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# Pollination Parameter Optimization and Field Verification of UAV-Based Pollination of 'Kuerle Xiangli'

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**Abstract:** In this study, we investigated unmanned aerial vehicle (UAV) pollination of 'Kuerle Xiangli', and screened the pollination operation parameters to determine the precise parameters needed for the implementation of a 'Kuerle Xiangli' UAV pollination operation. Different flight height gradients, nozzle atomization particle sizes, spraying volume, and flight routes were tested and their effects on the droplets deposited were compared. UAV operation parameters were screened and field operations were conducted, comparing the fruit set rate, cost, and efficiency of different pollination methods of 'Kuerle Xiangli'. The results show that the mist droplet effect of 1 m above the top of the tree is higher compared with that of 2 m and 3 m. The mist droplet effect of 2 L/667 m$^2$ is better compared with that of 1.5 L/667 m$^2$ and 1 L/667 m$^2$. The mist droplet effect of 120 μm nozzle atomization particle size is better than that of 110 μm, 135 μm, and 150 μm. The mist droplet effect of flying above the canopy is better than that of flying between the rows of the canopy. The inflorescence and flower fruiting rates of 'Kuerle Xiangli' are 63.27% and 28.84%, respectively, and the inflorescence fruiting rate is not significantly different from hand and liquid sprayer pollination. The UAV pollination saves 12.69 USD/667 m$^2$ and 3.32 USD/667 m$^2$ compared with hand and liquid spray pollination, respectively. The efficiency of UAV pollination is greater than that of liquid and hand pollination. The best combination of parameters for pollination using a quadrotor UAV is 1 m from the top of the tree, 2 L/667 m$^2$ spray volume, 120 μm spray nozzle particle size, and the flight path above the canopy. The cost of UAV pollination is 11.83 USD/667 m$^2$ and the pollination efficiency 2.67 hm$^{2/}$unit·h.

**Keywords:** 'Kuerle Xiangli'; UAV pollination; mist droplet deposition distribution; fruit set rate; cost

## 1. Introduction

'Kuerle Xiangli' is referred to as a "famous, special and excellent" fruit in Xinjiang, with a long history of cultivation [1]. This occupies an important position in Xinjiang's fruit production. The 'Kuerle Xiangli' is an auto-flowering fruit tree [2], which must be equipped with a certain proportion of pollination trees or artificial assisted pollination to produce normal fruit. However, the low output value of pollinated varieties often leads to an insufficient number of pollinated trees in production, which this does not satisfy the 'Kuerle Xiangli' pollination, or is affected by adverse weather, leading to pollen dysplasia and other problems. The current production mainly relies on artificial pollination. Artificial pollination is effective, but there are problems such as low pollination efficiency, high cost, and pollination time can be easily missed [3,4]. The advent of intelligent agriculture era means that pollination by unmanned aerial vehicle (UAV) has gradually become more popular. Previous studies reported the successful use of UAV-assisted pollination for hybrid rice [5], pecan [6], cedar [7], and maize [8]. At present, UAV pollination has been preliminarily tried on pears. Wang Shilin studied the particle size and coverage results of fog droplets deposited in the pear canopy during Dangshan crisp pear pollination by multi-rotor UAV under different spray amounts [9]. The results show that the flight parameters and spray amount of UAV need to be further optimized. A study by Yang Jian determined the optimal pollination parameters for UAV-assisted liquid pollination of 'Kuerle Xiangli' [10], but he did not study the UAV flight operation parameters. Wang Lu studied the effect of spray parameters of UAV on the deposition and distribution of fog droplets in the canopy of pears during flowering [11]. The results show that the main factors affecting the deposition density of fog droplets are the spray volume per mu, flight altitude, and flight speed. Up until now the operational index parameters and operational technical procedures for 'Kuerle Xiangli' UAV pollination have not yet formed, and the pollination effect, cost, and benefit are not clear. This study screened the optimal operational parameters of 'Kuerle Xiangli' UAV pollination using a quadrotor UAV (XAG XP 2020) and compared the effects of different pollination methods. This research provides reliable operational parameters for UAV pollination of 'Kuerle Xiangli', and provides scientific and technological support for the high-quality and efficient cultivation of balsam pears within the fruit production industry.

## 2. Materials and Methods

### 2.1. Test Materials

The drone (XAG XP 2020) used and its respective performance indexes are presented in Table 1. The UAV was operated by Xinjiang Kefei Integrated Agricultural Services Co. Water-sensitive paper (China, Chongqing, Chongqing Liuliu Shanxia Plant Protection Technology Co., Ltd.) 3.5 × 5.5 cm, temperature and humidity meter (Jingchuang, RC-5 waterproof high-precision instrument), SM5398 wind speed and direction integrated sensor (China, Shanghai, Shanghai Sobo Industrial Co., Ltd.), duck pear pollen (China, Shandong, Changsheng pollen, Laiyang Shunxin Fruit Co., Ltd.; China, Hebei, Tengxin pollen, Hebei Tengxin Pear Pollen Cooperative), and xanthan gum solution (Zhang Shaoling) were purchased from the Heshun Market in Kuerle City.

