}^{-1}$; V_{dii} is the volume of eluent, mL; ρ_{spray} is the concentration of allure red AC spray liquid, $\text{mg} \cdot \text{L}^{-1}$; A_{col} is the area of the polyester card, cm^2 ; m is the weight of the collected plant samples, g; and S_m is the plant weight per unit area, $\text{g} \cdot \text{cm}^{-2}$.

The spray deposition rate was shown as Equation (3), which was obtained by the ratio of the amount of pesticides deposited per unit area and the spray amount per unit area:

$$\beta_{dep\%} = \frac{\beta_{dep} \times 10^5}{\beta_V} \times 100\%, \quad (3)$$

where, $\beta_{dep\%}$ is the spray deposition rate, %; β_{dep} is the deposition amount per unit area, $\text{mL} \cdot \text{cm}^{-2}$; and β_V is the spray amount per unit area, $\text{L} \cdot \text{ha}^{-1}$.

The pesticide-mixture utilization rate of the wheat plant was the spray deposition rate of the wheat plant. However, the pesticide-mixture utilization rate of the polyester card refers to the deposition rate tested by the top polyester card minus the pesticide loss rate tested by the bottom polyester card [26].

2.5.4. Labor Productivity

Labor productivity refers to the spraying area of a person in a unit of time. In order to reduce the time consumption caused by turning around and the acceleration/deceleration of PAE, the area of the production efficiency assessment should be greater than 2 ha. Labor productivity was calculated according to Equation (4):

$$G = \frac{U}{T_b \cdot A}, \quad (4)$$

where, G is labor productivity, ha per man-hour; U is the spraying area, ha; T_b is the working time, h; and A is the number of operators.

2.5.5. Control Efficacy of Wheat Powdery Mildew and Fusarium Head Blight

The control efficacy of wheat powdery mildew and Fusarium head blight was investigated 20 days after the second application. Five sites were investigated in each test area. The investigation method of wheat Fusarium head blight control efficacy was that about 500 plants were investigated in each site, which was divided into 5 grades according to the proportion of diseased ear parts compared to the whole ear; the number of ears at each grade was recorded. The investigation method of wheat powdery mildew control efficacy: about 100 leaves of 30–40 plants were investigated at each site. According to the proportion of the diseased leaf area compared to the total leaf area, the severity of powdery mildew was divided into 9 grades, respectively. They were 0%, 1%, 5%, 10%, 20%, 40%, 60%, 80%, and 100% and the number of leaves at each grade was recorded. The disease index of Fusarium head blight was calculated according to Equation (5) and the disease index of powdery mildew was calculated according to Equation (6). The control efficacy

was calculated by the difference between the disease index of the blank control area and the treatment area divided by the blank control area disease index [32,33]:

$$I = \frac{\sum(n_i \times i)}{N \times 4} \times 100, \quad (5)$$

$$J = \frac{\sum(n_j \times j)}{N} \times 100, \quad (6)$$

where, I and J are the index of the wheat powdery mildew and Fusarium head blight disease, respectively, %; n_i and n_j are the corresponding number of diseased ears and leaves at each grade, respectively; N is the total number of ears or leaves; i is the wheat Fusarium head blight severity level, $i = 0, 1, 2, 3, 4$; and j is the proportion of the diseased leaf area compared to the total leaf area, $j = 0\%, 1\%, 5\%, 10\%, 20\%, 40\%, 60\%, 80\%, 100\%$.

2.5.6. Performance Comprehensive Evaluation of PAE

The performance of the PAE was comprehensively evaluated based on four indicators: penetration rate, pesticide utilization rate, labor productivity, and control efficacy of Fusarium head blight. All four indicators had the same weight factor of 0.25. The comprehensive score of each PAE was calculated according to Equation (7). The closer the score was to 1, the better the performance of the PAE:

$$s_a = \frac{\sum_{k=1}^4 (p_{k,a} / p_{k,max})}{4}, \quad (7)$$

where, s_a is the comprehensive score of the PAE a , $a = \text{XP2020, T16, CE20, 3WPZ-700, 3WBD-18}$; k is the evaluation indicator, numbers from 1 to 4 are penetration rate, pesticide utilization rate, labor productivity, and control efficacy of Fusarium head blight, respectively; $p_{k,a}$ is the value of the k evaluation indicator of PAE a ; and $p_{k,max}$ is the maximum value of the k evaluation indicator of all PAE.

