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Innovative and Effective Spray Method for Artificial Pollination of Date Palm Using Drone

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Abstract. **Traditional pollination of date palms is a time-consuming and labor-intensive process. Hence, the objectives of this study were 1) to develop a rapid, efficient, and low-cost pollination method that results in an acceptable level of fruit set (FS) with smaller amount of pollen grains, and labor costs using a platform-mounted robotic (drone) supplemented with water-suspended pollen grains, and 2) to investigate the effect of this method on date palm FS percentage, pollination efficiency (PE), fruit retention, total yield, and fruit quality. Date palm cultivars Barhi, Lulu, and Khesab were pollinated using traditional hand pollination (HP), spray pollination (HS), and drone pollination (DS) with water-suspended pollen grains (3 g/L). The results revealed that DS had a significantly lower FS percentage than the HP and HS methods in the Lulu and Khesab cultivars, but the difference was not statistically significant in Barhi cultivar. Fruit PE was unaffected by any of the pollination methods in Barhi and Lulu cultivars, but in the Khesab cultivar, DS pollination had lower PE (0.81) than HS (0.94) and HP (0.99) methods. DS had significantly lower levels of fruit retention and bunch weight than other methods. DS significantly improved fruit physical quality at harvest in all cultivars compared with HP and HS methods. Nevertheless, fruit color, firmness, total soluble solids (TSS) %, acidity, pH, and vitamin C level were unaffected by any of the pollination methods. Although the DS method produced lower FS percentage and bunch weight, the obtained FS percentages were within the commercially acceptable range for all cultivars. To the best of our knowledge, this is the first field study to indicate the possibility of pollinating date palm using drones with water-suspended pollen grain. To validate the commercial application, more research is needed to justify the optimum time and duration of application, which may vary according to cultivar and region.**

The date palm (*Phoenix dactylifera* L.) is one of the most productive plants in semiarid and arid environments worldwide, and it is considered an important subsistence crop (Ahmed et al., 2021a). It is a unisexual (dioecious) plant, which means female (pistillate) and male (staminate) flowers are produced on separate trees (Mostaan, 2012). In dioecious species like the date palm, pollination is significant for fruit setting (Akhavan et al., 2021). It is regarded as one of the most critical processes in date production, as fruit yield and quality are dependent on the proper application of pollen (Al-Yahyai and Khan, 2015; Awad, 2006; Munir, 2019; Salomón-Torres et al., 2021). Pollination can be affected by other factors, such as type of pollen feed, pollen grain quality, skilled labor, and environmental conditions (e.g., temperature, soil characteristics, and irrigation) (Awad, 2006, 2010; Salomón-Torres et al., 2021).

Natural pollination by insects and wind may occur in date palm, resulting in partial fertility and inferior FS due to insufficient pollination (Akhavan et al., 2021). Thus, commercial date palm production necessitates artificial pollination that ensures enough fruit setting and reduces the number of required male palms (Akhavan et al., 2021; Awad, 2006). Artificial pollination methods can be carried out manually or mechanically (Zaid and De Wet, 1999). These techniques include manual pollination with fresh spikelets or dried pollen, mechanical pollination with dry pollen, and pollination using a liquid suspension of pollen grains (Salomón-Torres et al., 2021).

In traditional pollination practice, several strands of male flowers (four to ten) from freshly opened male spathe are manually placed upside down between the strands of the female flowers (Akhavan et al., 2021). This method needs a great amount of work, time, and pollen grains (Salomón-Torres et al., 2021). In addition, it yields a high FS (85% to 95%) for most cultivars, thus thinning (flower and/or fruit) is necessary to improve fruit quality and increase marketable yield (Awad, 2010). Another method of pollination is the dusting of dried pollen grains on female inflorescence. In this technique, pollens are combined in different proportions with inert filler material (e.g., wheat flour, talc) and brushed or dusted on the female inflorescences by hand or with help of a mechanical duster. The downside of this strategy is that it requires more pollen and results in a significant proportion of parthenocarpic fruit (Munir, 2019). Overall, manual pollination of large date orchards is difficult and not economically effective owing to the high production costs (labor intensive) (Akhavan et al., 2021; Zaid and De Wet, 1999).

Several studies have recommended the liquid-suspended pollen (water-suspended) technique either alone or in conjunction with one or more substances such as starch, sugar, vinasse, treacle, ascorbic, and boric acid, as an alternative to the traditional method in a range of fruit crops, including pistachio, peach trees, date palm, and kiwifruit (Awad, 2006, 2010; Barnett et al., 2017; Karimi and Zeraatkar, 2016; Mizuno et al., 2002; Munir, 2019; Yano et al., 2007). The liquid suspension is usually made up of water and pollen grains at concentrations ranging from 0.5 to 4 g pollen per liter of water, and ≈100 mL/inflorescence is sprayed using a hand or mechanical sprayer (Salomón-Torres et al., 2021). This technique is more practical, effective, and considerably reduces labor, thinning, and pollen expenses; minimizes bunch breaking; and enhances fruit quality in date palm compared with the manual HP (Awad, 2010). However, mechanical sprayers are heavy machines and require a human worker in their operation (Abutalipov et al., 2016).

Robotic pollination (using of robotic pollinators such as drones) has also been proposed as an alternative to the traditional pollination

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that substantially reduces the production costs (Abutalipov et al., 2016); however, it is still in its early stages. The pollination of agricultural plants using drones can enable pollen delivery in an automated manner (Abutalipov et al., 2016). Although pollinator drone technology has recently been investigated (Salomón-Torres et al., 2021), no field trials on date palm using water-suspended pollen grains have yet been reported. Hence, the objective of this study was 1) to develop a rapid, effective, reliable, and low-cost pollination method that results in an acceptable level of FS with a smaller amount of pollen grains, and lower labor costs using a platform-mounted robotic (drone); and 2) to investigate the impact of using a pollinator drone supplemented with water-suspended pollen grains on FS percentage, PE, fruit retention, total yield, and fruit quality.

Fig. 1. The main parts of the platform-mounted robotic system (an agriculture drone DJI Agras T16) used for date palm pollination during the experimental orchard trials. Spray tank (**A**), propulsion system (**B**), battery (**C**), radar (**D**), spraying system (**E**), and remote controller (**F**).