**Table 1.** Main performance indexes of XP 2020 UAV.

| Main Performance Indexes | Numerical Value |
|---|---|
| Model | 3WWDZ-20A |
| Whole machine size | 1380 × 1355 × 552 mm |
| Battery capacity | 18,000 mAh |
| Net weight of the whole machine | 26.6 kg |
| Maximum take-off weight | 46.6 kg |
| Rated capacity of the liquid tank | 20 L |
| Operational flight speed | 0~12 $m \cdot s^{-1}$ |
| Spraying width | 4.5 m |
| Fogging particle size | 85~550 μm |
| Number of centrifugal fogging nozzles | 4 |
| Centrifugal atomizing nozzle models | SNZ-18000A |

The screening of the UAV operation parameters took place between 18 March and 7 April 2021, at the germplasm resource nursery of the Second Division Agricultural Science Research Institute of the Xinjiang Production and Construction Corps. The trees were 6 years old, high spindle tree shape, and were spaced 1 × 4 m.

The UAV field operations were performed from 8 April to 17 April 2021. The out the 'Kuerle Xiangli' UAV liquid spray pollination verification operations were carried in Garden 9 Company of 28 Mission, 28 Mission Huxin Village and Garden 14 Company of 29 Mission, Second Division of Xinjiang Production and Construction Corps. The trees were 5–8 years old. The tree shape was a high spindle shape and plant spacing was 1 × 4 m.

### 2.2. Test Methods

#### 2.2.1. UAV-Pollinated Water-Sensitive Paper Sampling Site Design

The water-sensitive paper was laid out according to the height of the high spindle shape and the spacing between the trees. Five trees were selected using the five-point sampling method. A horizontal plane was set at 1.5 m in the vertical direction (Figure 1), two 0.9 m wooden poles were built in the east–west direction according to the spacing between the trees, which was 1 × 4 m, and 6 × 8 cm foam plates were fixed with pins at 0.3, 0.6, and 0.9 m from the main trunk. The 3.5 × 5.5 cm water-sensitive paper was fixed to the corresponding foam board with a large headpin and marked with a pencil. Two 1.8 m wooden poles were erected in the north–south direction, and 6 × 8 cm bubble plates were fixed with pins at 0.3, 0.6, 0.9, 1.2, 1.5, and 1.8 m from the main trunk. The 3.5 × 5.5 cm water-sensitive paper was fixed to the corresponding foam board with large pins and marked with a pencil. Figure 2 shows the field pollination of the UAV.

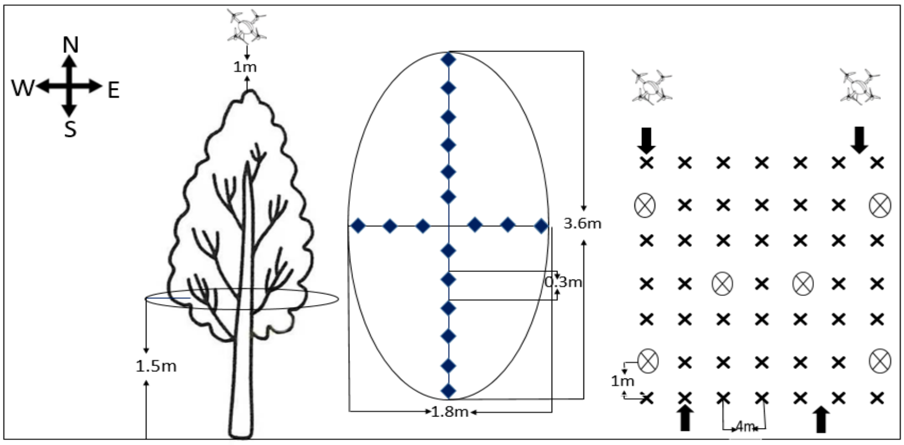


**Figure 1.** Schematic diagram of the water-sensitive paper sampling points and UAV flight path.

**Figure 2.** UAV pollination field test.

#### 2.2.2. Design of UAV Operational Parameters

Flight height was set to a gradient of 1, 2, and 3 m from the top of the tree, and nozzle atomization particle size was set to 110, 120, 135, and 150 µm.

The spray rates tested were 1 L/667 $m^2$, 1.5 L/667 $m^2$, and 2 L/667 $m^2$. The flight paths were designed to fly the UAV above the canopy and the rows (Table 2). At the end of each flight, water-sensitive paper was collected for analysis.

**Table 2.** UAV operation parameters.

| Experimental Treatment | Flight Height (m) | Nozzle Size | Spraying Quantity L/667 $m^2$ | Flight Line | Flight Speed ($m \cdot s^{-1}$) | Wind Speed ($m \cdot s^{-1}$) | Environment of the Wind | Environment Temperature (°C) |
|---|---|---|---|---|---|---|---|---|
| G1 | 1 | 120 | 2 | Top of the tree | 3 | 2.0 | South wind | 23 |
| G2 | 2 | 120 | 2 | Top of the tree | 3 | 1.8 | South wind | 23 |
| G3 | 3 | 120 | 2 | Top of the tree | 3 | 1.8 | South wind | 23 |
| L1 | 1 | 110 | 2 | Top of the tree | 3 | 2.0 | North wind | 22 |
| L2 | 1 | 120 | 2 | Top of the tree | 3 | 2.0 | North wind | 22.3 |
| L3 | 1 | 135 | 2 | Top of the tree | 3 | 2.0 | North wind | 23 |
| L4 | 1 | 150 | 2 | Top of the tree | 3 | 2.0 | North wind | 24 |
| P1 | 1 | 120 | 1 | Top of the tree | 3 | 1.0 | North wind | 24.8 |
| P2 | 1 | 120 | 1.5 | Top of the tree | 3 | 1.5 | North wind | 24.5 |
| P3 | 1 | 120 | 2 | Top of the tree | 3 | 1.5 | North wind | 25 |
| H1 | 1 | 120 | 2 | Top of the tree | 3 | 2.2 | North wind | 24.5 |
| H2 | 1 | 120 | 2 | Between | 3 | 2.0 | North wind | 24.5 |

