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Evaluating the Engineering Characteristics of Date Palm Pollen Grains Carrier Materials

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This study evaluates the engineering properties of various carriers for date palm pollen grains, including Wheat Flour (WF), Wheat Bran (WB), Banana Peels (BP), Male Spathe Flowers (MSF), and Female Bunch Strands (FBS). The focus is on bulk density, repose angle, dynamic coefficient of friction, and terminal velocity. Bulk density ranged from 0.321 to 0.831 g cm^{-3}, with date palm pollen grain (*DPP*) showing the highest value, suggesting efficient storage but potential flowability issues. Repose angles varied from 24 to 47 degrees; *DPP* and *DPP+FBS* (Female bunch strands) had the lowest angles, favoring smooth flow during pollination, while wheat flour (*WF*) had the highest, indicating resistance and clumping. Friction analysis across different surfaces (acrylic, *PVC*, aluminum, and stainless steel) highlighted material-surface interactions. Terminal velocity results showed *DPP* with a balanced value of 0.96 m s^{-1}, while mixtures like *DPP+FBS* and *DPP+BP* (banana peels) had low to moderate velocities (0.6 m s^{-1} and 1.02 m s^{-1}), enhancing dispersion. *DPP* and its mixtures, especially *DPP+FBS*, exhibited favorable pollination properties with good flowability and moderate friction, promoting efficient distribution. In contrast, higher friction materials like *FBS* could hinder application. The study emphasizes the need to select carriers with optimal density, repose angle, and friction to improve pollination efficiency, supporting better agricultural outcomes. Mixtures *DPP+FBS* and *DPP+MSF* emerged as the best option, balancing physical, mechanical and aerodynamic characteristics for effective pollination.

Keywords: Date palm, Pollen grains, Carrier material, Physical and mechanical characteristics.

Introduction

Date palm pollination is considered one of the most important processes in successful date production, since fruit yield and quality depend on the correct application of pollen grains. Pollination efficiency and the fruit set depends on several factors such as male flowering time, pollinizer source, the viability and amount of pollen grains, pollination time, and the receptivity of female flowers (Ali-Dinar et al., 2021). Previous studies have reported that correct pollination method determine fruit yield, quality and the consumption need of *DPP* (Salomón-Torres et al., 2021 and Anushma et al., 2018). The benefits of the pollination process lie in obtaining large-sized high quality fruits, avoiding the presence of small fruits (Salomón-Torres et al., 2021). The yield of date palms is mainly determined by the fruit set percentage (*FSP*) of the racemes. This in turn depends on several factors such as the date palm pollen grains (*DPP*) source and quality, pollination period, pollination method, female–male compatibility, and other factors such as temperature, fertilization, irrigation, and soil characteristics (Salomón-Torres et al., 2022). Pollen grains are prepared for use in automatic processes by mixing them with some carrier materials such as flour or talcum powder to save on the amount of pollen. The pollen-carrier materials must be characterized by having no effect on pollen grains or their germination, they must be cheap and available in the market, easy to flow from pollination machines, and not clump or collect in pollinator tubes, especially in humid areas. Among

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the materials used to mix with pollen grains are wheat flour, bran flour, flour leftover from palm blossoms, talcum powder, etc. Evaluating the characteristics of date palm pollen grains carrier materials is essential for ensuring the effectiveness of the pollination process. Various materials such as wheat flour, bran, talcum powder, dried banana peel, female bunch strands, and the male inflorescence spadix have been studied for their suitability as pollen carriers. These materials vary in their physical properties, cost, and impact on the pollination process, necessitating a comprehensive evaluation to determine the most effective and economical options. Wheat flour is commonly used as a carrier due to its availability and cost-effectiveness. However, it is crucial to ensure that the flour does not negatively impact on the viability or germination of pollen grains. Studies have shown that wheat flour can be an effective carrier, provided it is free from contaminants and moisture that might cause clumping (Al-Yahyai and Khan, 2015). Similarly, bran, which is a by-product of the milling process, has also been tested. Bran flour is lightweight and easy to handle, but its hygroscopic nature requires careful storage to prevent moisture absorption. Talcum powder, a mineral-based carrier, is another commonly used material. It is inert and does not affect the pollen grains' viability. However, the fine particles of talcum powder can pose respiratory hazards if not handled properly. Therefore, while it is effective in preventing clumping and ensuring a smooth flow through pollination machines, safety measures must be in place during its use (Muti Ullah et al., 2018). Dried banana peel is a novel carrier that has gained attention due to its organic nature and availability. Banana peels are rich in nutrients and can potentially enhance the pollen grains' effectiveness. However, the preparation of banana peel powder requires thorough drying and grinding processes to ensure consistency and prevent moisture-related issues (Ahmed et al., 2021). Additionally, its impact on the germination and viability of pollen grains needs further research to establish its suitability as a carrier. Female bunch strands, which are parts of the date palm's female inflorescence, can also be used as a carrier material. These strands are readily available during the pollination season and can be processed into a fine powder. Using female bunch strands as a carrier aligns with sustainable agricultural practices by utilizing by-products of the date palm itself (Salomón-Torres et al., 2021). However, their impact on the pollination process must be carefully evaluated to ensure they do not hinder the pollen grains' performance. The male inflorescence spadix, another by-product of the date palm, is also considered for use as a carrier. The spadix can be dried and ground into a fine powder, providing a sustainable and cost-effective option. However, similar to other organic carriers, the spadix powder's impact on pollen viability and germination must be thoroughly assessed (Al-Khayri et al., 2018). Temperature, fertilization, irrigation, and soil characteristics also play significant roles in the success of the pollination process. Optimal conditions must be maintained to ensure the pollen grains remain viable and effective throughout the pollination period. High temperatures can lead to desiccation of pollen grains, reducing their viability, while inadequate fertilization and irrigation can stress the date palms, negatively impacting fruit set and quality (Zaid and de Wet, 1999). The evaluation of date palm pollen grains carrier materials is crucial for optimizing the pollination process and ensuring high fruit yield and quality. Materials such as wheat flour, bran, talcum powder, dried banana peel, female bunch strands, and male inflorescence spadix offer various benefits and challenges. Thorough research and evaluation are necessary to determine the most effective and economical carriers, taking into consideration their impact on pollen viability, ease of use, cost, and availability. Ensuring the correct application of these carriers, along with maintaining optimal environmental conditions will significantly contribute to successful date palm pollination and production. Ashour et al. (2008) mentioned that the mixing of pollen grains with various carriers was beneficial for obtaining an economical yield with good fruit quality. Density of talc powder is 2.78 g cm^{-3}, particle median diameter (D50) of 1.9 μm (Wang et al., 2013), coefficient of friction $\mu = 0.24–0.36$ for dry talc and $\mu \leq 0.2$ for water-saturated talc (Chen et al., 2017). El-salhy (2012) reported that mixing of pollen at 0.4, 0.6, 0.8, and 1.0 g with talc powder in a ratio of 1:24 ,16, 12 and 9 dilution on bunch weight and fruit quality of Sewy date palm. At lower concentrations a reduction was found in fruit quality and bunch weight and no significant differences in bunch weight due to pollination with 1.0 g pollen. Fruit set, bunch weight, fruit dimensions, fruit weight and tree yield decreased by mixed dried pollen grains with talcum powder to dusting *DPP* with pollinator on open female spath (Imtiaz et al., 2018). A ratio of 1:5 of *DDP* mixed with filler agent wheat flour, grade zero in Jordan of Hayani date palm was carried out to compare between manual and hand duster pollination (Alasasfa, 2021). The physical and aerodynamic properties of the carrier materials are one of the most important properties that affect pollination. The characteristics of these materials can affect its transmission from date palm pollinating machines to female flowers. Thus, the main objective of this research work is to evaluate the physical, mechanical and aerodynamic characteristics of date palm pollen grains carrier materials because these properties significantly impact on the performance of date palm pollination machines.