Materials and Methods

Plant materials and experimental procedures

During the 2021 flowering period and in the middle of the flowering period (24 Feb.–4 Mar.), the study was carried out on three date palm (*Phoenix dactylifera* L.) cultivars, namely Lulu, Barhi, and Khesab at the experimental farm of the College of Agriculture and Veterinary Medicine located in the Al Foah region, Al Ain, United Arab Emirates (24.2191° N and 55.7146° E). The selected trees were 20 years old, planted in sandy loam soil, drip irrigated, and subjected to conventional agricultural operations. The experiment was set up as a complete block randomized design with 10 uniform trees per treatment of each cultivar. Fresh pollen used in this study, "Ghanami," was obtained from a commercial farm.

Drone design and characteristics

An agriculture drone DJI Agras T16 (Shenzhen, Guangdong, China) was used (Fig. 1); Airframe, propulsion system [motor, foldable propellers (R3390), ESC], IP16 core module, RTK centimeter-level positioning, DBF imaging radar (RD2418R), wide-angle FPV camera, AI engine, spraying system [16 L spray tank, nozzle XR11001VS (standard), flow meter], remote controller (GL300N), and intelligent battery (WB37-4920m Ah-7.6V).

Pollination process

In this study, the same pollen was used for all pollination methods. Traditional pollination (control) was done by placing five strands of male flowers, lengthwise and in an inverted position between the strands of the female inflorescence, and tying them with a strip torn from a palm leaflet (Fig. 2). Directly before the pollination process, pollen grains were mixed with water at a concentration of 3.0 g/L using an electrical agitator (BLD09-11-0.75KW, Shanghai, China) until a homogenized suspension was obtained. Hand spray pollination was applied to the bunches with a hand sprayer by targeting the nozzle close to the bunch; each bunch received ≈100 mL of the suspension. Hand spray and drone pollination was repeated three times at 2-day intervals. The pressure during the delivery of suspension was ≈2 to 3 kg/cm^2. Drone pollination was done using the same suspension concentration of 3.0 g/L. The drone has eight nozzles, at a height of 1.5 to 2 m above the palm tree spathe and the spray time was 16 s per tree (1 L/tree). The spray pressure was 2 to 4 kg/cm^2, with 3.6 L/min and width of 4 to 6.5 m.

Evaluation of fresh pollen viability and germinability

In vitro evaluation of fresh pollen viability. The viability of fresh pollens was assessed according to Shaheen (2004). The staining of fresh pollen grains with 1% acetocarmine was done according to Moreira and Gurgel (1941). Pollens (50 each) were counted per slide with nine slides as replicates. Pollen grains stained red with normal appearance were considered viable, whereas poorly stained or colorless were recorded as nonviable. The pollen viability % was calculated using the following formula:

$$\text{Viability \%} = (\text{Number of viable pollen}/\text{Total pollen}) \times 100 \quad [1]$$

In vitro evaluation of fresh pollen germinability. The pollen germination was evaluated using a typical medium composed of Ca $(NO_3)_2.2H_2O$ (0.200 g), H_3BO_3 (0.200 g), KNO_3 (0.100 g), $MgSO_4.7H_2O$ (0.200 g), sucrose (150 g), and agar (10 g) per liter (Brewbaker and Kwack, 1963). Before sterilization, the pH of the media was adjusted to 5.7, and then sterilized in the autoclave at 121 °C and 15 psi for 20 min. After, sterilization media was poured into three petri plates in a laminar air flow cabinet and kept at room temperature to settle down and cool. Following, pollens were sown on the petri plates using brushes and incubated at 30 °C for a period of 24 h. Pollen grain germination and pollen tube length were observed. The germinated pollens were counted using an optical microscope Nikon Eclipse 90i at ×40 magnification and an average of nine microscopic fields of vision was attained. During the observation, a pollen grain was considered germinated when the pollen tube length was equal to or greater than the diameter of the pollen grain (Ahmed et al., 2021b; Kav et al., 2014). The pollen germination % was calculated using the following formula:

$$\text{Germination \%} = (\text{Number of germinated pollen}/\text{Total pollen}) \times 100 \quad [2]$$

Determination of FS percentage

After 6 weeks of pollination (at the Kimri stage), 10 strands of five bunches from each tree were randomly collected, and normal,

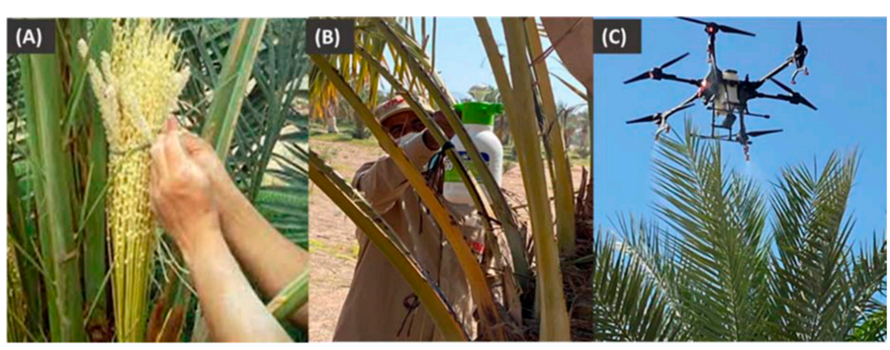

Fig. 2. Different pollination methods used to pollinate date palms, traditional hand pollination (**A**), hand spray (**B**), and drone pollination (**C**).

abnormal, and retention fruits per strand were counted (the initial FS). For the final FS, 10 additional strands of five bunches from each tree were randomly selected after 12 weeks. FS percentage, PE, fruit setting efficiency (FSE), and fruit retention percentage were calculated (El-Dengawy 2017; Iqbal 2010) as follows:

$$\text{Fruit set }(\%) = [(\text{Normal fruits} - \text{abnormal fruits})/\text{total fruits}] \times 100 \quad [3]$$

$$\text{Pollination efficiency} = \text{No. of normal fruits}/\text{total fruits} \quad [4]$$

$$\text{Fruit setting efficiency }(\%) = (\text{No. of normal fruits}/\text{total fruit sites}) \times 100 \quad [5]$$

$$\text{Fruit retention }(\%) = (\text{Total No. of the retained fruits on a strand}/\text{Total No. of the nodes}) \times 100 \quad [6]$$

Bunch and fruit characteristics

Bunch characteristics. At the commercial harvest time (Bisr stage; the fruit is mature hard full colored), ≈15 weeks from pollination, three net-packed bunches from five palms were collected and the weight was recorded. The number of strands/bunch; number of fruit/strand; and weight of Bisr, Rutab (soft brown fruit), and dropped fruit per bunch were recorded. Bunch weight from all palms at the end of the season when the fruit became Tamr (firm raisin-like fruit) was also recorded for each bunch (Awad, 2006; Iqbal, 2010). The total yield (kg/tree) was obtained by multiplying the mean bunch weight by the total number of bunches per tree (Awad, 2011).