#### 2.2.3. Field Validation Parameters

The optimal level of each parameter was selected through screening tests and then used as the operational parameter. 'Kuerle Xiangli' high spindle shape was selected and the trial design included four treatments of natural, hand, liquid, and UAV pollination, with five replications of each treatment. Natural pollination consisted of 3 acres, without human intervention. Hand pollination consisted of 10 acres, in which pollen and starch was mixed in a 1:6 ratio, evenly filled into the stocking, then the stocking was tied to the top of the long pole, and shaken above the flowering branches for pollination. The drone pollination consisted of 44.3 acres, utilising a spray solution consisting of 2 L/667 $m^2$ water, 100 g xanthan gum solution, and 8 g/667 $m^2$ pollen. Liquid pollination consisted of 10 acres, utilising the same mixture used in the drone pollination, configuring the solution to add to the sprayer and applying manually (Table 3).

**Table 3.** Field validation trial design.

| Dealing with Numbers | Pollination Method | Location | Date of Establishment | Test Area /667 $m^2$ |
|---|---|---|---|---|
| 1 | UAV pollination | 14 lian of 29 tuan | 2016 | 6 |
| | | 14 lian of 29 tuan | 2013 | 3.6 |
| | | 2 lian of 29 tuan | 2014 | 5.5 |
| | | Lake village of 28 tuan | 2015 | 24 |
| | | 9 lian of 28 tuan | 2015 | 5.2 |
| 2 | Hand pollination | 14 lian of 29 tuan | 2016 | 2 |
| | | 14 lian of 29 tuan | 2013 | 2 |
| | | 2 lian of 29 tuan | 2014 | 2 |
| | | Lake village of 28 tuan | 2015 | 2 |
| | | 9 lian of 28 tuan | 2015 | 2 |
| 3 | Liquid pollination | 14 lian of 29 tuan | 2016 | 2 |
| | | 14 lian of 29 tuan | 2013 | 2 |
| | | 2 lian of 29 tuan | 2014 | 2 |
| | | Lake village of 28 tuan | 2015 | 2 |
| | | 9 lian of 28 tuan | 2015 | 2 |
| 4 | Natural pollination | 14 lian of 29 tuan | 2016 | 0.5 |
| | | 14 lian of 29 tuan | 2013 | 0.5 |
| | | 2 lian of 29 tuan | 2014 | 0.5 |
| | | Lake village of 28 tuan | 2015 | 1 |
| | | 9 lian of 28 tuan | 2015 | 0.5 |

#### 2.2.4. Fruit Set Rate Survey, Pollination Costs, and Efficiency

On the day of pollination, three trees were randomly selected from each treatment; each tree was selected from the upper, middle, and lower layers. Each layer was divided into four directions of branches, and the number of inflorescences and flowers of each branch were counted and marked with a tag. The number of inflorescences and the percentage of flowers set were counted between 25 April and 1 May when the fruit were 6–8 mm longitudinal and 4–5 mm transverse.

(1) The percentage inflorescence set was calculated by the number of inflorescences set/total number of inflorescences × 100%;
(2) The flower set rate was calculated by the total number of fruit/total number of flowers × 100%;
(3) The pollination cost per acre was calculated by the pollen unit price × pollen use + labor costs (UAV service fee).

The pollination efficiency is the pollinated area per person (or per UAV) per day, with the effective pollination time being between 7–12 am.

### *2.3. Data Acquisition and Processing*

The collected water-sensitive paper was scanned using a scanner (HP LaserJet Pro M1136 MFP) and the fog droplets on the water-sensitive paper were analyzed using DepositScan software. The fog droplet coverage, density, and droplets deposited in all four directions were determined, and the collated data were processed using DPS 7.05. The treatments were compared using the Tukey test ($p < 0.05$). Plots were prepared using Origin Pro 2018.

## 3. Results

### *3.1. Comparison of Different Height Treatments on the Effect of Mist Droplets in Four Directions on the 'Kullua Balsam Pear' Canopy*

The droplet coverage rate differs significantly in the east, west, and north directions when comparing the flight heights of 1 m and 3 m (Figure 3). The droplet coverage rate of 1 m is 2.66, 2.68, and 2.13 times higher than that at 3 m, respectively, and there is no significant difference in the south direction. The droplet density differs significantly in the east, west, north, and south directions, and the droplet density at 1 m is 5.35, 5.84, 7.61, and 2.71 times higher, respectively than that at 3 m. The amount of droplet deposition is significantly different in the east and south directions, with the amount of droplet deposition at 1 m being 3.75 and 1.92 times higher than that at 3 m, respectively. There is no significant difference in the number of droplets in the west and north direction applications. There are no significant differences in droplet coverage, density, and droplet deposition in the east, west, north, and south directions when comparing flight heights of 1 and 2 m. There is no significant difference in droplet coverage between flight altitudes of 2 and 3 m in the east, west, and north directions. However, there is a significant difference in the south direction, with a 50.4% reduction in droplet coverage at a flight altitude of 3 m compared to 2 m.

