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Review Article

Advances in Pollen Biology, and Pollination Strategies for Date Palm: A Review

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ABSTRACT

Date palm (*Phoenix dactylifera* L.) is an economically important dioecious plant relying on viable pollen for ideal fertilisation. This investigation analyses the influence of pollen viability, germination, and storage on enhanced pollination efficiency. Genetic diversity, environmental factors, and storage techniques influence pollen viability. Storage conditions significantly affect pollen viability; pollen stored at -30°C maintains higher viability than at 4°C or 28°C. The viability and nuclear integrity of stored pollen have been further proved through the acetocarmine test. Drone-assisted pollination has shown potential as an effective method, enabling large-scale and precise pollen application, though further research is needed to confirm its efficiency in date palm cultivation. Biotechnological methods, like genetic engineering and transcriptomic analyses, have enhanced pollen viability, stress resistance, and overall quality. Additionally, the advancement in pollen storage techniques has prolonged viability, boosting fertilisation potential. The breeding strategies focusing on genetic diversity and marker-assisted selection have optimised pollination efficiency and improved crop resilience. The metaxenic effects of diverse pollen sources were also examined, revealing significant impacts on fruit size and quality, with notable variations depending on the pollen source. The analysis emphasises the importance of modern pollination techniques and their integration with conventional pollen management to improve the fruit yield and quality of date palm.

Keywords: *Date palm, storage condition, acetocarmine test, pollen viability, pollination, fruit set, date palm cultivation.*

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INTRODUCTION

Date palm (*Phoenix dactylifera* L.; 2n = 36) is a monocotyledonous and dioecious plant belonging to Arecaceae and native to northern Africa and the Middle East. It is an economically and culturally significant crop in many arid regions. The Arecaceae family comprises over 200 genera and approximately 500 species of palms and related plants (Maryam et al., 2023). The yield of date palms primarily relies on the percentage of fruit set within the racemes. This is influenced by various determinants such as the source and quality of date palm pollen, the pollination period, the pollination method, female-male compatibility, and environmental factors including temperature, fertilization, irrigation and soil characteristics. Naturally, date palm pollination occurs through wind dispersal. However, for commercial production, it is necessary to manually pollinate the date palms. Farmers typically select the pollen extraction technique that yields the best results. One healthy and fully grown male date palm can pollinate approximately 50 female palms (Salhi et al., 2024).

Parthenocarpy in date palms is rare and usually results in underdeveloped fruits. Wind pollination alone often leads to incomplete fertilization, not true parthenocarpy (Salomón-Torres et al., 2021; Radwan et al., 2022a). Date palm reproduction depends entirely on precise pollination, a complex process further complicated by their dioecious nature. Individual date palms develop solely as either male or female, with males bearing the pollen and females blossoming with flowers which will eventually cradle the ripening fruit. The commercial date production relies on the manual transfer of pollen from male to female flowers, optimizing fruit formation and yield. Once pollination is successful and fertilization occurs, that leads to floral development and fruit maturation. The mature date contains a seed, which can grow into a new date palm when planted, sustaining the life cycle (Ali-Dinar et al., 2021).

Pollination efficiency is affected by many factors, such as pollinator type, environmental conditions, and the pollination period (Radwan et al., 2022b). The pollen quality is a key factor for successful pollination and fruit development. Studies have shown the impact of pollen storage temperature and duration on pollen viability and the need for optimal conditions for

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maintaining high germination rates (Kadri et al., 2022). The assortment of hereditary variety among male date palm cultivars can impact pollen qualities. Various cultivars exhibit differences in terms of phenolic mixes and flavonoids, which can affect the quality of organic products and pollen execution (Shahsavar and Shahhosseini, 2022; Karim et al., 2022a). The choice of suitable male cultivars for dusting can enhance the fruit set and yield of date palms (Gadalla, 2021). Different techniques have been developed to build the productivity of pollen exchange in date palms. Conventionally, specialists would physically climb the trees and apply pollen specifically to the female blooms. However, this approach had been laborious and had never brought about the ideal results (Rehna, 2024). Studies have demonstrated that utilizing drones for dusting can significantly diminish work expenses and time while keeping up viable dusting rates (Alyafei et al., 2022). This strategy permits pollen application over vast territories in a quick and proficient way, making it an encouraging choice to conventional strategies. Other fluid dusting techniques have additionally been considered, including applying pollen in a fluid medium. This strategy has been shown to guarantee improvements in natural product yield and quality, particularly for specific cultivars (Munir, 2020).