2.5.7. Data Analysis

The statistical analysis software SAS was applied for variance analysis and Duncan's method for multiple comparative analysis; the coverage rate, penetration rate, and pesticide utilization rate of different PAE were graded. The significant difference between the polyester card method and the plant method was analyzed by a paired t -test and the significant level of α was 0.05.

3. Results

3.1. Droplet Deposition and Penetration

The droplet coverage rate and penetration rate of various sprayers are shown in Figure 4. The results of the four tests were analyzed by variance analysis and multiple comparison analysis. The 3WPZ-700 self-propelled boom sprayer had the highest upper-layer coverage rate of 57% and it also had the highest penetration rate of 63.9%. The coverage rate of the 3WBD-18 knapsack electric sprayer was the second highest, 24.83%; meanwhile, it had the lowest penetration rate of 12.6%. The coverage rate of the UAVs was the smallest, no more than 8%, and the penetration rate was between 30 and 45%. There was no significant difference in the upper coverage rate and penetration rate of the three UAVs.

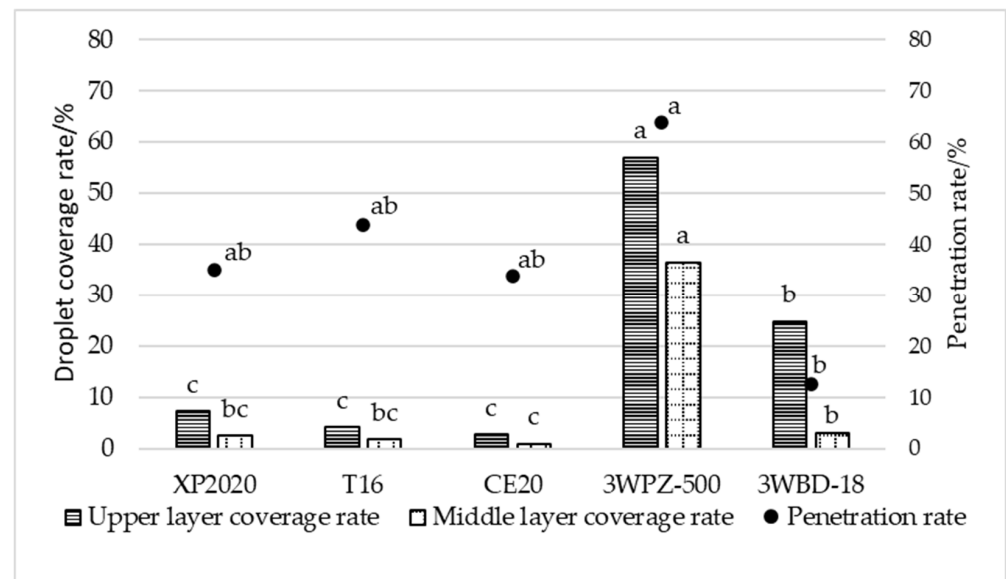


Figure 4. Droplet coverage rate and penetration rate of different PAE items. Note: The different letters on the bar chart or scatter plot indicate statistically significant differences, at $\alpha = 0.05$, with Duncan's method for multiple comparison analysis.

3.2. Pesticide-Mixture Utilization Rate

The pesticide-mixture utilization rate results of four tests and the average values detected by the polyester cards of the UAVs are shown in Figure 5. The results of the four tests were analyzed by variance analysis and multiple comparison analysis. The pesticide-mixture utilization rate of the XP2020 electric four-rotor UAV was stable and at the highest level, which indicated that the sprayer had good deposition uniformity. On the contrary, the pesticide-mixture utilization rate monitor value of the T16 electric six-rotor UAV fluctuated while the pesticide-mixture utilization rate monitor value of the CE20 electric single-rotor UAV was at a relatively low level.