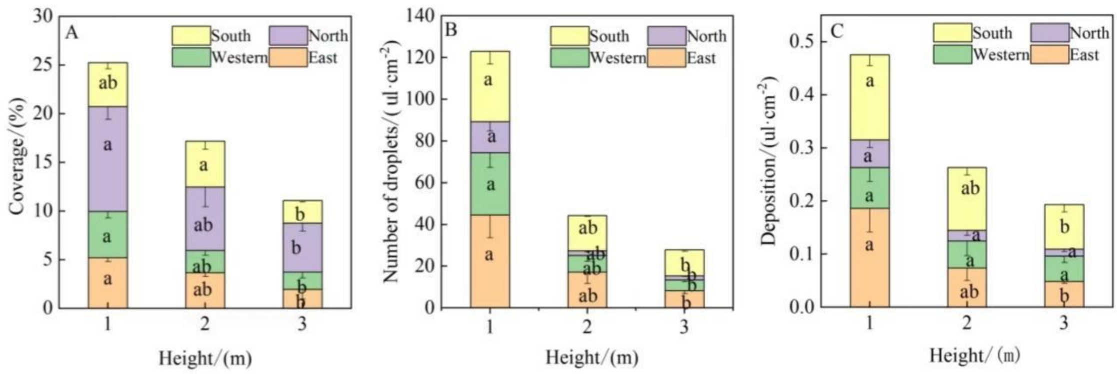


**Figure 3.** Comparison of canopy fog droplet effects of 'Kuerle Xiangli' treated at different heights: (**A**). comparison of the droplet coverage of 'Kuerle Xiangli' treated at different heights, (**B**). comparison of the droplet density of 'Kuerle Xiangli' treated at different heights, (**C**). comparison of the amount of droplet deposition of 'Korla Fragrant Pear' treated at different heights. The data are presented as mean ± standard error. Different lowercase letters indicate significant difference in the same direction among different treatments ($p < 0.05$).

### *3.2. Comparison of the Effect of Mist Droplets in the Four Directions of the 'Kuerle Xiangli' Canopy under Different Nozzle Atomization Particle Sizes*

Using the nozzle atomization particle size of 120 μm results in droplet coverage in the east and north direction being significantly higher compared with using a particle size of 150 μm, with droplet coverage being 2.15 and 27.29 times higher, respectively (Figure 4A), whereas there is no significant difference in the west and south direction. While spraying in the north direction, there is a significant difference using a 120 μm particle size, which is 14.44 times higher compared with the 135 μm particle size droplet coverage in the east and west, and there is no significant difference between the north and south directions. The droplet coverage is 4.28 times higher when using a 120 μm particle size compared with the 110 μm particle size in the north, and no significant difference is observed in the east, west, and south directions. There is no significant difference in droplet coverage in all four directions between 110 μm and 135 μm particle sizes. However, these particle sizes are significantly higher in the east direction compared with the 150 μm particle size, and no significant difference is observed in the west, north, and south directions. The 135 μm particle size is not significantly different from 150 μm in all four directions.

Droplet density in the east, west, north, and south is significantly higher using a particle size of 120 μm compared with 150 μm, being 4.41, 3.87, 27.53, and 1.28 times higher, respectively. Using the 120 μm particle size in the north direction is significantly higher compared with the 135 μm particle size droplet density, by 9.22 times, but in the east, west, and south, the difference is insignificant. Using the 120 μm particle in the north direction is 3.15 times higher than the droplet density of the 110 μm particle size, and is not significantly different from the other three directions. There is no significant difference in droplet density between the nozzle atomization particle size of 110 μm and 135 μm in all four directions. The 110 µm particle size used in the east, west, and south is significantly higher than the droplet density of the 150 µm particle size, with no significant difference in the north direction (Figure 4B). There is no significant difference in droplet density between nozzle atomization particle size 135 µm and 150 µm in all four directions.

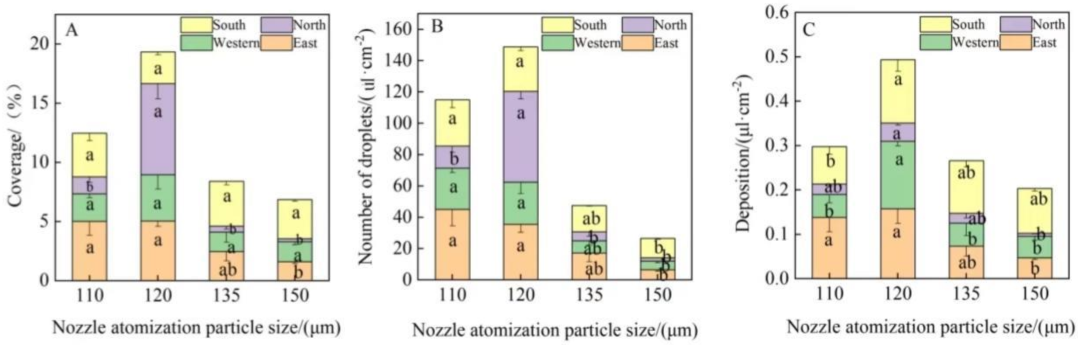


**Figure 4.** Comparison of atomizing particle sizes of different nozzles on the spray droplet effects in four directions of the 'Kuerle Xiangli' canopy: (**A**). comparison of atomizing particle sizes of different nozzles on the droplet coverage in four directions of the 'Kuerle Xiangli' canopy, (**B**). comparison of atomizing particle sizes of different nozzles on the droplet density in four directions of the 'Kuerle Xiangli' canopy, (**C**). comparison of atomizing particle sizes of different nozzles on the amount of droplet deposition in four directions of the 'Kuerle Xiangli' canopy. Different lowercase letters indicate significant difference in the same direction among different treatments ($p < 0.05$).