Materials and Methods

This experiment has been implemented in Bioenvironmental Engineering laboratory, Agricultural Engineering Department, Faculty of Agriculture, Cairo University, Giza, Egypt.

Materials preparation

Date palm pollen grains carrier

In this study, five carrier materials were used to enhance date palm pollen grains: Wheat Flour (*WF*), Wheat Bran (*WB*), Banana Peels (*BP*), Male Spathe Flowers (*MSF*), and Female Bunch Strands (*FBS*). These materials were carefully selected to improve the functional properties of the pollen grains specifically for the pollination process. Below is an explanation of the preparation process for each of these materials.

Wheat Flour (*WF*), derived from the milling of *Triticum aestivum* L., is a fine powder that serves as a versatile material in various applications beyond food production. In this study, a one-kilogram sample of wheat flour was sourced from the local market, specifically from the South Cairo and Giza Mills Company in Egypt. The flour used had an extraction rate of 82%, indicating that 82% of the wheat grain was converted into flour. The choice of wheat flour with this extraction rate ensures the desired consistency and particle size needed for its role as a carrier in the pollination process of date palms. This material contributes to the overall texture and dispersal properties of the pollen grains, facilitating their application in the field.

Wheat Bran (*WB*), the outer protective layer of the wheat kernel removed during the milling process, it is another valuable material used in this study. Although typically considered a by-product, wheat bran is rich in dietary fiber and other components that can enhance the structural properties of pollen grains. A one-kilogram sample of wheat bran was utilized, with careful milling to achieve uniform particle size. This uniformity is crucial for ensuring the even distribution of the bran when mixed with pollen grains, which aids in the controlled release and effective coverage during the pollination process.

Banana Peels (*BP*), Banana Peels (*BP*) represent an innovative and underutilized material that has been introduced as a carrier in this study. Accounting for approximately 30% of the total fruit weight and containing about 20% dry matter, banana peels are rich in minerals, amino acids, carbohydrates, proteins, and fiber. These components, while typically overlooked in food applications, offer unique properties that can improve the adhesion and stability of pollen grains. Fresh banana peels were sourced from local juice shops, thoroughly cleaned, sliced, and washed to prepare them for use (Figure 1). The inclusion of banana peels is particularly significant because they have not been previously explored in this context, adding a novel element to the enhancement of pollen grain properties, specifically for pollination efficiency. Banana peels were obtained from the waste of juice shops resulting from the use of bananas, where the processes of washing, cutting, weighing and then solar drying were carried out to get rid of moisture and then grinding the sample more than once. The size grading was carried out using different sieves to determine the diameter of the sample. The size sieves that used were (2 mm, 1 mm, 0.85 mm, 0.43 mm, 0.3 mm and 0.106 mm). Banana peel is considered a new material that has not been used previously as a material that carries pollen grains.

Male Spathe Flowers (*MSF*), *MSF* are the floral inflorescences of the date palm, recognized for their creamy white spadix. In this study, the covers of the floral inflorescences stacked on the pollen strands were separated during the extraction process and utilized as a carrier. The preparation of Male Spathe Flowers involves careful separation and drying to preserve their structural integrity and functional properties. The *MSF* was speed in indoor to get rid of moisture, and then grinding the sample more than once. The *MSF* was size grading using different sieves to determine the diameter of the sample. The size sieves that used were 2 mm, 1 mm, 0.85 mm, 0.43 mm, 0.3 mm and 0.106 mm (Figure 1). By adding these flower components, the pollen grains may benefit from improved texture and stability, contributing to more effective and uniform application during pollination.

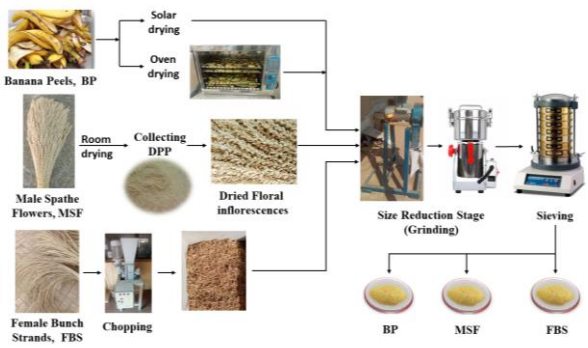

Fig. 1. Preparation process of carrier materials: Banana Peels (*BP*) ,Male Spathe Flowers (*MSF*) and Female Bunch Strands (*FBS*).

Female Bunch Strands (*FBS*), *FBS* are the remnants of the date palm harvesting process; specifically, the strands left after the dates have been collected. These strands, typically discarded, contain valuable fibers that can be repurposed as a carrier material. In this study, Female Bunch Strands were collected after the date harvesting process, cleaned, washed using water and spread in sun-drying to get rid of moisture, and then chopping operations were carried out several times, as well as grinding the sample more than once. Size grading was using different sieves to determine the diameter of the sample. The size sieves that used were 2 mm, 1 mm, 0.85 mm, 0.43 mm, 0.3 mm and 0.106 mm (Figure 1). Their fibrous nature helps to enhance the structural integrity of the pollen grains, making them more resilient and improving their dispersal characteristics in the field.