Fruit characteristics. **Fruit physical characteristics.** The fruit weight and dimensions at harvest (Bisr stage) were determined using a digital caliper. Briefly, 20 fruits from five bunches/tree were collected, then weight and dimensions were measured and recorded.

Fruit surface color. The surface color values of fruit, including L^* (Lightness), a^* (red-green), and b^* (blue-yellow), were determined using HunterLab (HunterLab–Lab-Scan XE; Hunter Associates Laboratory Inc., Reston, VA) according to Ahmed and Palta (2010). The results were expressed in terms of L^*, a^*, and b^* values.

Fruit firmness. A texture analyzer (Brookfield CTX USB UK Cord, Middleboro, MA) was used to determine the fruit firmness on two opposite sides at the equator of each fruit with a fruit firmness tester fitted with 6-mm flat probe. The probe penetration depth was 5 mm. Firmness was expressed in Newton force (N).

Total soluble solids. Fifty grams of pitted fruit from each replication was mixed with 100 mL distilled water to extract the juice (1:2 dilution). The Brix value of TSS was measured for each extract using a digital refractometer (DR 6000; A. Kruss Optronic GmbH, Hamburg, Germany) and calculated to the original fruit weight (Ahmed et al., 2022).

Acidity and pH. Titratable acidity was determined in fruit juice by titrating with NaOH (0.1N) using five drops of phenolphthalein as an indicator. The results were expressed as % of malic acid. The pH of the juice was estimated using a pH meter (Orion Versa Star Pro pH/LogR Benchtop Meter, Paisley, UK).

Vitamin C. Vitamin C content was estimated by the 2,6-dichloroindophenol titrimetric method and results were expressed as milligrams ascorbic acid per 100 g of fresh weight (mg·100 g^{-1}) (AOAC, 2007; Xylia et al., 2021).

Statistical analysis

The data from the randomized complete block design with 10 replicates were subjected to analysis of variance using SAS statistical software (SAS Institute Inc., Cary, NC). Least significant differences at level $P \leq 0.05$ were used to compare means among the three methods of pollination within a cultivar and between cultivars.

Results and Discussion

Pollen viability. Because good-quality pollen is more likely to result in a high yield, it was critical to test pollen vitality before the pollination process. Figure 3 shows results for the viability and germination assessment test of the date pollen grains (Ghanami). The obtained fresh pollen grains had 92% viability and 94% germination as determined by acetocarmine staining and in vitro germination tests, respectively. Recently, In vitro tests revealed that fresh pollens had the highest viability (96%) and germination (85%) and result in the greatest fruit percentage as compared with stored pollens (Kadri et al., 2022). Thus, increasing pollen application in female inflorescences does not guarantee high FS unless the pollen used is viable and has a high degree of germination (Kav et al., 2014). Success of artificial pollination with viable pollens is a crucial process in the production of date palm (Kadri et al., 2022).

FS percentage. Table 1 shows the results for FS percentages of date palm cultivars pollinated with different methods. After 6 weeks of pollination (initial FS), FS percentage was significantly ($P < 0.05$) affected by the pollination method in the Lulu and Khesab cultivars. In both cultivars, the DS pollination produced significantly ($P < 0.05$) lowest FS percentages, with 95.8% and 62.1%, compared with HP (99.04% and 97.60%) and HS (100% and 88.88%), for Lulu and Khesab cultivars, respectively (Table 1). However, in 'Barhi', the differences between pollination methods were not statistically significant (Table 1). A similar trend was observed after 12 weeks (final FS) (Table 2). Awad and Al-Qurashi (2012) reported comparable findings for spray pollination, which had a decreased FS. The observed differences in FS percentage between date palm cultivars in response to different pollination methods could be due to the variation in the pollination period following spathe cracking, which usually lasts up to 40 d and varies greatly depending on cultivar and climatic conditions, particularly temperature (Kadri et al., 2022). Generally, depending on the date palm cultivar, the length of the receptivity period of pistillate flowers can range from 3 to 10 d (8 d for Ghars and Jihel, 7 d for Deglet Nour, and ≈3 d for Boufeggous, Medjhool, and Iklane) (Shaheen et al., 1986). Furthermore, the time of day for pollination application may influence FS %. According to Iqbal et al. (2014), pollination between 12:00 and 1:00 PM resulted in the greatest FS and production in the Dhakki date palm cultivar. Hence, the observed differences between pollination methods in Khesab cultivar could be attributed to pollination period, application timing, or stigma receptivity. The DS had a significantly lower FS than HP and HS, but it was still in the acceptable range for commercial production (60% to 80%) (Chao and Krueger, 2007). Also, FS ranges between 85% and 95% for most cultivars by traditional pollination technique are considered high, thus requiring flowers and/or fruit thinning process for improving fruit quality and increasing the marketable yield (Awad, 2011). Thus, DS pollination resulted in an acceptable FS percentage, and hence thinning (flower and/or fruit thinning) was not necessary to reduce bunch load, particularly in Khesab cultivar.

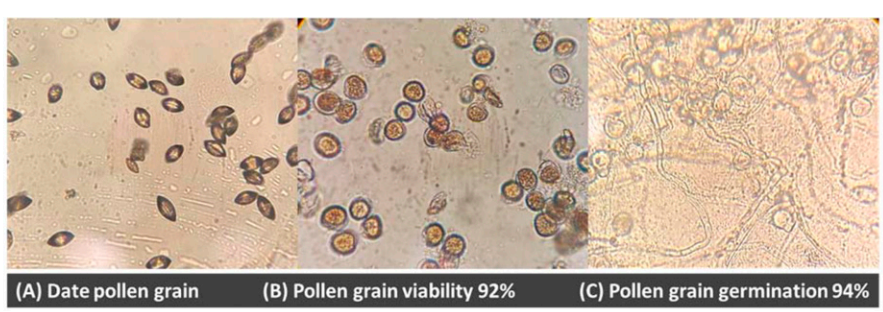

Fig. 3. Viability and germinability evaluation of the date pollen grains (Ghanami) (**A**) using acetocarmine staining (**B**) and in vitro germination method (**C**).