Using the nozzle atomization particle size of 120 µm, the droplets deposited in the east, west, and north are higher than the 150 µm nozzle atomization particle size by 2.75, 2.75, and 61.27 times, respectively, and no significant difference is observed in the south direction (Figure 4C). Using the particle size of 120 µm in the west direction is significantly higher than the 135 µm size droplets deposited, by two times, and the other three directions are not significantly different. Using the particle size of 120 µm in the west and south directions means a 2 and 0.57 times higher number of droplets are deposited compared with the 110 µm particle size, and there is no significant difference from the east and north directions. There is no significant difference in the amount of droplets deposited between the 110 µm and 135 µm nozzle atomization particle sizes in any of the four directions. Using the 110 µm particle size, the amount of droplets deposited in the east direction is significantly higher than by the 150 µm nozzle atomization particle size, while the other three directions are not significantly different. There is no significant difference in droplets deposited between the 135 µm and 150 µm nozzle atomization particle sizes in any of the four directions.

### *3.3. Comparison of Different Spraying Treatments and Their Effect on Mist Droplets in Four Directions on the 'Kuerle Xiangli' Canopy*

The spray rate of 2.0 L/667 m$^2$ results in a significantly higher droplet coverage in all four directions compared with 1.0 L/667 m$^2$ (Figure 5). The spray rate of 2.0 L/667 m$^2$ is also significantly higher the east and north directions compared with that that of 1.5 L/667 m$^2$ by factors of 1.45 and 2.53 in droplet coverage, respectively, whereas in the west and south directions, the difference is insignificant. There is no significant difference in droplet coverage between the 1.5 L/667 m$^2$ and the 1.0 L/667 m$^2$ spray rate in any of the four directions (Figure 5A). At 2.0 L/667 m$^2$, droplet density is significantly higher than that of 1.0 L/667 m$^2$ in all four directions; in the east, west, and north directions, it is 1.61, 0.36 and 1.97 times higher compared with that of 1.5 L/667 m$^2$, respectively. The difference in droplet density between 1.5 L/667 m$^2$ and 1.0 L/667 m$^2$ is only significant in the southern direction, but not in any of the other three directions (Figure 5B). At 2.0 L/667 m$^2$, droplet deposition is significantly higher compared with that of 1.0 L/667 m$^2$ in all four directions, 2.46 times higher compared with that of 1.5 L/667 m$^2$ in the northern direction, and not significantly different in the eastern, western, and southern directions. The 1.5 L/667 m$^2$ spray rate is significantly higher than 1.0 L/667 m$^2$ in droplet coverage in the southern direction, and not significantly different in the other three directions (Figure 5C). No significant differences are found in the other three directions (Figure 5C).

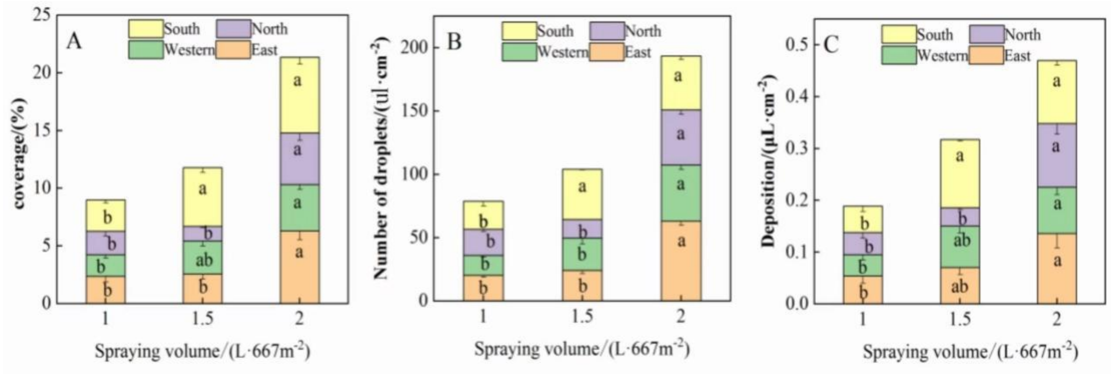


**Figure 5.** Comparison of different spray amounts on fog droplet effects in four directions of the 'Kuerle Xiangli' canopy: (**A**). comparison of different spray amounts on the droplet coverage in four directions of the 'Kuerle Xiangli' canopy, (**B**). comparison of different spray amounts on the droplet density in four directions of the 'Kuerle Xiangli' canopy, (**C**). comparison of different spray amounts on the amount of droplet deposition in four directions of the 'Kuerle Xiangli' canopy. Different lowercase letters indicate significant difference in the same direction among different treatments ($p < 0.05$).