Environmental conditions play a crucial role in the success of pollination in date palms. Factors such as temperature, humidity, and flowering time can significantly influence pollen viability and the receptivity of female flowers (Zahiri, 2023). For instance, studies have indicated that lower temperatures during the pollination period can enhance the development of parthenocarpic fruits, which may be beneficial under certain conditions (Karim, 2022). Moreover, the interaction between pollinators and environmental factors is complex. The presence of diverse pollinator species can enhance pollination efficiency, while adverse environmental conditions may reduce pollinator activity (Gintoron, 2023). Understanding these interactions is essential for developing effective pollination strategies and ensuring the sustainability of date palm cultivation.

POLLEN ULTRASTRUCTURE

Date palm pollen plays a vital part in the reproduction of the date palm tree. This plant species exhibits dioecy, with male and female flowers occurring separately. The morphology and composition of date palm pollen are uniquely defined in ways that enable its functions in fertilisation and diverse applications. Date palm pollen grains exhibit spherical to ellipsoidal shapes, typically measuring between 20 and 50 µm (Mosquera et al., 2021). A complex exine coating of sporopollenin, a protective biopolymer, encases the genetic material within each grain. This robust casing ensures viability despite transport and facilitates germination upon reaching a compatible female flower (Mosquera et al., 2021). Undeniably, surface features on date palm pollen grains vary among genotypes, as characterised by their smooth exteriors and assorted markings. Such distinguishing traits likely serve recognition and adhesion roles during pollination through interactions with stigma tissues (Zhang et al., 2020). Moreover, the internal constitution includes an abundance of cytoplasmic organelles that fuel metabolic activities essential for pollen tube growth. Date palm pollen possesses significance not only from structural viewpoints but also due to its rich biochemical compositions. An array of nutrients like carbohydrates, proteins, lipids, vitamins and minerals endow it with nutritional value. Specifically, proteins and fatty acids, flavonoids, saponins, and more provide health benefits related to fertility and antioxidation. Carotenoids and flavonoids notably contribute antioxidant effects combatting oxidative stress. This protective capacity relates directly to medical uses, examining pollen's ability to prevent toxicity induced in various organs (Lamo, 2024). Preserving pollen viability proves critical to fertilization success. Moisture content and storage methods heavily impact the viability over time. Optimal moisture levels around 4.2±0.4%, coupled with appropriate desiccation like salt solution drying, sustain quality during storage, as shown in previous work. Traditional techniques have served to maintain pollen grain quality for agricultural purposes (Fig. 1).

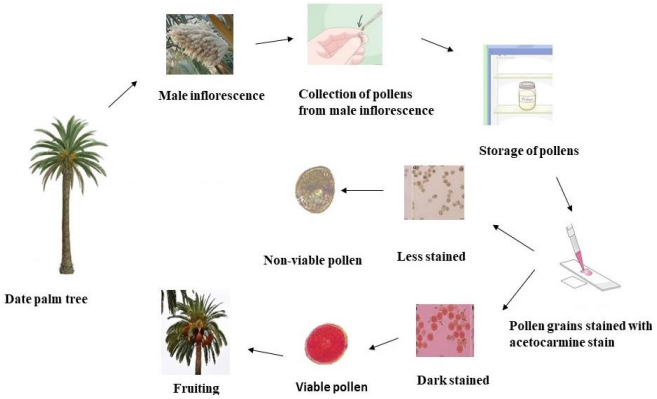

Figure 1: Illustrates the process of collecting pollen from male inflorescences, storing it, and assessing its viability using acetocarmine staining.