Date Palm Pollen grains (DPP)

The pollen extracted from the mature male spathes collected from Ezab Al Qasr, El Dakhla, Elwady El Gadeed Governorate, (longitude of 25.75 ° N and latitude 28.84 ° E), during spring 2024. Another sample was given from Date Palm Central Lab, Agricultural Research Center, Giza, Egypt. Mature male spathe is opened, the bulk inflorescence completely removed and separated to 2-3 strands to be dried over a layer of polyethylene film at ambient room temperature 18-22 °C with low relative humidity 40 - 45% in a shaded place to avoid direct sun light, until its flowers begin to open and release the pollen grains, a handheld separator was used to extract the pollen from the inflorescence.

Mixing *DPP* with different carriers materials

The mixing ratio between *DPP* grains and the carrier materials *WF*, *WB*, *BP*, *MSF* and *FBS* was one-gram pollen grain to six grams carrier material, according to (Sharma et al., 2023)

Material types

Eleven material types were determined based on the carriers and their mixing with pollen grains, as outlined in Table (1).

Table 1. Experimental material types.

Material type description	Material type symbol
Date Palm Pollen grains	*DPP*
Wheat Flour	*WF*
Wheat Bran	*WB*
Banana Peels	*BP*
Male Spathe Flowers	*MSF*
Female Bunch Strands	*FBS*
Date Palm Pollen grains + Wheat Flour	*DPP+WF*
Date Palm Pollen grains + Wheat Bran	*DPP+WB*
Date Palm Pollen grains + Banana Peels	*DPP+BP*
Date Palm Pollen grains + Male Spathe Flowers	*DPP+MSF*
Date Palm Pollen grains + Female Bunch Strands	*DPP+FBS*

Measurements and calculations of physical, mechanical and aerodynamic characteristics

Moisture content

Moisture content for each material type was determined using a convection oven drying method. A fresh sample mass of 1.715 kg was placed in the oven set to 60°C and dried for 72 hours according to AOAC (1986). After drying, the mass of each sample was recorded as 0.133 kg. The moisture content was then calculated using the difference between the initial and final mass. This method was applied consistently across all material types, including Date Palm Pollen grains, Wheat Flour, Wheat Bran, Banana Peels, Male Spathe Flowers, Female Bunch Strands, and their combinations with Date Palm Pollen grains.

The moisture content of female bunch strands was determined by solar drying according to the equation (1):

$$Moistuer\ content, wb\ (\%) = \frac{w_2 - w_3}{w_2 - w_1} \times 100 \qquad (1)$$

where, w_1 is weight of container with lid; w_2 is weight of container with lid and sample before drying; and w_3 is weight of container with lid and sample after drying.

Bulk density

The Bulk density for each material type was calculated using equation (2):

$$\rho_b = \frac{S_m}{V} \qquad (2)$$

Where, ρ_b is the bulk density, g cm^{-3}; S_m is the mass of the sample, g; and V is the volume of the sample, cm^3.

Dynamic repose angle

The dynamic angle of repose was determined using a funnel apparatus (Figure 2) clamped onto a stand. The funnel was carefully filled with an accurately weighed sample of Date Palm Pollen (*DPP*), carrier material, or their mixture (10 g) while keeping the funnel's throat closed. Once it is filled, the throat was fully opened to allow the powder to flow freely onto a circular plate of known diameter (d) positioned below the funnel. The powder formed a conical shape on the plate. The angle of repose (θ) was calculated using the height (h) and base diameter (d) of the powder cone according to equation (3) (Teferra, 2019):

$$\theta = Tan^{-1}\frac{2h}{d} \qquad (3)$$

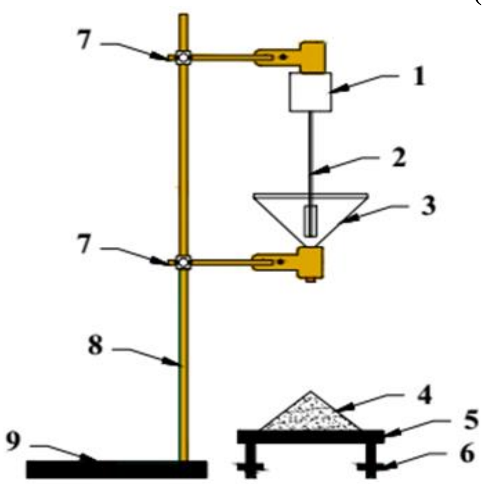

Fig. 2. Apparatus for measuring dynamic repose angle: 1- DC motor, 2- Plate carriage, 3- Funnel, 4- Followed material, 5- Horizontal plate, 6- Adjustable screw, 7- Clamp, 8- Stand, and 6- Base.

The flowability of the powders was assessed based on the measured angle of repose, with the flowability categories outlined in Table 2.

Table 2. Flowability indicators and categories of powder flow.

Description of flow	Angle of repose (degree)
Excellent/very free flow	25–30
Good/free flow	31–35
Fair	36–40
Passable	41–45
Poor/cohesive	46–55
Very poor/very cohesive	56–65
Very very poor approx non-flow	> 66

(Source: Pharmacopeia, 2006)

Dynamic coefficient of friction

The dynamic friction coefficient (μd) of each material type sliding on acrylic, polyvinyl chloride (*PVC*), aluminum, and stainless-steel surfaces was determined using the apparatus is shown in Figure 3. The constructed device consists of a vertically oriented hollow cylindrical container with open ends and an inner diameter of 3.2 cm, fixed at the center of a horizontal plate carriage measuring 26×13.5×4.5 cm and equipped with four roller wheels. The container's lower end is positioned very close to the tested material surface, maintaining a 1 mm clearance, and aligned above a 30 cm wide, 50 cm long material sheet without contact. The setup includes key components such as the sliding surface (material on which the sample slides), the plate carriage (a platform holding the cylindrical container), calibration masses (for adjusting the normal load), a hollow cylindrical container (holding the sample), powder material (the tested sample), roller wheels (for smooth movement), a hook (connecting the pulling mechanism), a hand wheel (to control motion), a test stand (supporting the structure), a small pulley (guiding the pulling wire), a wire (transmitting the pulling force), a force gauge (measuring the pulling force opposing friction), and a sliding ruler (sliding the head of the force gauge upper and down). The cylinder is partially filled with the sample, and a normal load compresses the sample against the tested surface. The combined mass of the sample, weights, and plate carriage is pulled horizontally by a steel rod connected to a digital force gauge (MARK-10, Model M3-10, USA) to measure the force required to counteract the dynamic friction and maintain motion. The dynamic coefficient of friction was calculated using equation (4) according to Marey et al., (2017):

$$\mu_d = \frac{F_f}{N_l} = \frac{F_T - F_E}{N_l} \qquad (4)$$

where μd is the dynamic coefficient of friction, F_f is the friction force (F_L=F_T-F_E) (N), *FT* is force required to start motion of filled wooden frame (N); *FE* is force required to start motion of empty wooden frame (N); and N_l is the normal load (weight) pressing the sample to the contact surface (N).