Table 1. Fruit set percentage (FS %), pollination efficiency (PE), and fruit retention percentage (FR %) of Barhi, Lulu, and Khesab date palm cultivars after 6 weeks of pollination (initial fruit set) as affected by different pollination methods.

Treatment	Total node no.[i]	Normal fruit no.	Abnormal fruit no.	Empty node no.	FS (%)	PE	FR (%)
Barhi cultivar							
HP[ii]	52.10 ± 2.31 Ba	46.33 ± 1.51 Ca	0.13 ± 0.03 Ca	8.33 ± 0.96 Ab	98.18 ± 5.63 Aa	1.00 ± 0.00 Aa	85.08 ± 4.1 Ba
HS	51.00 ± 3.35 Ba	40.83 ± 2.32 Bb	0.17 ± 0.06 Ba	9.97 ± 0.83 Ab	99.16 ± 4.91 Aa	1.00 ± 0.00 Aa	80.36 ± 5.5 Ab
DS	52.29 ± 2.74 Ba	33.07 ± 1.34 Bc	0.11 ± 0.04 Ba	19.11 ± 0.73 Ba	99.30 ± 5.53 Aa	1.00 ± 0.00 Aa	63.67 ± 3.7 Bc
Lulu cultivar							
HP	55.83 ± 3.15 Ba	50.43 ± 6.23 Ba	0.27 ± 0.02 Bb	4.13 ± 0.32 Bc	99.04 ± 2.33 Aa	1.00 ± 0.00 Aa	92.62 ± 4.23 Aa
HS	55.70 ± 2.58 Ba	45.47 ± 3.72 Ab	0.12 ± 0.00 Bc	10.23 ± 0.74 Ab	100.00 ± 0.00 Aa	1.00 ± 0.00 Aa	81.47 ± 3.98 Ab
DS	56.00 ± 6.11 Ba	38.97 ± 4.33 Ac	0.73 ± 0.01 Ba	16.30 ± 0.83 Ca	95.88 ± 2.87 Bb	0.98 ± 0.03 Aa	71.28 ± 5.11 Ac
Khesab cultivar							
HP	60.70 ± 4.22 Aa	55.67 ± 2.53 Aa	0.70 ± 0.03 Ac	4.33 ± 0.66 Bc	97.60 ± 2.29 Ba	0.99 ± 0.01 Aa	92.82 ± 5.34 Aa
HS	58.53 ± 3.61 Aa	45.60 ± 2.76 Ab	2.30 ± 0.09 Ab	10.63 ± 1.22 Ab	88.88 ± 5.43 Bb	0.94 ± 0.02 Bb	81.15 ± 6.17 Ab
DS	58.03 ± 5.13 Aa	25.91 ± 1.81 Cc	7.41 ± 0.82 Aa	23.71 ± 2.13 Aa	62.14 ± 3.21 Cc	0.81 ± 0.01 Bc	58.29 ± 3.55 Cc

[i] Values are the mean ± SE. Comparison between treatment means was made using least significant difference test at $P \leq 0.05$. Means with different letter(s) between treatments within a cultivar (lowercase letter), and between different cultivars (uppercase letter) are significantly different.
[ii] HP = hand pollination; HS = hand spray pollination; DS = drone spray pollination.

Drone pollination was able to achieve an acceptable level of FS with a minimum amount of pollen grains, labor, time, and cost. A single trained person could fly the drone twice during the season to pollinate a row of ten palms in ≈6 min. In traditional pollination, the laborer must climb the tree and can pollinate 40 to 60 medium-height trees/day (7-hour effective work/day), with an average of 50 trees/day (Ibrahim, 1988). The traditional pollination method is a labor-intensive process resulting in high costs (Salomón-Torres et al., 2021). In contrast, pollination using pollen grain-water suspension spray was found to minimize labor and costs (Abu-Zahra and Shatnawi, 2019; Mizuno et al., 2002). Pollinating date palm trees using a drone with water-suspended pollen grain is a novel technique presented in our study for the first time.

PE, FSE, and fruit retention percentage. The results for PE, retained fruit percentage, and FSE are presented in Tables 1 and 2, and Fig. 3, respectively. After 6 weeks of pollination, no significant differences in PE were observed by comparison between pollination methods for 'Lulu' and 'Barhi'; however, for 'Khesab', the DS pollination had significantly ($P < 0.05$) lower PE (0.81) compared with HP and HS methods (0.99 and 0.94, respectively) (Table 1). Similar trends were observed for the final FS after 12 weeks of pollination. The failure in the pollination process of date flowers results in abnormal fruit with three carpels that grow into a little fruit with no seed inside and will never ripen. The numbers of normal (pollinated) and abnormal fruit (unpollinated) were significantly ($P < 0.05$) affected by the pollination method (Table 1). For example, although Barhi and Lulu cultivars had less than 1% of abnormal for all pollination methods, Khesab cultivar showed the highest number of abnormal fruits in DS followed by HS pollination, with 7.4% and 2.3%, respectively (Table 1), suggesting that Khesab cultivar may have different flowering behavior or pollination period or stigma receptivity compared with Lulu and Barhi. The FSE depends on the abnormal fruit number per strand. The FSE parameter defines the FS by considering dropped fruits as well (Akhavan et al., 2021). Pollination method significantly ($P < 0.05$) affected the FSE in all cultivars, after 6 weeks of pollination (Fig. 4A and B). The DS pollination had significantly ($P < 0.05$) the lowest FSE percentage, followed by HS and HP, for all cultivars. After 12 weeks, a similar pattern was observed (Fig. 4C and D). This can be associated with fruit drop occurring a few weeks after pollination (Tables 1 and 2), caused by many null fruit sites owing to incomplete pollination (Akhavan et al., 2021). The flower that did not receive pollen eventually dropped. After 6 weeks of pollination, significant ($P < 0.05$) variations in retained fruit percentage were observed between different pollination methods, for all date cultivars (Table 1). The lowest level of retained fruit percentage was observed in DS followed by HS and HP pollination. After 12 weeks of pollination, fruit retention decreased for all the methods with a significant decrease for DS (Table 2). The pollination technique critically affects the level of FS and eventually the fruit production and yield (Akhavan et al., 2021; Awad, 2006). In the present study, PE, FSE, and fruit retention percentage observed with DS pollination are still within the acceptable range for commercial production, for all examined cultivars. This confirms that DS pollination could be a feasible alternative for date palm tree pollination when compared with conventional pollination. Using minimum amounts of pollen grains, with acceptable FS, without a further need for fruit thinning is vital for date palm production (Awad, 2010). According to our findings, using a drone to pollinate date palms and manage pollination process saves time and cost, and has proven its applicability.