POLLEN STORAGE

Pollen storage remains pivotal for seed-bearing flora as plant breeders refine crops and blooms through selective cultivation. The dynamism of pollen grains proves integral to cross-pollination success and subsequent fruit germination. Prior analysis surveyed the impacts of fluctuating conditions on pollen viability, the propensity of grains to germinate, and overall quality. Temperature during pollen storage plays a substantial role in sustaining viability for extended durations. Research has indicated that cooler storage temperatures typically lengthen pollen longevity more so than warmer alternatives. One study uncovered that pollen stored at -20°C and -80°C demonstrated a viability decline ranging from 32% to 69% following one year, with the fewest viable grains detected at -80°C rather than 0°C or -20°C. Further investigations may refine our understanding of optimal storage methods (Özcan, 2020). Pollen stored under colder, drier conditions maintained its vitality, indicating the importance of optimal storage environments for preserving pollen viability. In contrast, storage at higher temperatures, such as 25°C, resulted in rapid deterioration of pollen quality, highlighting the detrimental impacts of elevated temperatures on pollen longevity (Korkut et al., 2022).

Investigations showed that pollen's original water volume

Table 1: Effect of room temperature storage (23 - 30°C) on pollen viability and quality.

Storage temp.	Storage period	Effect	Reference
23°C	2 hours	Highest germination (60 ± 2%).	de Oliveira et al. (2021)
30°C	4h	71.11% pollen germination.	Munir (2021)
25-30°C	16 months	Pollen viability and successful germination were found to steadily decline the longer the storage lasted.	Kumawat et al. (2022)
23-25°C	6 months	Pollen viability was significantly reduced; germination rates decreased compared to fresh pollen.	Kadri and Mimoun (2020a)
25-30°C	1 year	Reduced pollen viability, germination, and fruit-setting percentages negatively impacted yields, bunch weights, and fruit quality when the least effective storage method was utilized.	Ahmed (2021)

heavily influences longevity potential, with pollen containing less loose moisture being more enduring over time (Du et al., 2019). For instance, Pollen moisture substantially impacted the longevity and germination potential at old storage around 0°C for very damp pollen (Boleček et al., 2021). Moisture levels and temperature are pivotal determinants of pollen germination capacity and growth (Du et al., 2019). Storage time also considerably influences pollen viability. The germination ability of pollen progressively decreased over time in storage, reaching a minimum after three months (Perveen and Ali, 2019). Cryopreservation has emerged as a practical method for long-term pollen storage, especially for certain plant species necessitating supplementary pollination in breeding initiatives. Stored pollen maintained high viability and germination rates for up to a year. However, fresh pollen generally results in higher fertilization efficiency and fruit quality. This technique is especially helpful for types exhibiting asynchronous blooming times, permitting conservation of genetic information for potential exploitation in the future. Pollen maintained excellent viability and germination, even after twelve months of freezing, guaranteeing high-quality produce when used to fertilize blooms (Borghezan et al., 2011).

POLLEN VIABILITY

Pollen viability in date palms proves pivotal for fertilization success and bountiful harvests (Althiab-Almasaud et al., 2024). The tiny male gametophyte, pollen, has evolved to transport sperm cells to the distant female gametophyte for fertilization through pollen tube elongation, leading to the copious fruits and seeds that form the foundation of the human diet (Mesnoua et al., 2024). To exchange the genetic heritage between distinctive individuals, pollen must remain resilient in the environment for diverse periods that widely differ among species, whether briefly, from minutes to days, moderately, from one to three months, or substantially, over six months. The competence of the pollen grain to endure in the environment while still maintaining its capacity to germinate and develop a pollen tube on a receptive stigma or pistil is known as pollen viability (Merwad et al., 2015). This pollen tube bears its payload of sperm cells to the ovule, where fertilization launches the growth of seed and fruit. The fundamental factors for the dissemination of plant varieties in nature depend on the collection, storage, and transportation of pollen to develop new hybrids, and farmers' livelihoods are reliant on high fruit yields, all dependent on the viability, longevity, and potency of the pollen tube (Althiab-Almasaud et al., 2024).