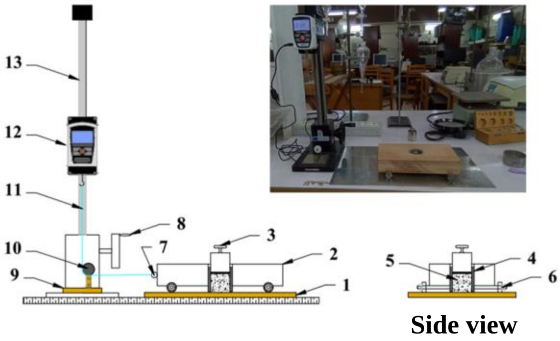

Fig. 3. Setup for measuring the dynamic friction force: 1-Sliding surface, 2-Plate carriage, 3-Calibration masses, 4-Hollow cylindrical, 5- Powder material, 6- Roller wheels, 7- Hook. 8-Hand wheel, 9- Test stand, 10- Small pulley. 11- Wire, 12- Force gauge, and 13- Sliding ruler.

Terminal velocity

The terminal velocity (V_t) of each material type was measured using the experimental setup shown in Figure 4. A vertical wind column equipped with a control system and a positive low pneumatic air pressure device was designed and manufactured at the Bioenvironmental Engineering Laboratory, Agricultural Engineering Department, Faculty of Agriculture, Cairo University, Egypt (Ibrahim et al., 2023). The air velocity was measured using a Lutron AM-4204 anemometer. The system includes a centrifugal fan powered by a Dayton 1/70 HP electric motor, with air velocity controlled by a digital switch/inverter connected to the blower motor for speed adjustments (Ibrahim et al., 2023). The setup consists of a cylindrical tube divided into three sections: the first section is a 200 mm long, 50 mm diameter PVC pipe with a grid at the top to ensure uniform airflow; the second section is a 700 mm long, 50 mm diameter PVC pipe ending in a perforated screen to hold pollen and featuring two 5 mm diameter holes for airspeed sensor installation; and the third section is a 900 mm long, 50 mm diameter transparent acrylic tube that allows observation of pollen particles in the air stream. The terminal velocity of the particles is determined by measuring the air velocity required to suspend the particles in the vertical flow, using a TENMARS TM-4001 hot wire anemometer with a velocity probe range of 0.01 to 25 m s^{-1}.

Color

Color parameters (*L**, *a**, *b**, *C** and *h*) of *DPP* and carrier materials powder were determined using Chroma meter KONICA MINOLTA CR-400 (φ 8, 5 VDC, 2.8 A , JAPAN).

Browning index *(BI)*, which gives an indication for browning of samples after drying, was calculated for powdered samples as:

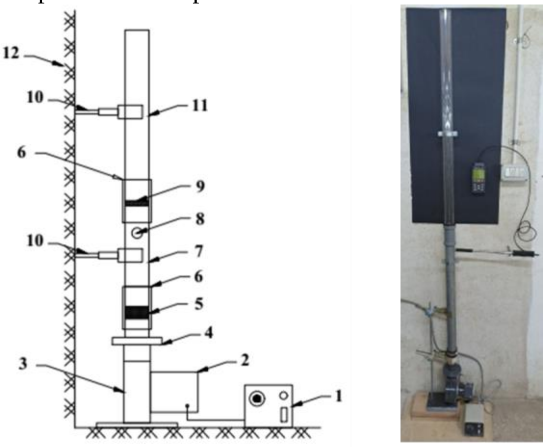

Fig. 4. Experimental set-up used for measuring the terminal velocity (1- Electrical controller, 2- Electrical motor and blower the base of motor, 3- Centrifugal fan, 4- First part, 5- Straighteners, 6- Collar, 7 -The second part, 8- A hole for air speed measurement, 9- Screen for placing samples, 10- Clamp, 11- Cylindrical transparent glass tube, and 12- The wall.).

$$BI = \frac{100\,(x-0.31)}{0.17} \quad (5)$$

$$x = \frac{a^{*}+1.75L^{*}}{5.645L^{*}+a-0.3012\,b^{*}} \quad (6)$$

Also, The Hue angle (h°) and Chroma or intensity (C*) were calculated according to the following equations:

$$h^{0} = arc\ \tan(\frac{b^{*}}{a^{*}}) \quad (7)$$

$$C^{*} = \sqrt{(a^{*2} + b^{*2})} \quad (8)$$

Results and Discussion

Moisture content

The moisture content of the carrier material used with date palm pollen grains varies widely. Date Palm Pollen (*DPP*) has the highest moisture content at 21.16%, followed by Male Spathe Flowers (*MSF*) at 18.32%, Banana Peels (*BP*) at 15.86%, Female Bunch Strands (*FBS*) at 15.54%, and Wheat Flour (*WF*) at 13.98%, with Wheat Bran (*WB*) having the lowest at 8.23%. Among the mixtures, *DPP+MSF* had the highest moisture content at 18.73%, followed by *DPP+BP* at 16.62%, *DPP+FBS* at 16.34%, *DPP+WF* at 15.01%, and *DPP+WB* at the lowest moisture content of 10.08%. These values highlight the varying moisture characteristics of each material and their combinations.

Bulk densities (ρd)

Figure 5 illustrates the bulk densities (*ρd*) of various materials used in this study, which range from 0.321 to 0.831 g cm^{-3}. Date palm pollen grains (*DPP*) showed the highest bulk density at 0.831 g cm^{-3}, while female bunch strands (*FBS*) had the lowest at 0.321 g cm^{-3}. Among the individual carriers, wheat flour (*WF*) had a bulk density of 0.534 g cm^{-3}, wheat bran (*WB*) was 0.371 g cm^{-3}, banana peels (*BP*) measured 0.474 g cm^{-3}, and male spathe flowers (*MSF*) had a value of 0.547 g cm^{-3}. In mixtures with *DPP*, the bulk density varied: *DPP+WF* at 0.522 g cm^{-3}, *DPP+WB* at 0.361 g cm^{-3}, *DPP+BP* at 0.414 g cm^{-3}, *DPP+MSF* at 0.538 g cm^{-3}, and *DPP+FBS* at 0.36 g cm^{-3}.