Bunch characteristics. Data in Table 3 show bunch characteristics of the date cultivars in response to the pollination methods. In all cultivars, the bunch weight was significantly ($P < 0.05$) affected by pollination methods. DS pollination produced significantly ($P < 0.05$) lower bunch weight than HP pollination in Barhi and Khesab cultivars. Also, the bunch weight was lower in the HS

Table 2. Fruit set percentage (FS %), pollination efficiency (PE), and fruit retention percentage (FR %) of Barhi, Lulu, and Khesab date palm cultivars after 12 weeks of pollination (final fruit set) as affected by different pollination methods.

Treatment	Total node no.[i]	Normal fruit no.	Abnormal fruit no.	Empty node no.	FS (%)	PE	FR (%)
Barhi cultivar							
HP[ii]	47.06 ± 2.44 Ba	30.35 ± 3.23 Ba	0.03 ± 0.00 Ba	14.77 ± 0.93 Bc	99.80 ± 5.23 Aa	1.00 ± 0.00 Aa	67.50 ± 3.48 Ba
HS	46.00 ± 2.53 Ba	27.03 ± 1.42 Bb	0.00 ± 0.00 Ba	18.97 ± 0.81 Bb	100.00 ± 0.00 Aa	1.00 ± 0.00 Aa	59.17 ± 2.33 Ab
DS	49.47 ± 1.89 Ba	23.97 ± 1.16 Bc	0.03 ± 0.00 Ba	25.20 ± 1.56 Aa	99.76 ± 4.62 Aa	1.00 ± 0.00 Aa	48.80 ± 2.74 Bc
Lulu cultivar							
HP	57.67 ± 4.43 Aa	40.83 ± 2.13 Aa	0.00 ± 0.00 Ba	20.83 ± 0.79 Ab	100.00 ± 0.00 Aa	1.00 ± 0.00 Aa	66.64 ± 3.91 Ba
HS	55.10 ± 3.24 Aa	35.50 ± 1.77 Ab	0.00 ± 0.00 Ba	19.60 ± 0.91 Bb	100.00 ± 0.00 Aa	1.00 ± 0.00 Aa	65.10 ± 3.21 Aa
DS	55.52 ± 5.26 Aa	30.80 ± 1.24 Ac	0.00 ± 0.00 Ba	24.72 ± 0.86 Aa	100.00 ± 0.00 Aa	1.00 ± 0.00 Aa	55.79 ± 2.84 Ab
Khesab cultivar							
HP	55.42 ± 6.01 Aa	39.21 ± 2.19 Aa	0.40 ± 0.04 Ab	15.81 ± 1.06 Bb	97.95 ± 5.74 Aa	0.99 ± 0.03 Aa	71.14 ± 5.22 Aa
HS	58.15 ± 5.26 Aa	34.67 ± 1.98 Ab	0.17 ± 0.03 Ab	24.31 ± 2.18 Aa	97.22 ± 5.77 Aa	0.99 ± 0.01 Aa	58.06 ± 2.89 Bb
DS	56.32 ± 2.22 Aa	28.33 ± 2.27 Ac	4.01 ± 0.63 Aa	22.79 ± 1.13 Ba	82.81 ± 6.23 Bb	0.91 ± 0.01 Bb	56.01 ± 3.01 Ab

[i] Values are the mean ± SE. Comparison between treatment means was made using least significant difference test at $P \leq 0.05$. Means with different letter(s) between treatments within a cultivar (lowercase letter), and between different cultivars (uppercase letter) are significantly different.
[ii] HP = hand pollination; HS = hand spray pollination; DS = drone spray pollination.