### *3.4. Comparison of the Effect of Mist Droplets in the Four Directions of the 'Kuerle Xiangli' Canopy Pollinated Using Different Flight Routes*

The fog droplet coverage differs significantly in the east, west, and south directions when the flight path is over the tree canopy compared with inter-row flight, being 4.05, 2.66, and 0.75 times higher, respectively. This did not differ significantly in the north direction (Figure 6A). There is no significant difference in droplet density between the tree-top and inter-row flights in all four directions: east, west, south and north (Figure 6B). Fog droplet deposition is significantly higher in the south direction when the flight path is over the top of the tree compared with the inter-row flight path by a factor of 1.18, with no significant differences in the east, west, and north directions (Figure 6C).

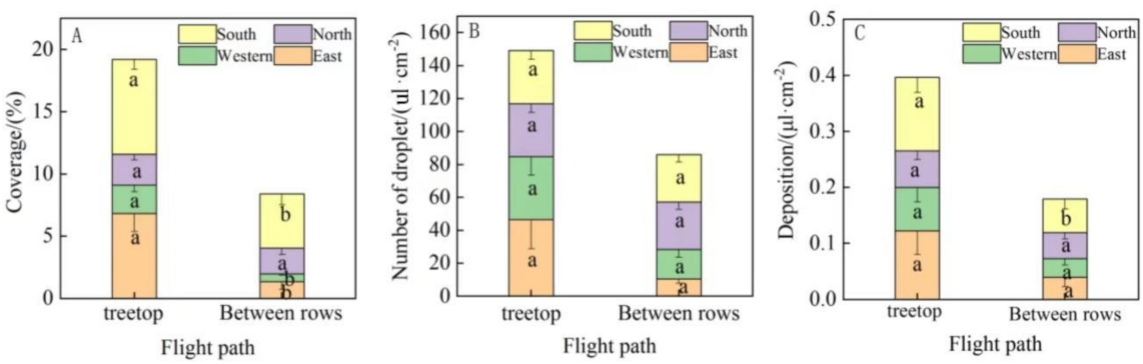


**Figure 6.** Comparison of different UAV flight routes and the effect on mist droplets in four directions of the 'Kuerle Xiangli' canopy: (**A**). comparison of different UAV flight routes and the droplet coverage in four directions of the 'Kuerle Xiangli' canopy, (**B**). comparison of different UAV flight routes and the droplet density in four directions of the 'Kuerle Xiangli' canopy, (**C**). comparison of different UAV flight routes and the amount of droplet deposition in four directions of the 'Kuerle Xiangli' canopy. Different lowercase letters indicate significant difference in the same direction among different treatments ($p < 0.05$).

### 3.5. Effect of Different Pollination Methods on Fruit Set Rate

The inflorescence set by UAV, hand shaking, and liquid pollination is 63.27%, 72%, and 65.1%, respectively, with no significant difference between the three treatments. The inflorescence set by natural pollination is 16.98%, which is significantly lower compared with the other three treatments (Figure 7).

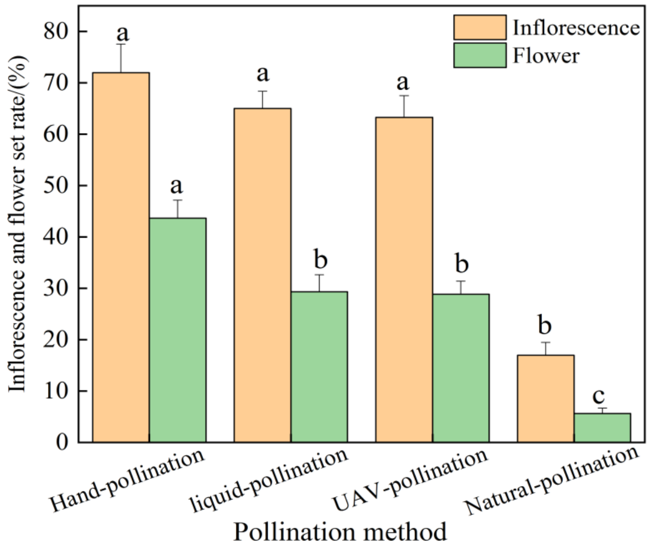


**Figure 7.** Comparison of fruit setting rates of inflorescence and flowers using different pollination methods. Different lowercase letters indicate significant differences in the same pollination position among different treatments ($p < 0.05$).

The fruit set rate for UAV, hand, and liquid pollinated flowers is 28.84%, 43.65% and 29.34%, respectively, with a significantly lower fruit set rate of 14.41% for UAV pollinated flowers and no significant difference with liquid pollination.

### 3.6. Comparison of the Cost and Efficiency of Different Pollination Methods

The cost of UAV pollination is 51.7% and 21.9% lower compared with that of hand pollination and liquid pollination, respectively. Comparing the costs associated with UAV pollination with that of manual shaking and liquid pollination, the pollen costs are 60% and 20% lower, respectively; and labor costs are 25% and 25% lower, respectively. The pollination efficiency of using the UAV is 2.67 hm$^2$/table·h. The liquid pollination efficiency is 0.13 hm$^2$/person·h, and the hand pollination efficiency is 0.07 hm$^2$/person·h (Table 4). The pollination efficiency of the UAV is 40 and 20 times better compared with that of hand pollination and liquid pollination, respectively.