Bulk density is a crucial factor that significantly affects the performance of materials used as carriers for pollen grains, influencing storage efficiency, mixing consistency, and application uniformity. Higher bulk density materials, such as *DPP*, allow for more material to be stored in a smaller space, enhancing logistics and reducing costs (Ragué et al., 2022). However, high bulk density can also pose challenges in mixing and application due to potential flowability issues, leading to blockages in application equipment (Tomas and Kleinschmidt, 2009). In contrast, lower-density materials like *FBS* can improve aeration and ease of mixing but may result in uneven distribution during application. The interaction of bulk density with other physical properties, such as moisture content, impacts pollen adhesion and overall pollination efficiency (Lin et al., 2015). Materials like *BP*, *MSF*, and *FBS*, with moderate densities, are suggested by some researchers to be more suitable than *WF* and *WB* due to their balance between storage efficiency and flowability, which facilitates better pollen distribution (Ibrahim et al., 2023). However, opinions differ, as some studies highlight potential challenges with high-density materials in achieving uniform application (Tomas and Kleinschmidt, 2009). Therefore, selecting carriers with the correct bulk density is essential for optimizing date palm pollination effectiveness and achieving cost-efficient agricultural practices (Ibrahim et al., 2023; Ragué et al., 2022; DeVetter et al., 2022; Lin et al., 2015).

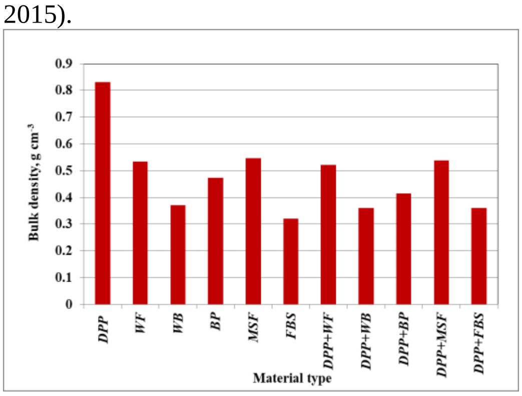

Fig. 5. The bulk density of the different materials (*DPP*: Date Palm Pollen grains, *WF*: Wheat Flour, *WB*: Wheat Bran, *BP*: Banana Peels, *MSF*: Male Spathe Flowers, *FBS*: Female Bunch Strands, *DPP+WF*: Date Palm Pollen grains + Wheat Flour, *DPP+WB*: Date Palm Pollen grains + Wheat Bran, *DPP+BP*: Date Palm Pollen grains + Banana Peels,

***DPP+MSF*: Date Palm Pollen grains + Male Spathe Flowers and *DPP+FBS*: Date Palm Pollen grains + Female Bunch Strands).**

Dynamic repose angle

Figure 6 shows the repose angles of various materials used in this study, ranging from 24 to 47 degrees. The wheat flour (*WF*) exhibited the highest repose angle at 47 degrees, indicating that it forms the steepest and least stable piles among the tested materials. On the other hand, the date palm pollen grains (*DPP*) had the lowest repose angle at 24 degrees, suggesting excellent flowability and stability. The repose angles of the other materials were as follows: wheat bran (*WB*) at 33 degrees, banana peels (*BP*) at 30 degrees, male spathe flowers (*MSF*) at 37 degrees, and female bunch strands (*FBS*) at 29 degrees. For mixtures, the repose angles were *DPP+WF* at 35 degrees, *DPP+WB* at 31 degrees, *DPP+BP* at 27 degrees, *DPP+MSF* at 32 degrees, and *DPP+FBS* at 26 degrees. These varying repose angles play a significant role in determining the suitability of each material as a carrier for date palm pollen grains, directly affecting how these materials behave during handling, storage, and application processes.

The repose angle is crucial for designing efficient systems for pollen application. A low repose angle, such as that observed in *DPP* and *DPP+FBS* mixtures, indicates good flowability, which is advantageous for uniform distribution during pollination. Materials with lower repose angles flow more easily, reducing the risk of blockages in applicators and ensuring that pollen is evenly distributed, which is critical for successful pollination and maximized yield. This is particularly important in mechanized pollination systems, where flowability can greatly influence the efficiency of the process. The low repose angle of *DPP* also suggests that it remains stable in storage, minimizing spillage and waste, and allowing for more controlled release during application. These properties are essential for maintaining the quality and effectiveness of the pollen, ensuring that it can be delivered precisely where needed.

Materials with higher repose angles, such as *WF*, tend to clump together and resist flow. This can complicate their use in pollination, as the material may not disperse evenly, leading to inconsistencies in pollen application. High repose angles indicate a steeper and less stable pile, which can pose challenges during both storage and application. *WF*'s high repose angle means that it is more prone to forming clumps, which can hinder the smooth flow through distribution equipment, potentially causing blockages that disrupt the pollination process. The higher repose angle also suggests that *WF* may require additional handling or mixing steps to break up clumps and ensure even distribution, increasing the complexity and cost of the pollination operation. The interaction between repose angle and other physical properties, such as bulk density and moisture content, further affects the performance of these materials as pollen carriers. For example, while *MSF* has a moderate repose angle of 37 degrees, its combination of good flowability and appropriate bulk density makes it a balanced choice for pollination applications. *MSF* provides a compromise between storage efficiency and flowability, supporting smooth distribution without significant risks of clumping or uneven application. On the other hand, *FBS*, with a repose angle of 29 degrees, offers good aeration and flow but may require careful calibration of application equipment to optimize pollen dispersal.

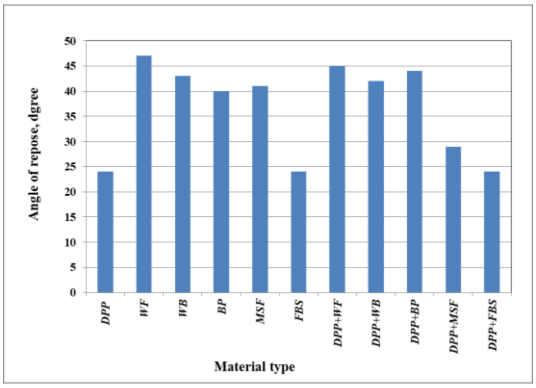

Fig. 6. The repose angle of the different materials (*DPP*: Date Palm Pollen grains, *WF*: Wheat Flour, *WB*: Wheat Bran, *BP*: Banana Peels, *MSF*: Male Spathe Flowers, *FBS*: Female Bunch Strands, *DPP+WF*: Date Palm Pollen grains + Wheat Flour, *DPP+WB*: Date Palm Pollen grains + Wheat Bran, *DPP+BP*: Date Palm Pollen grains + Banana Peels, *DPP+MSF*: Date Palm Pollen grains + Male Spathe Flowers and *DPP+FBS*: Date Palm Pollen grains + Female Bunch Strands).