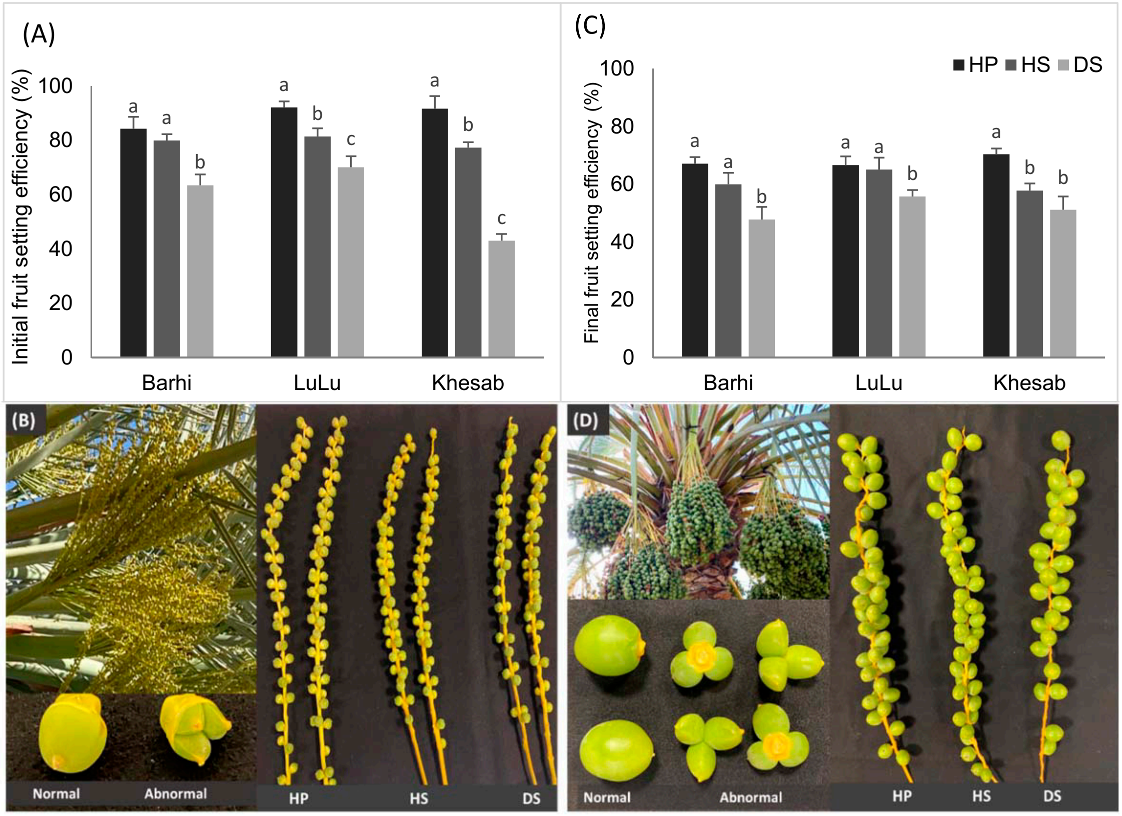

Fig. 4. Effect of different pollination methods on the initial fruit setting efficiency (6 weeks after pollination) (**A** and **B**), and final fruit setting efficiency (12 weeks after pollination) (**C** and **D**) of Barhi, Lulu, and Khesab date palm cultivars. Means with different letters between treatments within a cultivar are significantly different. HP = hand pollination; HS = hand spray pollination; DS = drone spray pollination.

than in the HP pollination for the same cultivars. However, there was no significant difference in bunch weight between DS and HP pollination methods in the Lulu cultivar (Table 3). HS pollinated Barhi and Lulu cultivars had the lowest bunch weight (14.15, 9.75 kg) followed by DS (14.07, 11.12 kg), respectively. Although, in Khesab cultivar, DS pollination resulted in significantly ($P < 0.05$) lower bunch weight (14.85 kg) in comparison with HP and HS pollination, with 22.20 and 20.70 kg, respectively. The DS application considerably reduced overall bunch weight and yield per tree in 'Barhi' and 'Khesab' (Table 3). This might be because of the lower FS percentage observed with DS pollination as compared with other methods (Tables 2 and 3). It is worth mentioning that date palm yield increases as bunch weight increases (Akhavan et al., 2021). Bunch weight is the product of a combination of parameters including fruit number, weight, size, and other associated factors (Awad, 2010). These factors are commonly proportionately negatively associated with each other. The attained levels of FS in this experiment, particularly with the DS pollination, had a substantial positive impact on achieving more consistent bunch sizes based on the percentage of FS. However, Awad and Al-Qurashi (2012) reported comparable results for spray pollination, which had a lower FS but a much larger bunch weight than the traditional method. This contradiction could be attributed to differences in cultivars, meteorological conditions, and mechanical pollination mechanisms and procedures. Despite the lower FS percentage observed in the DS pollination (Table 1), the yield was sufficient, as the fruit weight was higher in DS than in HP and HS pollination (Table 4).

Table 3. Bunch characteristics of Barhi, Lulu, and Khesab date palm cultivars at harvest as affected by different pollination methods.

	Harvested at Bisr stage						Harvested at Tamr stage	
Treatment	Bunch W (kg)[i]	Strand no./ bunch	Fruit no./ strand	Bisr fruit W (kg)	Rutab fruit W (kg)	Drop fruit W (kg)	Bunch W (kg)	Yield/Tree (kg)
Barhi cultivar								
HP[ii]	18.00 ± 1.41 Ba	100.00 ± 5.76 Aa	18.7 ± 1.44 Ca	9.75 ± 0.74 Ba	7.53 ± 0.63 Aa	5.73 ± 0.74 Aa	9.12 ± 0.54 Ba	69.31 ± 3.22 Ba
HS	14.15 ± 2.17 Bb	101.50 ± 8.34 Aa	17.6 ± 1.61 Ba	5.43 ± 0.86 Bb	7.48 ± 0.77 Aa	5.68 ± 0.91 Aa	8.76 ± 0.55 Ba	65.42 ± 5.51 Ba
DS	14.07 ± 1.33 Ab	105.33 ± 6.88 Aa	14.6 ± 0.98 Bb	7.59 ± 0.79 Ab	3.20 ± 0.24 Bb	1.72 ± 0.08 Bb	8.53 ± 0.94 Aa	66.12 ± 3.43 Aa
Lulu cultivar								
HP	11.68 ± 1.40 Ca	50.50 ± 3.64 Cb	26.9 ± 1.51 Ba	5.40 ± 0.44 Ca	5.13 ± 0.71 Ba	2.13 ± 0.71 Ba	7.09 ± 0.62 Ca	54.81 ± 2.19 Ca
HS	9.75 ± 0.85 Cb	60.50 ± 2.83 Ca	26.1 ± 2.03 Aa	5.88 ± 0.31 Ba	5.00 ± 0.33 Ba	2.93 ± 0.62 Ba	6.12 ± 0.88 Ca	49.28 ± 3.37 Ba
DS	11.12 ± 1.04 Ba	58.50 ± 2.21 Ca	23.4 ± 2.14 Ab	5.40 ± 0.64 Ba	5.93 ± 0.45 Aa	3.43 ± 0.48 Aa	6.82 ± 0.94 Ba	48.99 ± 3.11 Ba
Khesab cultivar								
HP	22.20 ± 3.61 Aa	75.00 ± 8.11 Ba	32.1 ± 2.14 Aa	18.80 ± 1.72 Aa	4.35 ± 0.36 Aa	2.48 ± 0.04 Ba	14.3 ± 1.01 Aa	112.24 ± 6.11 Aa
HS	20.70 ± 1.56 Aa	77.00 ± 5.61 Ba	28.5 ± 3.39 Aa	15.80 ± 1.36 Ab	3.38 ± 0.24 Ca	1.75 ± 0.07 Cb	13.7 ± 1.00 Aa	105.32 ± 4.32 Ab
DS	14.85 ± 1.24 Ab	68.00 ± 7.45 Bc	22.3 ± 1.47 Ab	9.35 ± 0.94 Ac	4.05 ± 0.55 ABa	1.25 ± 0.14 Bb	8.6 ± 0.29 Ab	69.96 ± 3.33 Ac

[i] Values are the mean ± SE. Comparison between treatments means was made using least significant difference test at $P \leq 0.05$. Means with different letter(s) between treatments within a cultivar (lowercase letter), and between different cultivars (uppercase letter) are significantly different.
[ii] HP = hand pollination; HS = hand spray pollination; DS = drone spray pollination; W = weight.