**Table 4.** Analysis of pollination cost and efficiency per unit area of different pollination methods of 'Kuerle Xiangli'.

| Treatment | Pollination Cost | | | | | Pollination Efficiency | |
|---|---|---|---|---|---|---|---|
| | Pollen Unit Price USD/g | The Pollen Amount g/667 m$^2$ | Cost of Pollen USD/667 m$^2$ | Labor Cost USD/667 m$^2$ | Total Cost USD/667 m$^2$ | Work Efficiency hm$^2$/Person (Table)·d | Timeliness hm$^2$/Person (Table)·h |
| Hand pollination | 0.93 | 20 | 18.67 | 5.74 | 24.40 | 0.33 | 0.07 |
| Liquid pollination | 0.93 | 10 | 9.33 | 5.74 | 15.01 | 0.66 | 0.13 |
| UAV pollination | 0.93 | 8 | 7.46 | 4.31 | 11.77 | 13.33 | 2.67 |

## 4. Discussion

The characteristics of pesticide droplets deposited are influenced by the UAV operating parameters, which include the UAV operating height, operating speed, and droplet size [5,12]. According to the UAV application trials, the ideal spraying protocol using the UAV is to apply droplets evenly on the foliage of the target crop [13]. The data from this trial show that the 'Kuerle Xiangli' UAV pollination operation is more effective at a height of 1 m from the top of the canopy, and as the height increases, the coverage of droplets deposited on the sampling points decreases. This is consistent with the results obtained by Hu Hongyan [14], in which cotton field UAV spraying trials show that as the flight height increases with the gradient, the more severe the susceptibility to wind speed and ambient wind direction, and the lower the droplet density deposited at the sampling point. The larger the particle size settling in the canopy of 'Kuerle Xiangli' at 1.5 m from the ground, the less effective the droplets that are deposited, resulting in the loss in pollination liquid. Smaller particle sizes of 110 µm result in decreases in droplet distribution. The main reason for this result is that in the high temperature and low humidity of Xinjiang, the total number of 110 µm droplets evaporating during the descent decreases. The results are consistent with a previous study in which plant protection UAVs sprayed different droplet particle sizes on their cotton canopy [15]. The UAV spray volume per unit area of 2 L/667 m$^2$ is consistent with a previous study on spray pollination technology for pear trees [9]. The flight path of the UAV is good for droplets above the tree, because the UAV has high droplet coverage above the tree, which are deposited below due to the wind field, whereas between the rows, the droplets do not cover the whole tree resulting in poor spraying results [16].

The fruit setting rate at inflorescence level and at flower level of 'Kuerle Xiangli' pollinated by UAV are 63.27% and 28.84%, respectively. Compared with hand and liquid pollination, there is no significant difference in fruit setting rate at the inflorescence level. The fruit setting rate at flower level is significantly lower compared with hand pollination, and there is no significant difference compared with liquid pollination. Studies show that under artificial pollination, a flower fruit set rate of 25% can meet production needs, and more than double fruits, triple, or even quadruple fruits under the condition of artificial pollination [17]. The fruit setting rate at flower level using UAV pollination is 28.84%, and that of hand pollination is 29.34%. Although the fruit setting rate of UAV pollination is significantly lower compared with hand pollination, it meets the production needs and saves the cost of flower and fruit thinning.

In this experiment, compared with hand pollination and liquid pollination, UAV pollination saves 12.69 USD/667 m$^2$ and 3.32 USD/667 m$^2$, respectively. The pollination efficiency using the UAV is 13.33 hm$^2$/day, 0.66 hm$^2$/day for liquid pollination, and 0.33 hm$^2$/day for hand pollination. This is inconsistent with the parameter optimization and economic benefit analysis of hand pollination cost compared with UAV-assisted pollination liquid. Through the analysis, the reason for this difference is found to be the use of pollen and differing pollen prices. In this study, the pollen price is 0.94 USD/g, and the amount used is 20 g/667 m$^2$. This means that UAV pollination saves 12.69 USD/667 m$^2$ compared with artificial pollination. The pollen price listed in the study by Yangjian et al. [10] is 1.01 USD/g, and the amount used is 50 g/667 m$^2$. Using these figure, hand pollination then saves 44.42 USD/667 m$^2$ compared with UAV pollination.

In this experiment, the UAV pollination efficiency is 2.67 hm$^2$/table·h, liquid pollination efficiency is 0.13 hm$^2$/person·h, and hand pollination efficiency is 0.07 hm$^2$/person·h. The efficiency of UAV pollination per hour is 40 and 20 times that of manual shaking and liquid pollination, respectively, and the current efficiency of using UAV pollination in production is significantly improved. However, for the future large-area intensive production of 'Kuerle Xiangli' by UAV pollination, efficiency needs to be further improved. Further improvement is needed because the load capacity of the UAV is only 20 L (XAG XP 2020), and the repeated configuration of liquid pollen causes the pollination efficiency of 'Kuerle Xiangli' to decrease. However, whether a UAV model with a higher load capacity can improve the pollination efficiency according to the production needs requires further investigation.