In another study, eleven male date palms were closely inspected, finding their potential, as P169 demonstrated an exceptional 86.3% sprouting rate. The selection of pollen sources notably affects fruit set and quality, pinpointing the need for proficient pollinators. Some varieties contributed vigorous, hardier pollen in comparison, while fluctuating climates or deficient protection might deteriorate pollen potency prior to use. Therefore, the industrious date growers are trying their best to maximize conditions conducive for robust pollination and high yields, understanding variances in pollen sources, climate changes, and proper safekeeping influenced success (Kadri et al., 2024). Temperature greatly influences the sprouting of pollen. Pollen grains held at 30 degrees Celsius showed a robust sprouting rate of over 81%, whereas cooler temperatures greatly weakened the viability. The pollens collected from spathes unfolding later within the season sprout more readily than those harvested from spathes opening earlier in the flowering cycle (Munir, 2021). While the germination potential and longevity of various pollen types differed greatly, the impact extended beyond viability. Australian selections outperformed after storage, with the standout "Tanunda" maintaining over 60% germination, notwithstanding the passage of seasons. Metaxenic influences lionized dissimilar sources, their pollen print shaping yield as well as delicate fruit qualities (Al-Najm et al., 2021).

According to Munir (2021) findings, great diversity exists among date palm pollen germination habits. Pollen incubated at warmer 30°C and 25°C exhibited the highest percentages of 81.07 and 78.17, respectively. A drop to 10°C saw a considerable slowing to a meagre 5.90, demonstrating temperature's importance. Time played a role in a full 71.11 percent sprouting after just 4 hours at 30 degrees, but shorter or longer durations decreased this to 63.26 and lower. The palms proffered their flowering structures, spathes, at varying points. Those presenting earliest far underperformed with only 57.58 percent viability, while later ones boasted much higher germination and up to 91.53% for mid-season spathes. Clearly, date palm pollen thrives under warm conditions yet allows brief germination windows. Both 25 and 30 degrees facilitated maximal sprouting within 4 hours alone. While early contributors offered the greatest quantity, later periods' pollen consistently proved the highest quality for fertilising palms (Table 1).

Acetocarmine test

Acetocarmine stains reveal life through colour, with stained

grains under the microscope showcasing nuclear integrity, indicating pollination potential. Researchers find this test effectively verifies genetic vigour, a clear sign of the capacity to conceive. Studies prove the process clarifies, distinguishing pollen with the stamina to germinate, to nurture burgeoning branches with new growth, flourishing wherever rainfall relents (Mosquera et al., 2021). While the nucleus is crucial for germination and fertilization success, ensuring pollen viability relies upon a delicate balance. Environmental influences heavily impact viability, as demonstrated through varying storage conditions and their effects on germination rates. Studies found that pollen preserved at subzero temperatures significantly outperformed counterparts held at above-freezing levels, highlighting storage method intricacies. The nucleus integrity test remains a mainstay of research and agriculture, chiefly as it affords insight into the interplay between external factors and pollen's inner functions governing plant propagation (Al-Najm et al., 2021). Maintaining this monitoring's critical role will further illuminate pollen's vulnerabilities and potentials under different conditions (Lamo, 2024).

Indeed, the acetocarmine test has frequently provided insights into pollen viability from an assortment of date palm cultivars through diverse investigations. For example, one significant examination directed in Tunisia evaluated the practicality of pollen from various geological locales and found critical contrasts in germination rates. This emphasized the way ecological contrasts and hereditary assorted qualities can influence the achievement of pollination and yield creation. Nevertheless, the previous research did not consider the impact of distribution on cultivar health and diversity. It remains a challenge for future studies to ensure the sustainability of this vital industry by considering these factors and maintaining a diverse and resilient range of cultivars. The success of pollination and enduring agriculture will depend on understanding how to support distribution and genetic diversity (Kadri and Mimoun, 2020b). This variability proves pivotal for cultivation campaigns focused on boosting produce and calibre. Additionally, acetocarmine screening, TTC trials (triphenyl tetrazolium chloride) screening and Alexander's stain have been helpful in generating a thorough evaluation of pollen viability (Buchner et al., 2022).