Table 4. Fruit physical characteristics of Barhi, Lulu, and Khesab date palm cultivars at harvest as affected by different pollination methods.

Treatment	Fruit wt (g)[i]	Length (mm)	Width (mm)	Color L*	Color a*	Color b*	Firmness (N)
Barhi cultivar							
HP[ii]	9.70 ± 0.71 Ab	30.44 ± 2.41 Bb	22.87 ± 1.23 Aa	65.75 ± 4.21 Aa	13.98 ± 1.11 Cb	46.44 ± 2.31 Aa	12.61 ± 1.09 Ba
HS	8.97 ± 0.72 Ab	30.90 ± 2.55 Bb	22.70 ± 1.30 Aa	64.81 ± 2.89 Aa	16.45 ± 1.36 Ba	46.18 ± 1.87 Aa	12.84 ± 1.51 Ba
DS	10.89 ± 0.31 Aa	35.21 ± 1.47 Ba	22.51 ± 1.06 Aa	65.04 ± 6.44 Aa	14.04 ± 1.27 Cb	47.20 ± 3.33 Aa	13.20 ± 1.45 Ba
Lulu cultivar							
HP	8.10 ± 0.66 Bb	29.26 ± 1.82 Ba	21.58 ± 1.46 Aa	63.54 ± 5.22 Ba	16.18 ± 1.21 Ba	42.74 ± 3.42 Ba	14.90 ± 1.41 Aa
HS	8.03 ± 0.48 Bb	28.88 ± 1.73 Ba	21.83 ± 1.15 Aa	62.28 ± 3.78 Ba	15.83 ± 1.11 Ba	41.80 ± 4.11 Ba	14.86 ± 1.20 Aa
DS	9.51 ± 0.21 Ba	30.12 ± 1.45 Ba	23.13 ± 1.43 Aa	63.02 ± 4.48 Ba	16.58 ± 1.03 Ba	41.88 ± 3.19 Ba	15.54 ± 1.31 Aa
Khesab cultivar							
HP	10.05 ± 0.60 Ab	34.37 ± 2.51 Ab	22.36 ± 1.87 Aa	29.38 ± 1.97 Bc	18.07 ± 1.22 Ac	7.02 ± 0.47 Cc	16.56 ± 1.32 Aa
HS	9.53 ± 0.97 Ab	34.34 ± 3.66 Ab	22.21 ± 1.37 Aa	31.20 ± 1.44 Bb	21.03 ± 1.37 Ab	9.07 ± 0.81 Cb	15.69 ± 1.35 Aa
DS	11.42 ± 0.71 Aa	36.92 ± 1.76 Aa	23.81 ± 2.04 Aa	33.87 ± 1.41 Ba	25.36 ± 1.63 Aa	13.30 ± 1.11 Ca	16.82 ± 1.19 Aa

[i] Values are the mean ± SE. Comparison between treatment means was made using least significant difference test at $P \le 0.05$. Means with different letter(s) between treatments within a cultivar (lowercase letter), and between different cultivars (uppercase letter) are significantly different.
[ii] HP = hand pollination, HS = hand spray pollination; DS = drone spray pollination.

Fruit number per strand was significantly ($P < 0.05$) lower in the DS than in HP and HS pollination, for all date cultivars (Table 3). Also, significant differences in the number of Bisr, Rutab, and Tamr fruits per bunch were observed between different pollination methods. For example, in 'Barhi', DS pollination produced a significantly ($P < 0.05$) lower amount of Rutab fruit per bunch (3.20 kg) than HP (7.53 kg) and HS (7.48 kg) pollination, whereas in 'Khesab', it resulted in a lower amount of Bisr fruit (9.35 kg) compared with HP (18.80 kg) and HS (15.80 kg) (Table 3). In addition, in 'Barhi' and 'Khesab', DS pollination provided a significantly ($P < 0.05$) lower amount of fruit drop/bunch than the HP and HS. However, in 'Lulu', the amount of fruit drop/bunch was slightly higher in the DS pollination (3.43 kg) than in HP (2.13 kg) and HS (2.93 kg), but the difference was not statistically significant ($P > 0.05$). This variability might be due to the difference in the harvesting time between cultivars despite the same time of pollination.

Fruit characteristics. Table 4 shows the physical properties of the fruit at Bisir, Rutab, or Tamr stages in response to different pollination methods. The average fruit weight was significantly ($P < 0.05$) higher in DS pollination compared with HP and HS methods, for all cultivars (Table 4, Fig. 5). Also, all DS-pollinated cultivars had a significantly ($P < 0.05$) greater average fruit length than the HP and HS treatments, but in 'Lulu', the increase was not statistically significant ($P > 0.05$). Furthermore, DS-pollinated Lulu and Khesab cultivars had slightly wider fruit compared with HP and HS methods (Table 4, Fig. 5). The observed improvements in fruit physical characteristics of the DS treatment could be due to less competition between fruits within a bunch (Awad, 2010).

This finding is also consistent with the decreased percentage of FS observed with DS pollination (Tables 1 and 2). Awad and Al-Qurashi (2012) reported similar results for spray pollination. They suggested that pollination methods had a substantial impact on the physical and biochemical quality attributes of the fruit. Fruit thinning has been shown to improve fruit weight, size, and sugar content while decreasing overall yield per tree in several date palm cultivars (Awad, 2010). In the present investigation, the obtained FS levels with the DS pollination had a significant favorable impact on fruit physical quality characteristics at harvest (Table 4).

Concerning fruit color characteristics, there were no significant ($P > 0.05$) differences in color parameters; L^*, a^*, and b^* values between pollination methods within a cultivar, except in 'Khesab' where DS pollination had significantly higher L^*, a^*, and b^* values than HS and HP methods (Table 4). No significant ($P > 0.05$) difference was observed between pollination methods in fruit firmness (Table 4). Correspondingly, at all maturity stages (Bisir, Rutab, and Tamr), fruit chemical characteristics, TSS, acidity, pH, and vitamin C levels, were not impacted by any of the applied pollination methods compared with the control (Table 5).