## 5. Conclusions

In this study, the operating parameters of the quadrotor (XAG XP 2020) UAV for pollination of 'Kuerle Xiangli' were 1 m from the top of the tree, a spray rate of 2 L/667 $m^2$, 120 µm spray particle size, and the best flight path was above the canopy. The fruiting rate at inflorescence and flower levels of 'Kuerle Xiangli' is 63.27% and 28.84%, respectively, which are not significantly different compared with that of hand and liquid pollination. The fruiting rate at flower level is significantly lower compared with that of manual pollination, and is not significantly different from that of liquid pollination. The cost savings of UAV pollination compared with hand and liquid pollination are 12.69 USD/667 $m^2$ and 3.32 USD/667 $m^2$, respectively. The timeliness of UAV pollination is 2.67 $hm^2$/table·h, which is 40 and 20 times faster than that of manual shaking and liquid pollination, respectively.

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## References

1. Gao, Q.M.; Hou, J.T.; Li, J. Production status and research progress of Kuerle Xiangli. *China Agric. Sci. Bull.* **2005**, *21*, 233–236. [CrossRef]
2. Qi, K.J.; Tao, S.T.; Wu, J.Y.; Zhang, S.L. Labor-saving liquid pollination techniques for pear trees. *South China Fruits* **2017**, *46*, 168–169. [CrossRef]
3. Yang, D.D. Effects of different pollination methods on fruit setting rate of golden Pear. *Agric. Henan* **2012**, *15*, 46. [CrossRef]
4. Wang, Z.L.; Wang, Y.J.; Jiang, F.D.; Mou, H.M.; Xue, M.; Li, Y.J. Research progress on different pollination measures of pear. *Yantai Fruits* **2019**, *2*, 3–4. [CrossRef]
5. Li, J.Y.; Lan, Y.B.; Wang, J.W.; Chen, S.D.; Huang, C.; Liu, Q.; Liang, Q.P. Distribution law of rice pollen in the wind field of small UAV. *Int. J. Agric. Biol. Eng.* **2017**, *10*, 32–40. [CrossRef]
6. Wang, J.B.; Cheng, J.B.; Wang, N.J.; Yao, X.H. The fruit-xenia effects of interspecies pollination assisted by unmanned aerial vehicle (UAV) on Zhejiang pecan (*Carya cathayensis*). *J. Fujian For. Sci. Technol.* **2019**, *46*, 42–45. [CrossRef]
7. Wang, B.F.; Huang, Y.P.; Fan, F.R.; Li, E.J.; Ye, D.Q.; Lin, F.M.; Shen, Q.T. Assisted pollination of chinese fir seed orchard UAV effect analysis. *J. Fujian For. Sci. Technol.* **2019**, *46*, 35–38. [CrossRef]
8. Kong, D.S.; Zhao, Y.L.; Hui, X.H.; Xu, L.; Wang, X.H. Methods and exploration of improving maize yield by plant protection UAV assisted pollination. *China Agric. Technol. Ext.* **2019**, *35*, 32–33. [CrossRef]
9. Wang, S.L.; Lei, X.H.; Tang, Y.X.; Chang, C.H.; Lv, X.L. Spray pollination technology of pear tree based on multi-totor UAV. *Jiangsu Agric. Sci.* **2020**, *48*, 210–214. [CrossRef]
10. Yang, J.; Yang, H.P.; Xie, W.; Hao, H.T.; Feng, H.Z.; Wang, L. Parameter optimization and economic benefit analysis of UAV assisted liquid pollination of Kuerle Xiangli. *J. Fruit Sci.* **2021**, *38*, 1691–1698. [CrossRef]
11. Wang, L.; Ji, G.P.; Song, W.; Niu, X.L.; Zhang, D.H.; Zhao, S.F. Effect of UAV spray parameters on the canopy deposition distribution of fog droplets in the fragrant pear flower period. *Agric. Sci. Technol. Commun.* **2022**, *6*, 175–179. [CrossRef]
12. Zhang, P.; Deng, L.; Lv, Q.; He, S.L.; Yi, S.L.; Liu, Y.D.; Yu, Y.X.; Pan, H.Y. Effects of citrus tree-shape and spraying height of small unmanned aerial vehicle on droplet distribution. *Int. J. Agric. Biol. Eng.* **2016**, *9*, 45–52. [CrossRef]
13. Wang, B.J.; Pan, B.; Jiang, L.; Liang, J.Q.; Lin, Y. Effects of operating parameters of quad- rotor UAV on droplets deposition distribution on litchi canopy. *South China Fruits* **2020**, *49*, 61–66. [CrossRef]
14. Hu, H.Y.; Ren, X.L.; Jiang, W.L.; Ma, X.Y.; Ma, Y.J.; Wang, D.; Ma, Y. Effects of flight altitude and direction of an unmanned aerial vehicle on droplets depositionand distribution in cotton field. *China Cotton* **2017**, *44*, 16–19. [CrossRef]
15. Wang, G.B.; Wang, S.Z.; Chen, P.C.; Han, X.Q.; Shan, C.F.; Chen, S.D.; Lan, Y.B. Effect of spraying droplet size with drones on deposition, penetration, and cotton harvest-aid efficacy. *J. Plant Prot.* **2021**, *48*, 493–500. [CrossRef]

16. Meng, Y.H.; Wang, M.M.; Yao, W.X. Droplet distribution of two flight modes of unmanned aerial vehicle (UAV) on the orchard of Y-shaped pear trees. *South China Fruits* **2020**, *49*, 116–120. [CrossRef]
17. Kuang, Y.J.; Yu, Q. This year Kuerle Xiangli sitting fruit situation investigation and enlightenment. *Northwest Hortic.* **2005**, *10*, 38–39. [CrossRef]