***In vitro* germination of pollen**

Date palm pollen germination holds potential for advancing propagation techniques and species protection. Carefully calibrated conditions are crucial to coaxing pollen grains to sprout and proliferate in the lab setting, outside natural pollination events. Scientists have long probed the particulars of temperature, moisture content, and supplemental nutrients to flourish under artificial circumstances. Previous work uncovered that the tailored blending of growth factors can substantially boost success rates, with some mixtures facilitating remarkably strong outcomes. In parallel research, the degree of humidity was identified as particularly consequential, with paltry margins for error and pollen acutely responsive to deviations beyond those boundaries. Continuous questing is underway for customised formulations that achieve equilibrium, maximising rates through conscientious environmental stewardship while retaining the exquisiteness befitting life's earliest phases (Kadri and Mimoun, 2020b). Furthermore, the duration of pollen storage before germination is another critical factor. Pollen stored for extended periods often exhibits reduced viability (Table 2 and 3), which can be mitigated by employing proper storage techniques, such as cryopreservation (Lamo, 2024). This multifaceted approach has dependably maintained the hereditary material of pollen intact, permitting thriving sprouts even after extended safekeeping. Illuminating cell-based germination research additionally uncovered inner functions of the natural cycles overseeing pollen budding. For case, specific starches and turn of events components inside the sprouting condition were found to energetically incite pollen tubing development and augment fertility limit, while other compound blends were discovered to hinder or defer sprout headway through the style and ovary. In an unexpected way, under unexpected temperature and dampness situations, pollen grains showed changed germination paces and tubing development rates, uncovering the powerlessness of these establishing instruments to natural inconsistencies (Munir, 2021).

Other research has demonstrated that amino acids can decidedly or contrarily impact sprouting, while certain proteins intervene

Table 2: Effect of refrigeration storage (4-7°C) on pollen viability and quality.

Storage Temperature	Storage duration	Effect	Reference
4°C	4 months	Pollen quality decreased, but better viability retention at 4°C.	Karim et al. (2022b)
5°C	12 months	The viability of pollen increased.	Sharma et al. (2024)
		For cultivars, Ghers and Mech Deglet, larger fruits with high moisture content (23.96%).	Mohammed et al. (2024)
		Pollen stored at 5°C showed decreased viability over time	Sharma et al. (2024)
5-7°C	1 year	Improved pollen viability and germination.	Ahmed (2021); Zahiri et al. (2023)
4°C	1 year	Better retention of pollen viability; germination rates remain higher than those in room temperature storage.	Kadri and Mimoun (2020a)
	3 years	Significant variation between fresh and stored pollen.	Ahmed (2021)
5°C	8 days	Significant decline in fruit set and quality.	Zahiri et al. (2023)
	12 months	Moderate pollen viability and fruit retention. Better than ambient temperature but inferior to freezing.	Sharma et al. (2024)
	16 months	Moderate pollen viability; better than room temperature but inferior to deep freezing. Suitable for short-term storage.	Kumawat et al. (2022)

Table 3: Effect of freezing storage (-4 to -30°C) on pollen viability and quality.