Conclusion

Data presented in this study revealed that spraying water-suspended pollen grain using a drone is an effective method for pollinating

Fig. 5. Fruits of Barhi, Lulu, and Khesab date cultivars harvested at Bisr stage (left), normal and abnormal fruit of Khesab cultivar (right). HP = hand pollination; HS = hand spray pollination; DS = drone spray pollination.

Table 5. Chemical characteristics of 'Barhi', 'Lulu', and 'Khesab' date palm fruits at three maturation stages as affected by different pollination methods.

Treatment	Acidity (%)			pH			TSS (%)			Vitamin C (mg·100 g^{-1})		
	Bisr[i]	Rutab	Tamar	Bisr	Rutab	Tamar	Bisr	Rutab	Tamar	Bisr	Rutab	Tamar
Barhi cultivar												
HP[ii]	0.36 ± 0.07 Ba	0.28 ± 0.4 Aa	0.26 ± 0.03 Aa	5.4 ± 0.21 Aa	6.4 ± 0.22 Aa	6.5 ± 0.07 Ba	35.1 ± 2.56 Aa	45.4 ± 1.17 Ba	59.4 ± 4.53 Aa	3.78 ± 0.77 Aa	1.98 ± 0.55 Aa	0.48 ± 0.11 Aa
HS	0.30 ± 0.0 Ba	0.28 ± 0.3 Aa	0.24 ± 0.02 Aa	5.3 ± 0.17 Aa	6.5 ± 0.44 Aa	6.6 ± 0.16 Ba	33.6 ± 2.55 Aa	44.3 ± 1.52 Ba	62.2 ± 3.43 Aa	3.63 ± 0.69 Aa	2.02 ± 0.26 Aa	0.34 ± 0.17 Aa
DS	0.33 ± 0.01 Ba	0.32 ± 0.1 Aa	0.27 ± 0.01 Aa	5.2 ± 0.15 Aa	6.4 ± 0.38 Aa	6.5 ± 0.17 Ba	34.6 ± 2.17 Aa	45.2 ± 1.41 Ba	63.8 ± 5.68 Aa	3.72 ± 0.38 Aa	1.92 ± 0.41 Aa	0.42 ± 0.14 Aa
Lulu cultivar												
HP	0.52 ± 0.03 Aa	0.26 ± 0.0 Aa	0.12 ± 0.01 Ba	5.7 ± 0.17 Ba	6.5 ± 0.19 Aa	6.6 ± 0.13 Ba	36.5 ± 3.91 Aa	53.10 ± 2.07 Aa	62.5 ± 4.77 Aa	2.90 ± 0.07 Ba	1.20 ± 0.06 Aa	0.44 ± 0.03 Aa
HS	0.52 ± 0.08 Aa	0.28 ± 0.02 Aa	0.10 ± 0.02 Ba	5.8 ± 0.21 Ba	6.4 ± 0.14 Aa	6.6 ± 0.39 Ba	37.3 ± 3.44 Aa	50.50 ± 3.17 Aa	61.0 ± 4.63 Aa	2.08 ± 0.17 Ba	0.90 ± 0.21 Aa	0.48 ± 0.05 Aa
DS	0.49 ± 0.03 Aa	0.30 ± 0.01 Aa	0.10 ± 0.04 Ba	5.8 ± 0.16 Ba	6.5 ± 0.11 Aa	6.7 ± 0.27 Ba	36.3 ± 4.57 Aa	52.90 ± 2.81 Aa	62.5 ± 3.49 Aa	2.08 ± 0.10 Ba	1.16 ± 0.11 Aa	0.44 ± 0.04 Aa
Khesab cultivar												
HP	0.38 ± 0.06 Ba	0.24 ± 0.03 Aa	0.08 ± 0.00b Ba	5.4 ± 0.13 Aa	6.3 ± 0.07 Aa	6.9 ± 0.11 Aa	37.8 ± 5.21 Aa	49.2 ± 3.08 Aa	56.5 ± 3.11 Ba	2.68 ± 0.45 Ba	0.88 ± 0.17 Aa	0.49 ± 0.03 Aa
HS	0.33 ± 0.05 Ba	0.22 ± 0.0 Aa	0.08 ± 0.0 Ba	5.5 ± 0.30 Aa	6.5 ± 0.22 Aa	6.9 ± 0.13 Aa	36.0 ± 5.22 Aa	49.2 ± 2.45 Aa	56.5 ± 3.27 Ba	2.93 ± 0.42 Ba	0.92 ± 0.11 Aa	0.51 ± 0.02 Aa
DS	0.38 ± 0.02 Ba	0.28 ± 0.02 Aa	0.12 ± 0.01 Ba	5.5 ± 0.18 Aa	6.4 ± 0.15 Aa	6.8 ± 0.17 Aa	35.7 ± 3.47 Aa	48.4 ± 2.17 Aa	55.0 ± 3.16 Ba	2.92 ± 0.67 Ba	0.84 ± 0.12 Aa	0.54 ± 0.03 Aa

[i] Values are the mean ± SE. Comparison between treatment means was made using least significant difference test at $P \leq 0.05$. Means with different letter(s) between treatments within a cultivar (lowercase letter), and between different cultivars (uppercase letter) are significantly different.

[ii] HP = hand pollination; HS = hand spray pollination; DS = drone spray pollination.

date palm trees. The results of 'Barhi' and 'Lulu' using a drone were slightly different from the traditional pollination and spray methods, whereas in 'Khesab', there was significant decrease in the FS percentage with the drone pollination, this percentage is still commercially acceptable. Despite producing fewer fruits per strand, the DS pollination technique considerably enhanced fruit physical quality attributes at harvest as compared with the control. Fruit color, firmness, TSS, acidity, pH, and vitamin C level were unaffected by any of the pollination methods in all studied cultivars. In conclusion, this study was applied on three cultivars with a promising result and provides date palm growers with an innovative, effective, and accurate spray method for artificial pollination using a platform-mounted robotic drone. It could be a potential alternative to the traditional date palm pollination with an effective spray method speeding up the pollination process and reducing the labor requirements. However, further research is needed to optimize time and duration of the application, which may vary according to cultivar and region. Also, the next step is to develop a setting for an autonomous electronic pollination program using drones that can be used commercially in date palm farms all over the producing regions.

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