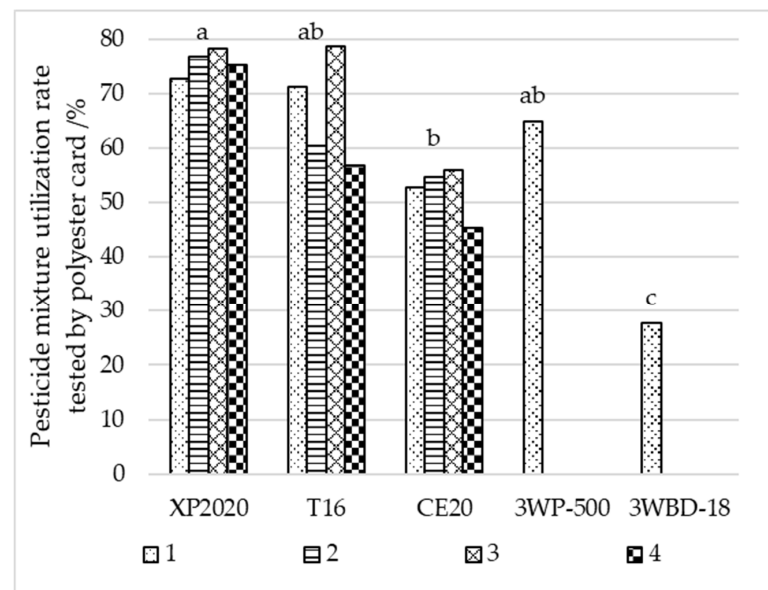


Figure 5. Pesticide-mixture utilization rate of different PAE items. Note: The different letters on the bar chart indicate statistically significant differences, at $\alpha = 0.05$, with Duncan's method for multiple comparison analysis.

The pesticide deposition rate, loss rate, pesticide-mixture utilization rate detected by the polyester card, and the pesticide-mixture utilization rate detected by the plant are shown in Table 3. It can be seen from Table 3 that the XP2020 electric four-rotor UAV had the highest pesticide deposition rate of 85.2% and the highest pesticide-mixture utilization rate, as detected by the polyester card of 75.7%. The 3WPZ-700 self-propelled boom sprayer had the second highest pesticide deposition rate of 83.6%; meanwhile, its pesticide loss rate was the most serious, which was 18.7%, resulting in a pesticide-mixture utilization rate that was 10.8% lower than that of the XP2020 electric four-rotor UAV. In general, the average pesticide-mixture utilization rate of the UAVs was 64.9%, which was similar to that of the boom spray. Meanwhile, the pesticide-mixture utilization rate of the 3WBD-18 knapsack electric sprayer was the lowest, at 27.8%.

Table 3. Pesticide-mixture utilization rates of sprayers.

PAE ¹	Pesticide Deposition Rate/%	Pesticide Loss Rate/%	Pesticide-Mixture Utilization Rate Detected by Polyester Card/%	Pesticide-Mixture Utilization Rate Detected by Plant/%
XP2020	85.2	9.5	75.7	77.8
T16	75.7	8.9	66.8	68.7
CE20	65.8	13.6	52.2	53.8
3WPZ-700	83.6	18.7	64.9	66.4
3WBD-18	31.2	3.4	27.8	27.2

¹ The full name of each PAE item was the same as in Table 1.

The paired *t*-test was applied for the mean results of the pesticide-mixture utilization rate, which were obtained by the polyester card method and the wheat plant method; they are shown in Table 4. The occurrence probability of the original hypothesis was 0.056, which was greater than the significance level α 0.05, indicating that there was no significant difference between the pesticide-mixture utilization rates detected by the polyester card and plant.

Table 4. Two sample paired *t*-test for mean results.

Test Statistic	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		T Value	Degree of Freedom	Sig.
				Lower Interval	Upper Interval			
PPUR ¹ –PCPUR ²	1.3	1.089	0.487	−0.05	2.65	2.67	4	0.056

¹ PPUR indicates the pesticide-mixture utilization rate detected by the plant. ² PCPUR indicates the pesticide-mixture utilization rate detected by the polyester card.

3.3. Labor Productivity

The labor productivity of various machines is shown in Table 5. The T16 electric six-rotor UAV had the highest labor productivity of 6.88 ha per man-hour. The XP2020 electric four-rotor UAV had the lowest labor productivity of 4.57 ha per man-hour, among the UAVs. The UAVs' average labor productivity was 5.75 ha per man-hour, which was similar to that of the 3WPZ-700 self-propelled boom sprayer and 21.3 times that of the 3WBD-18 knapsack electric sprayer.

Table 5. Labor productivity of each sprayer.

PAE ¹	Spray Area /(ha)	Number of Operators	Working Time/h	Labor Productivity /(ha per Man-Hour)
XP2020	2.33	1	0.51	4.57
T16	2.2	1	0.32	6.88
CE20	2.2	1	0.38	5.79
3WPZ-700	2.13	1	0.35	6.09
3WBD-18	0.15	1	0.56	0.27

¹ The full name of each PAE item was the same as in Table 1.