Supporting literature highlights the importance of selecting materials with appropriate repose angles for effective pollination. Zaalouk and Zabady (2009) found that lower repose angles enhance the uniformity of pollen application, leading to improved pollination efficiency and better crop yields. This finding is echoed by Stein et al. (2017), who noted that materials with lower repose angles are particularly advantageous in mechanized pollination systems due to their superior flow characteristics, which help maintain consistent application rates and reduce equipment downtime caused by clogs. Furthermore, Lin et al. (2015) emphasized that using materials with optimal flow properties can reduce the overall costs of pollination by minimizing wastage and improving application precision.

However, there are differing opinions on the best repose angle for pollen carriers. Al-Hashemi and Al-Amoudi (2018) argued that while low repose angles improve flowability, they can also increase the risk of excessive wastage, especially under windy conditions in open-field pollination settings.

The ease of flow might lead to unintended dispersal, reducing the efficiency of pollen application and necessitating more precise control measures. DeVetter et al. (2022) also pointed out that materials with high flow rates might require careful equipment calibration to avoid over-application, which could lead to resource inefficiency and increased costs. The repose angle is a critical factor in determining the performance of materials used as carriers for date palm pollen grains. It directly influences how these materials behave during storage, handling, and application, impacting the overall efficiency and effectiveness of the pollination process. Materials with low repose angles, such as *DPP* and *DPP+FBS*, offer superior flowability and stability, promoting even distribution and reducing the risk of blockages. However, selecting the right repose angle must balance the benefits of flowability with the need to minimize wastage and ensure precise application, making it a key consideration in the design of effective pollination systems. Understanding these interactions helps optimize the use of different materials in agricultural practices, supporting better pollination outcomes and more cost-effective operations.

Dynamic coefficient of friction

The average values of the dynamic coefficient of friction for Date Palm Pollen grains (*DPP*), Wheat Flour (*WF*), Wheat Bran (*WB*), Banana Peels (*BP*), Male Spathe Flowers (*MSF*), and Female Bunch Strands (*FBS*) on four different surfaces—acrylic, PVC, aluminum, and stainless steel—are shown in Figure 7. It's clear that the dynamic coefficient of friction varies significantly across different materials and surfaces. On the acrylic surface, the highest friction value was observed with Female Bunch Strands (*FBS*) at 0.568, indicating significant resistance to movement. This high friction is likely due to the fibrous nature of FBS, which increases surface interaction. In contrast, Wheat Bran (WB) exhibited the lowest friction at 0.121, suggesting smoother interaction with the acrylic surface, likely due to its less complex structure. Other materials showed moderate friction values, with Male Spathe Flowers (MSF) at 0.328 and Wheat Flour (WF) at 0.302, having higher friction than Date Palm Pollen grains (DPP) at 0.144 and Banana Peels (BP) at 0.176. These differences could be attributed to variations in texture, particle size, and the physical properties of the materials.

On PVC, the highest friction was noted with FBS at 0.769, consistent with its performance on acrylic. Date Palm Pollen grains (DPP) also showed a relatively high friction value of 0.472, likely due to its small and cohesive particles increasing surface adhesion. In contrast, MSF had the lowest value at 0.118, possibly due to reduced surface contact caused by its structural properties. The moderate values of WF at 0.212, WB at 0.42, and BP at 0.257 reflect variations in their physical characteristics and surface interactions.

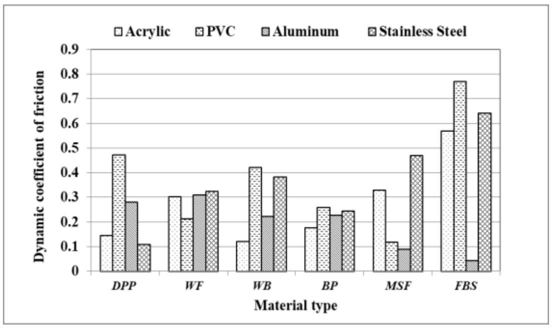

Fig. 7. The dynamic coefficient of friction of the different materials (*DPP*: Date Palm Pollen grains, *WF*: Wheat Flour, *WB*: Wheat Bran, *BP*: Banana Peels, *MSF*: Male Spathe Flowers and *FBS*: Female Bunch Strands).

Friction values on the aluminum surface varied significantly, with *FBS* recording the lowest value at 0.043, suggesting minimal interaction, likely due to its structural composition. *MSF* also had a low friction value at 0.089. The highest values were noted for *WF* at 0.308 and *WB* at 0.222, indicating that finer and more fibrous materials tend to interact more with metallic surfaces, leading to increased friction. *DPP* and *BP* had similar moderate values at 0.28 and 0.227, respectively, highlighting their intermediate behavior on this surface.

On stainless steel, *FBS* again showed high friction at 0.641, consistent with its tendency to interact strongly with most surfaces tested. *MSF* also had a relatively high friction value at 0.47. The lowest friction was seen with *DPP* at 0.109, indicating smooth movement and reduced interaction on this surface. The friction values of *WB* at 0.381, *BP* at 0.243, and *WF* at 0.324 show that these materials exhibit varying degrees of interaction, possibly influenced by their texture and moisture content.

The variation in friction coefficients across different surfaces and materials reflects the complex interplay between material properties and surface characteristics. Fibrous and coarse materials like *FBS* generally show higher friction due to increased surface contact and mechanical interlocking. Conversely, finer or less textured materials such as *DPP* and *BP* exhibit lower friction, indicating smoother interactions with the surfaces. These findings highlight the importance of considering material properties in applications where friction plays a crucial role, such as in handling and processing systems.

Figure (8) Also, shows the dynamic coefficient of friction of various material mixtures (*DPP+WF*: Date Palm Pollen grains + Wheat Flour, *DPP+WB*: Date Palm Pollen grains + Wheat Bran, *DPP+BP*: Date Palm Pollen grains + Banana Peels, *DPP+MSF*: Date Palm Pollen grains + Male Spathe Flowers, and *DPP+FBS*: Date Palm Pollen grains + Female Bunch Strands) on four different surfaces:

acrylic, *PVC*, aluminum, and stainless steel. It is clear that the dynamic coefficient of friction varies significantly across the mixtures and surfaces. On the acrylic surface, the highest friction was observed with *DPP+FBS* at 0.422, likely due to the rough texture and fibrous nature of the FBS, which enhances surface interaction. In contrast, *DPP+MSF* exhibited the lowest friction at 0.153, suggesting smoother movement and reduced interaction, possibly due to the lower surface area contact and finer particles. Other mixtures, such as *DPP+WF* (0.374) and *DPP+WB* (0.193), showed moderate friction values, indicating balanced interaction between their components and the acrylic surface.