Storage temp.	Storage period	Effect	Reference
-30°C	4 months	Highest pollen quality, both fresh and after storage. Retained quality when stored at -30°C.	Karim et al. (2022b)
-4°C	12 months	-4°C pollen showed good viability.	Sharma et al. (2024)
	12 months	Deglet Nour dates achieved the highest pollination success rate of any variety tested at 58.7%. The Ghers variety fared reasonably well at 36.9%, while Mech Deglat topped all others with an exceptional 60.8% setting rate.	Mohammed et al. (2024)
-4°C	12 months	Pollen stored at - 4°C in a glass bottle gave the second-best results for pollination.	Ahmed (2021)
-18°C	2, 4, or 8 years	When subjecting the samples to freezing temperatures for a sustained period of two years, optimal results were found for maintaining pollen viability, germination rates, fruit setting percentages, yield amounts, and overall fruit quality levels.	Ahmed (2021)
	2, 4, or 8 years	The best results for pollen viability, germination, fruit setting %, yield, and fruit quality, with freezing for two years showing optimal performance.	Ahmed (2021)
-15°C	16 months	The traditional method of using glass bottles to isolate flowers, labelled T_9, had superior results to even the more modern plastic bottle isolation shown as T_{10}.	Kumawat et al. (2022)
-4°C	12 months	While fresh pollen is ideal, stored pollen can still effectively pollinate flowers. Glass containers help maintain pollen's ability to fertilize over time, leading to full harvests even with stored powder.	Zahiri et al. (2023)
-18°C	2 years	High viability and germination.	Zahiri et al. (2023)
	6 months	While refrigeration and storage at room temperature diminished pollen viability, cryopreservation significantly improved germination rates.	Kadri and Mimoun (2020a)

with pollen tube directionality. These revelations give bits of knowledge into viable procedures to control sprouting and fructification rates for horticultural purposes (Kadri and Mimoun, 2020a). Studies have illuminated how date palm pollen behaves, which is crucial knowledge for cultivators seeking sustainable yields. Environmental influences, notably temperature and moisture, profoundly impact germination success. Prior investigations found that precise optimisation of *in vitro* conditions determines the extent of germination achievement. For example, holding temperatures at 25-30°C correlates with enhanced germination consequences. Meanwhile, understanding the internal mechanisms controlling dispersal and viability is important for creating effective pollination administration tactics (Karim et al., 2022b).

ADVANCES IN POLLINATION TECHNIQUES

Pollination is a critical ecological process upon which flowering plants depend to reproduce and sustain global food sources and biodiversity. Recent developments involving pollination techniques, especially the utilisation of drones and modern technologies for distributing pollen, biotechnological methods to enhance pollen quality, and innovative breeding approaches to heighten pollination effectiveness, have attracted considerable attention. The integration of drone application in agriculture has completely revolutionised the pollination process in fruit crops (Kämper et al., 2021). Drones outfitted with sophisticated sensors and spraying apparatuses can accurately and productively deliver pollen to blossoms, notably boosting pollination rates. For example, examinations demonstrate drone-assisted pollen distribution can augment fruit formation and yields in crops reliant on cross-pollination, such as almonds and strawberries. The ability to cover expansive areas swiftly and precisely diminishes the labour expenses related to traditional pollination practices and reduces the risk of human mistakes. Moreover, using drones allows monitoring environmental conditions affecting pollination, including temperature, humidity, and the presence of pollinators. This data can be used to optimise timing and techniques of pollen distribution to ensure that pollen is conveyed when circumstances are most favourable for fertilization (Radwan et al., 2022a). Drones may also be programmed to target specific plants, which is particularly beneficial in mixed-crop environments where various species may necessitate diverse pollination strategies. Biotechnology is pivotal in enhancing pollen quality, which is essential for successful fertilisation and fruit development. Recent advancements include genetic engineering techniques to develop pollen grains with improved nutritional content and longer viability durations. For example, in one study, researchers explored using nanocarriers to secretly deliver transgenes into pollen, enhancing traits without compromising longevity. This approach allows the introduction of desirable characteristics like resistance to stressors or optimized nutrients, which can lead to higher quality pollen (Zahng et al., 2020). Additionally, transcriptomic analyses have provided insights into molecular mechanisms governing pollen progress and quality. Investigations have indicated particular genes are involved in regulating viability and germination, and tweaking these genes can lead to improved pollen characteristics. For instance, enhancing the expression of genes connected to stress resistance can make pollen more resilient to adverse environmental conditions, thereby increasing the probability of successful fertilisation (Kadri et al., 2024).