The tank capacity of the 3WPZ-700 self-propelled boom sprayer was about 700 L and the spraying volume was 270 L/ha; a tank of pesticide mixture liquid can spray 2.6 ha. During the labor productivity test, the 3WPZ-700 self-propelled boom sprayer saved the time of the site transition and the filling of the pesticide mixture liquid; its time utilization rate was 100%. For other sprayers, pesticide mixture liquid should be added once more during the spraying operation.

3.4. Control Efficacy of Wheat Powdery Mildew and Fusarium Head Blight

The control efficacies of the wheat powdery mildew and Fusarium head blight of various machines are shown in Figure 6. The control efficacy of each sprayer on wheat Fusarium head blight was more than 90%. Meanwhile, the control efficacy of each sprayer on wheat powdery mildew was relatively poor, merely between 50 and 70%. In the blank control area, the Fusarium head blight disease index was 9.42% while the wheat powdery mildew disease index was 43.30%.

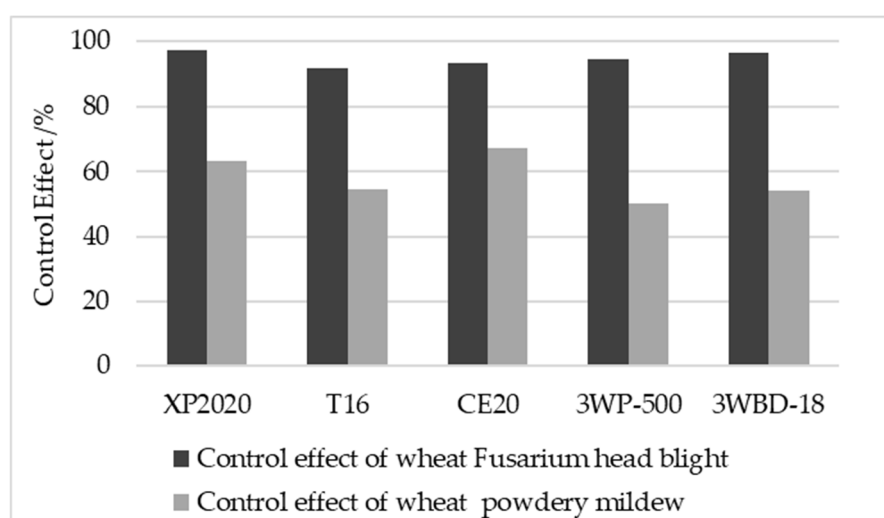


Figure 6. Control effect of wheat Fusarium head blight and powdery mildew of each PAE item.

3.5. Performance Comprehensive Score of PAE

The performance comprehensive scores of the five PAE items: XP2020, T16, CE20, 3WPZ-700, and 3WBD-18 were 0.803, 0.877, 0.755, 0.929, and 0.399, respectively. The closer the score was to 1, the better the performance of the PAE; so, the descending order of the performance comprehensive evaluation was 3WPZ-700 self-propelled boom sprayer, T16 electric six-rotor UAV, XP2020 electric four-rotor UAV, CE20 electric single-rotor UAV, and 3WBD-18 knapsack electric sprayer.

4. Discussion

The descending order of the upper droplet coverage was 3WPZ-700 self-propelled boom sprayer; 3WBD-18 knapsack electric sprayer; and UAVs. This was because the UAV was one of low-volume spray [19] and the spray volume in this experiment did not exceed $15 \text{ L} \cdot \text{ha}^{-1}$. Therefore, the influence of the droplet coverage rate was not calculated in the performance comprehensive evaluation of the PAE. The descending order of the droplet penetration rate was the 3WPZ-700 self-propelled boom sprayer, UAVs, and 3WBD-18 knapsack electric sprayer. The UAVs improved the penetration rate compared with the knapsack electric sprayer; this was due to airflow from the rotor wind field transporting droplets to the middle and lower layers of crops [21].