On the *PVC* surface, *DPP+WB* recorded the highest coefficient at 0.656, reflecting significant resistance, possibly due to the structural complexity and adhesion properties of *WB*. In contrast, *DPP+BP* exhibited the lowest friction at 0.076, indicating a very smooth interaction likely attributed to the softer, more pliable nature of *BP*, which reduces surface contact. These findings align with those reported by Abdelzaher et al. (2022) who found that organic mixtures with smoother components exhibited lower friction on synthetic surfaces, enhancing ease of movement. Conversely, other researchers like Abdelhady et al. (2023) suggested that mixtures containing fibrous elements generally have increased friction due to mechanical interlocking with rough surfaces.

On aluminum, *DPP+FBS* showed a relatively high friction value of 0.425, suggesting robust interaction between the fibrous strands and the metallic surface. Meanwhile, *DPP+BP* had the lowest friction at 0.021, reinforcing the observation that banana peels reduce friction due to their soft texture and low rigidity. The results are consistent with the work of Abdelzaher et al. (2022), who noted that mixtures containing smooth, pliable materials tend to exhibit lower friction coefficients on metallic surfaces. *DPP+WF* and *DPP+WB* showed intermediate friction values at 0.448 and 0.362, respectively, reflecting moderate interactions influenced by the physical characteristics of wheat-based materials.

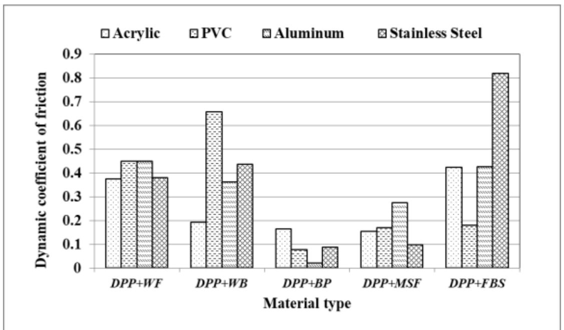

Fig. 8. The repose angle of the different materials (*DPP+WF*: Date Palm Pollen grains + Wheat Flour, *DPP+WB*: Date Palm Pollen grains + Wheat Bran, *DPP+BP*: Date Palm Pollen grains + Banana Peels, *DPP+MSF*: Date Palm Pollen grains + Male Spathe Flowers and *DPP+FBS*: Date Palm Pollen grains + Female Bunch Strands).

On the stainless-steel surface, the highest friction was noted for *DPP+FBS* at 0.817, aligning with its consistently high values across different surfaces due to its fibrous and abrasive nature, which enhances surface grip. In contrast, *DPP+MSF* and *DPP+BP* had significantly lower friction values at 0.098 and 0.087, respectively, indicating minimal interaction with the stainless steel surface. These findings are in line with Lu (2006), who reported that mixtures with smoother and less fibrous components generally perform better in terms of reduced friction on steel surfaces. The results suggest that the choice of mixture for pollination processes can greatly impact efficiency, as materials like *DPP+BP* consistently exhibit lower friction across surfaces, facilitating smoother movement and potentially enhancing pollination effectiveness. In contrast, mixtures containing fibrous components like *DPP+FBS*, while effective in certain applications, may encounter increased resistance that could affect performance in specific environments. Thus, selecting the appropriate mixture based on surface type and desired friction characteristics is crucial for optimizing pollination efficiency.

Terminal velocity

The terminal velocity values for various materials used in pollination, including Date Palm Pollen grains (*DPP*), Wheat Flour (*WF*), Wheat Bran (*WB*), Banana Peels (*BP*), Male Spathe Flowers (*MSF*), Female Bunch Strands (*FBS*), and their mixtures with *DPP*, are presented in Figure 9. It is clear that the *DPP* alone has a terminal velocity of 0.96 m s^{-1}, which is moderate compared to other materials, indicating balanced aerodynamic properties suitable for pollination. *WF* exhibited a lower terminal velocity of 0.51 m s^{-1}, suggesting lighter and more aerodynamic particles that settle slowly, potentially increasing dispersion time in the air. On the other hand, *WB* had the highest terminal velocity at 1.77 m s^{-1}, indicating denser and less aerodynamic particles that settle quickly, making it less suitable for prolonged airborne dispersion in pollination. Similar observations were reported by Niklas (1985), who noted that heavier particles with higher terminal velocities are less effective in achieving wide pollination coverage.

BP, with a terminal velocity of 0.98 m s^{-1} m s^{-1}, shows comparable behavior to *DPP*, suggesting it can be an effective carrier , enhancing pollen dispersion without significantly altering the dynamics. MSF and *FBS* showed velocities of 0.68 m s^{-1} and 0.46 m s^{-1}, respectively, highlighting the influence of their fibrous and lightweight structures, which enhance floating time and increase the chances of reaching target flowers. The combination of *DPP+WF* retained the same terminal velocity as *DPP* alone (0.96 m s^{-1}), indicating minimal impact on aerodynamic performance. This suggests that the addition of *WF* does not hinder the movement and settling behavior of *DPP*, supporting the findings of Timerman and Barrett (2021), who suggested that lighter carriers can enhance pollen stability without compromising dispersal efficiency.

The mixture of *DPP+WB* maintained the highest velocity (1.77 m s^{-1}), reinforcing the earlier observation of *WB*'s dense characteristics. This combination may not be ideal for maximizing pollination spread, as supported by Borrell (2012), who argued that higher terminal velocities reduce the suspension time of pollens, leading to quicker settling and limited reach. In contrast, the *DPP+BP* mixture showed a slight increase in terminal velocity to 1.02 m s^{-1}, suggesting a beneficial effect of *BP* in enhancing structural stability and aerodynamic properties while maintaining good dispersal potential.

DPP+MSF exhibited a terminal velocity of 1.5 m s^{-1}, indicating that the fibrous structure of MSF slightly increases the velocity, which may aid in targeted dispersion rather than widespread coverage. Meanwhile, *DPP+FBS* recorded a significantly lower terminal velocity of 0.6 m s^{-1}, highlighting its potential for maximizing airborne time and reach, which could be advantageous in enhancing pollination efficiency in broader areas. This observation aligns with the findings of Sofiev (2013), who emphasized the benefits of low terminal velocity in increasing the spatial distribution of pollens.