The descending order of pesticide-mixture utilization rate was the XP2020 electric four-rotor UAV; T16 electric six-rotor UAV, 3WPZ-700 self-propelled boom sprayer; CE20 electric single-rotor UAV; and 3WBD-18 knapsack electric sprayer. The XP2020 electric four-rotor UAV had a high pesticide deposition rate and a low pesticide loss rate; so,

the pesticide-mixture utilization rate had achieved the highest level. For the T16 electric six-rotor UAV, the nozzle layout [15] and variable spray control system should be further optimized to increase pesticide deposition uniformity. For the CE20 electric single-rotor UAV, the wind speed of the rotor wind field should be matched with the crop leaf area density [34,35] to further improve deposition and reduce pesticide loss. In general, for the UAV spraying with high drift risk [36], the low wind speed on the test day played a non-negligible role in achieving a high pesticide-mixture utilization rate for the UAV [37].

The UAVs had achieved comparable results with the boom sprayer in terms of labor productivity [24]. The average labor productivity of the UAVs was 5.75 ha per man-hour, which was 21.3 times that of the knapsack sprayer.

The control efficacy of each sprayer on wheat Fusarium head blight was more than 90%. However, the control effect of various PAE items on wheat powdery mildew was relatively poor. The possible reason was that the planting density of the wheat was very high and the permeability of the field was poor, resulting in the serious incidence of wheat powdery mildew [38,39]. The wheat powdery mildew disease index of the blank control area was 43.30%, which eventually lead to difficult treatment. Therefore, the influence of control efficacy on wheat powdery mildew was not calculated in the performance comprehensive evaluation of PAE.

The average performance comprehensive score of the UAVs was 0.812, which was slightly lower than the score of 0.929 for the 3WPZ-700 self-propelled boom sprayer but much higher than the score of 0.399 for the 3WBD-18 knapsack electric sprayer. In the future, the UAVs should be further optimized, in the aspects of their flight control, nozzle layout [15], variable spraying control, power, and load matching, to further improve the uniformity of droplet deposition and labor productivity.

5. Conclusions

According to the results, in terms of the pesticide-mixture utilization rate, labor productivity, and wheat-disease control effect, the UAVs achieved comparable results to the boom sprayer and were obviously better than the knapsack electric sprayer. However, in terms of droplet coverage and penetration, the UAVs were inferior to the boom sprayer because the spraying amount of the UAVs was much less than that of the boom sprayer.

Author Contributions: Conceptualization, Q.Z. and X.X.; methodology, Q.Z., S.Z. and C.C.; software, Q.Z. and S.Z.; validation, Q.Z. and C.C.; formal analysis, S.Z.; investigation, X.X.; resources, X.X. and B.W.; data curation, Q.Z.; writing—original draft preparation, Q.Z.; writing—review and editing, S.Z.; visualization, Q.Z. and B.W.; supervision, C.C.; project administration, X.X.; funding acquisition, X.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by Jiangsu Province and the Education Ministry Cosponsored Synergistic Innovation Center of Modern Agricultural Equipment Project (grant number XTCX1004), the Agricultural Science and Technology Innovation Project of the Chinese Academy of Agricultural Sciences, the Crop Protection Machinery Team (grant number CAAS-ASTIP-CPMT), the China Modern Agricultural Industrial Technology System (grant number CARS-12), and the Key Research and Development Project of Shandong Province (grant number 2022SFGC0204-NJS).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of this study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Figueroa, M.; Hammond-Kosack, K.E.; Solomon, P.S. A review of wheat diseases—A field perspective. *Mol. Plant Pathol.* **2018**, *19*, 1523–1536. [[CrossRef](#)]
2. Mielniczuk, E.; Skwaryło-Bednarz, B. Fusarium Head Blight, Mycotoxins and strategies for their reduction. *Agronomy* **2020**, *10*, 509. [[CrossRef](#)]

3. Kleczewski, N.M.; Butts-Willmsmeyer, C.; Scanlan, C. Assessing the curative and protective impacts of select fungicides for control of powdery mildew of wheat. *Plant Dis.* **2020**, *104*, 1195–1200. [\[CrossRef\]](#) [\[PubMed\]](#)
4. He, X. Research progress and developmental recommendations on precision spraying technology and equipment in China. *Smart Agric.* **2020**, *2*, 133–146. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Afolabi, B.; Adejumo, A.; Atere, A. Operations of knapsack sprayer and its impacts on physiological parameters of selected operators. *Engineering* **2023**, *15*, 59–67. [\[CrossRef\]](#)
6. Ghafoor, A.; Khan, F.A.; Khorsandi, F. Development and evaluation of a prototype self-propelled crop sprayer for agricultural sustainability in small farms. *Sustainability* **2022**, *14*, 9204. [\[CrossRef\]](#)
7. Lan, Y.; Qian, S.; Chen, S. Influence of the Downwash Wind Field of Plant Protection UAV on Droplet Deposition Distribution Characteristics at Different Flight Heights. *Agronomy* **2021**, *11*, 2399. [\[CrossRef\]](#)
8. Lan, Y.; Chen, S.; Deng, J. Development situation and problem analysis of plant protection unmanned aerial vehicle in China. *J. South China Agric. Univ.* **2019**, *40*, 217–225.
9. Xue, X.; Lan, Y.; Sun, Z.; Chang, C.; Hoffmann, W.C. Develop an unmanned aerial vehicle based automatic aerial spraying system. *Comput. Electron. Agric.* **2016**, *128*, 58–66. [\[CrossRef\]](#)
10. Zhang, S.; Cai, C.; Li, J.; Cheng, X.; Sun, T.; Liu, X.; Tian, Y.; Xue, X. The airflow field characteristics of the unmanned agricultural aerial system on oilseed rape (*Brassica napus*) canopy for supplementary pollination. *Agronomy* **2021**, *11*, 2035. [\[CrossRef\]](#)
11. Yang, S.; Yang, X.; Mo, J. The application of unmanned aircraft systems to plant protection in China. *Precis. Agric.* **2017**. [\[CrossRef\]](#)
12. Lan, Y.; Chen, S. Current status and trends of plant protection UAV and its spraying technology in China. *Int. J. Precis. Agric. Aviat.* **2018**, *1*, 1–9. [\[CrossRef\]](#)
13. Kim, J.; Kim, S.; Ju, C. Unmanned aerial vehicles in agriculture: A review of perspective of platform, control, and applications. *IEEE Access* **2019**, *99*, 1. [\[CrossRef\]](#)
14. Zhu, H.; Li, H.; Adam, A. Performance evaluation of a multi rotor unmanned agricultural aircraft system for chemical application application. *Int. J. Agric. Biol. Eng.* **2021**, *14*, 43–52. [\[CrossRef\]](#)
15. Yallappa, D. Influence of the downwash airflow in hexacopter drone on the spray distribution pattern of boom sprayer. *J. Appl. Nat. Sci.* **2023**, *5*, 391–400. [\[CrossRef\]](#)
16. Zhang, H.; Lan, Y.; Xu, T.; Yu, F. Application performance of fuel-powered multi-rotor unmanned aerial vehicles in maize plant protection. *Int. J. Precis. Agric. Aviat.* **2021**, *4*, 36–39. [\[CrossRef\]](#)
17. Tang, Y.; Hou, C.; Luo, S. Effects of operation height and tree shape on droplet deposition in citrus trees using an unmanned aerial vehicle. *Comput. Electron. Agric.* **2018**, *148*, 1–7. [\[CrossRef\]](#)
18. He, L.; Wang, G.; Hu, T. Influences of spray adjuvants and spray volume on the droplet deposition distribution with unmanned aerial vehicle (UAV) spraying on rice. *J. Plant Prot.* **2017**, *44*, 1046–1052, (In Chinese with English abstract).
19. Wang, G.; Lan, Y.; Qi, H. Field evaluation of an unmanned aerial vehicle (UAV) sprayer: Effect of spray volume on deposition and the control of pests and disease in wheat. *Pest Manag. Sci.* **2019**, *75*, 1546–1555. [\[CrossRef\]](#)
20. Chojnacki, J.; Pachuta, A. Impact of the Parameters of Spraying with a Small Unmanned Aerial Vehicle on the Distribution of Liquid on Young Cherry Trees. *Agriculture* **2021**, *11*, 1094. [\[CrossRef\]](#)
21. Zhang, S.; Xue, X.; Sun, T. Evaluation and comparison of two typical kinds UAAS based on the first industry standard of China. *Int. Agric. Eng. J.* **2020**, *29*, 331–340.
22. Wang, S.; Song, J.; He, X. Performances evaluation of four typical unmanned aerial vehicles used for pesticide application in China. *Int. J. Agric. Biol. Eng.* **2017**, *10*, 22–31.
23. Chen, S.; Lan, Y.; Li, J. Comparison of the pesticide effects of aerial and artificial spray applications for rice. *J. South China Agric. Univ.* **2017**, *38*, 103–109. [\[CrossRef\]](#)
24. Wang, G.; Lan, Y.; Yuan, H. Comparison of spray deposition, control efficacy on wheat aphids and working efficiency in the wheat field of the unmanned aerial vehicle with boom sprayer and two conventional knapsack sprayers. *Appl. Sci.* **2019**, *9*, 218. [\[CrossRef\]](#)
25. Julián, S.; Víctor, J.R.; Francisco, P. Field evaluation of a self-propelled sprayer and effects of the application rate on spray deposition and losses to the ground in greenhouse tomato crops. *Pest Manag. Sci.* **2011**, *67*, 942–947. [\[CrossRef\]](#)
26. Zhou, Q.; Xue, X.; Qin, W. Analysis of pesticide use efficiency of a UAV sprayer at different growth stages of rice. *Int. J. Precis. Agric. Aviat.* **2020**, *3*, 38–42. [\[CrossRef\]](#)
27. Xu, Y.; Xue, X.; Sun, Z.; Chang, C.; Gu, W.; Chen, C.; Jin, Y.; Peng, B. Online spraying quality assessment system of plant protection unmanned aerial vehicle based on Android client. *Comput. Electron. Agric.* **2019**, *166*, 104938. [\[CrossRef\]](#)
28. NY/T 3213-2018; Chinese Standard: Technical Specification of Quality Evaluation for Crop Protection UAS. The Ministry of Agriculture and Rural Affairs of the People's Republic of China: Beijing, China, 2018. (In Chinese)
29. Zhu, H.; Salyani, M.; Fox, R.D. A portable scanning system for evaluation of spray deposit distribution. *Comput. Electron. Agric.* **2011**, *76*, 38–43. [\[CrossRef\]](#)
30. ISO 24253-2:2015; Crop Protection Equipment. Spray Deposition Test for Field Crop: Part. 2: Measurement in a Crop. International Organization for Standardization (ISO): Geneva, Switzerland, 2015.
31. ISO 24253-1:2015; Crop Protection Equipment. Spray Deposition Test for Field Crop. Part. 1: Measurement in a Horizontal Plane. International Organization for Standardization (ISO): Geneva, Switzerland, 2015.