The results suggest that the best mixtures for pollination processes are those that maintain low to moderate terminal velocities, such as *DPP+BP* and *DPP+FBS*, as they offer extended suspension time and improved coverage. The findings emphasize the importance of selecting carriers that complement the aerodynamic properties of *DPP* without significantly increasing terminal velocity, thereby enhancing the overall effectiveness of the pollination process.

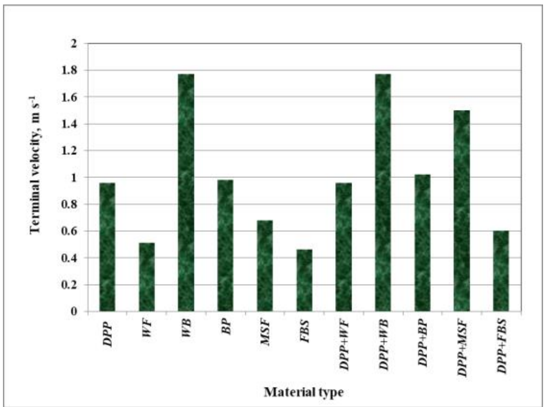

Fig. 9. Terminal velocity of the different materials (*DPP*: Date Palm Pollen grains, *WF*: Wheat Flour, *WB*: Wheat Bran, *BP*: Banana Peels, *MSF*: Male Spathe Flowers, *FBS*: Female Bunch Strands, DPP+WF: Date Palm Pollen grains + Wheat Flour, *DPP+WB*: Date Palm Pollen grains + Wheat Bran, *DPP+BP*: Date Palm Pollen grains + Banana Peels, *DPP+MSF*: Date Palm Pollen grains + Male Spathe Flowers and *DPP+FBS*: Date Palm Pollen grains + Female Bunch Strands).

Color

The color parameters; lightness (*L**), redness (*a**) and yellowness (*b**) were expressed in Table 3 accordance with the CIELab color space. The average L* value for all the carrier samples of powder varied from 35.74 to 88.72, which indicated a substantial difference between lightness values of samples. The results show a significantly higher luminosity (*L**) of the *WF, WB, DPP+WF, DPP, DPP+FBS, MSF, DPP+MSF, FBS* due to particle size reduction. The *a** parameter (green-red) values obtained for the different samples were in the positive range, indicating a red component, although to limited values. The BP and *DPP+BP* samples scored higher a* values due to anthocyanin content and the heat produced during drying process. In the case of *b** parameter (blue-yellow), all showed higher in range than the *a** values.

Also, the color change direction is defined by hue angle hº, the chromatic aberration model containing whole color parameter, for carrier materials hue angle ranged from 0.22º to 0.53º. Table (3) shows that the maximum values of hue angle were 0.53, 0.51, 0.47, 0.45 and 0.44º for WF, DPP+BP, BP, WB and DPP+WB, respectively. Larger values of hue angle signify more shift from red hue to yellow hue. Lowest hue angle value was 0.22º for DPP, on other hand, hº decreased by adding DPP to WF and WB, but for BP, MSF and FBS materials the hue angle values increased be adding DPP.

Table 3. The color space CIE of the date palm pollen grainsand different carrier materials.

	Color space CIE					
Carrier material	*L**	*a**	*b**	*BI*	*h°*	*C**
DPP	67.22	3.16	13.88	5.41	0.22	14.24
WF	88.72	4.47	7.56	4.43	0.53	8.78
WB	66.71	7.37	21.21	11.01	0.45	24.41
BP	35.74	11.07	21.89	27.63	0.47	24.53
MSF	63.25	7.86	19.64	11.89	0.38	21.16
FBS	59.76	7.40	20.77	12.24	0.34	22.05
DPP+WF	85.78	3.75	9.81	4.25	0.37	10.50
DPP+WB	64.33	7.97	20.09	11.89	0.44	24.4
DPP+BP	39.91	9.22	16.48	20.25	0.51	18.88
DPP+MSF	60.83	7.05	16.96	10.87	0.39	18.37
DPP+FBS	64.12	6.50	17.77	9.96	0.35	18.92

DPP: Date Palm Pollen grains, *WF*: Wheat Flour, *WB*: Wheat Bran, *BP*: Banana Peels, *MSF*: Male Spathe Flowers, *FBS*: Female Bunch Strands, DPP+WF: Date Palm Pollen grains + Wheat Flour, *DPP+WB*: Date Palm Pollen grains + Wheat Bran, *DPP+BP*: Date Palm Pollen grains + Banana Peels, *DPP+MSF*: Date Palm Pollen grains + Male Spathe

Flowers and *DPP+FBS*: Date Palm Pollen grains + Female Bunch Strands

Conclusions

The study evaluated the some properties of various materials used in the pollination of date palms, focusing on bulk density, dynamic repose angle, and dynamic coefficient of friction. These properties are critical for selecting the best material mixtures for efficient and effective pollen application. The bulk density results showed that date palm pollen grains (*DPP*) had the highest density, making them suitable for storage and handling but potentially challenging for flowability during application. Lower-density materials like Female Bunch Strands (*FBS*) provide good aeration and ease of mixing, though they may not distribute as uniformly. The repose angle results indicated that materials like *DPP* and *DPP+FBS* mixtures have lower repose angles, signifying excellent flowability, which is advantageous for uniform pollen distribution during pollination. In contrast, wheat flour (*WF*) had the highest repose angle, leading to clumping and uneven application, highlighting the importance of selecting materials with optimal flow properties for mechanized pollination systems. Dynamic coefficient of friction tests across various surfaces revealed that fibrous materials such as *FBS* had higher friction values, leading to potential challenges in handling and distribution. In contrast, *DPP* and Banana Peels (*BP*) exhibited lower friction, indicating smoother interactions with surfaces, which is beneficial in reducing blockages and ensuring consistent application.

Thus, the study emphasizes the importance of selecting materials with suitable physical, mechanical, and aerodynamic characteristics to optimize the pollination process. Mixtures like *DPP+FBS* and *DPP+MSF* offer balanced characteristics, combining good flowability and manageable friction levels, making them ideal choices for effective date palm pollination.

Consent for publication:

All authors declare their consent for publication.

Author contribution:

The manuscript was edited and revised by all authors.

Conflicts of Interest:

The author declares no conflict of interest.

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