32. NY/T 613-2002; Rules for Investigation and Forecast of Wheat Powdery Mildew [*Blumeria Graminis* (DC.) Speer]. The Ministry of Agriculture and Rural Affairs of the People's Republic of China: Beijing, China, 2002. (In Chinese)
33. GB/T 15796-2011; Rules for Monitoring and Forecast of the Wheat Head Blight (*Fusarium Graminearum* Schw./*Gibberella Zeae* (Schw.) Petch). General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, National Standardization Administration of China: Beijing, China, 2011. (In Chinese)
34. Tian, Z.; Xue, X.; Xu, Y. Effect of plant protection UAVs downwash on crop canopy. *Trans. Chin. Soc. Agric. Mach.* **2021**, *51*, 40–48. (In Chinese) [[CrossRef](#)]
35. Guo, Q.; Zhu, Y.; Tang, Y. CFD simulation and experimental verification of the spatial and temporal distributions of the downwash airflow of a quadrotor agricultural UAV in hover. *Comput. Electron. Agric.* **2020**, *172*, 105343. [[CrossRef](#)]
36. Coombes, M.; Newton, S.; Knowles, J.; Garmory, A. The influence of rotor downwash on spray distribution under a quadrotor unmanned aerial system. *Comput. Electron. Agric.* **2022**, *196*, 106807. [[CrossRef](#)]
37. Shi, X.; Chen, Y.; Du, Y. The influences of wind speed and flight parameters on droplet drift characteristics of multi-rotor plant protection unmanned aerial vehicle. *J. Plant Prot.* **2021**, *48*, 546–553. [[CrossRef](#)]
38. Zhang, S.; Qiu, B.; Xue, X. Effects of crop protection Unmanned Aerial System flight speed, height on effective spraying width, droplet deposition and penetration rate, and control effect analysis on wheat aphids, powdery mildew, and head blight. *Appl. Sci.* **2021**, *11*, 712. [[CrossRef](#)]
39. Mehta, A.; Basandrai, A.K.; Banyal, D.K. Effect of weather parameters on powdery mildew development of wheat at different location in Himachal Pradesh. *Indian Phytopathol.* **2018**, *71*, 349–353. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.