Furthermore, biotechnological interventions have been utilised to optimise pollen storage and handling methods. Research signifies specific drying techniques and storage environments can substantially affect the nutritional value and viability of bee-collected pollen, which is crucial for both pollinator health and agricultural productivity. By understanding the biochemical composition of pollen and the factors influencing quality, biotechnologists can develop strategies to preserve and enhance pollen for agricultural use. Breeding strategies to boost pollination proficiency are essential for enhancing crop yields and quality. Modern techniques like marker-assisted and genomic selection have supplemented traditional breeding methods, which allow for identifying traits connected to successful pollination (Sharma, et al., 2024). Moreover, genetic diversity within a crop population is crucial for effective pollination. Studies have demonstrated that higher diversity can enhance resilience to environmental stresses and improve overall reproductive success, which is particularly important in the context of climate change, where fluctuating conditions can impact pollination dynamics. Breeding programs prioritising diversity can lead to cultivars better adapted to changing conditions and more efficient in pollination strategies (Lew et al., 2020). In addition to genetic approaches, implementing integrated pest management strategies can enhance pollination efficiency. By cultivating an environment conducive for pollinators and minimising harmful pesticide use, farmers can improve pollinator population health and abundance, enhancing pollination success. This holistic approach to breeding and management is essential for sustainable agricultural practices (Zahng et al., 2020).

POLLINATION AND FRUIT SET

The relationship between pollination and fruit yield in date palms is undoubtedly critical for optimising production and quality. Various studies have highlighted the substantial impact that diverse pollen sources can have on fruit set, yield, and quality attributes. When effective pollination techniques are implemented, including novel liquid suspension methods along with the strategic use of specific high-performing pollen sources, they have clearly been shown to enhance fruit yield and quality notably. Conventional methods involve manual pollination using dry pollen alone, which can be a labour-intensive and inefficient approach. Research indicates that the timing of pollination is paramount, as the receptivity of female flowers fluctuates and is not consistent throughout their lifespan. The success of pollination relies heavily on synchronising the conditions of both the male and female flowers (Sharma et al., 2023). Recent studies have pioneered innovative suspension techniques, which allow for reduced pollen use while realising elevated fruiting rates. For example, research on the Mejhoul variety reported a 67.89% fruit set using a 4 g L^{-1} concentration, exceeding the 54.94% of the benchmark group (Salomón-Torres et al., 2024). Experiments have shown that enclosing clusters directly after pollination can dramatically boost yields and fruit set. In the Barhee date palm study, swift enclosing along with non-local pollen sources led to improved consequences (Ghanim et al., 2024). The selection of pollen donor plays a vital role in predetermining fruit qualities. An examination involving 11 male cultivars demonstrated that specific pollens, like P13, resulted in an astonishing 90.7% fruit set and enhanced retention rates (Kadri et al., 2024). This indicates that opting for high-quality pollination partners can directly influence yield and fruit quality. Distinct pollen sources also sway the biochemical composition of the fruit. For example, fruits pollinated with P90 exhibited higher total soluble solids, whereas P7-pollinated fruits had elevated reducing sugars (Kadri et al., 2024). This variation underscores the importance of pollen source selection in achieving the desired fruit qualities.

The dioecious characteristic of date palms necessitates the presence of male trees for successful pollination, which can substantially complicate management practices, particularly in areas where male trees exist scarcely. The timing of pollination is undoubtedly critical since environmental conditions can influence flower receptivity. Growers must vigilantly monitor the anthesis of female inflorescences to ensure effective pollination. The labour-intensive nature of conventional pollination methods poses a considerable challenge for large-scale date palm cultivation. Innovations, including mechanised pollination tools, are presently being explored to alleviate this issue, as utilising modern technology may greatly reduce the workload while maximising crop yields. However, further research is still required to fully optimise protocols (Sharma et al., 2023).

CONCLUSION

This review spotlights the significance of improving pollen viability, germination, and capacity conditions for advancing pollination proficiency in date palm (*Phoenix dactylifera* L.) cultivation. The literature showed that viable capacity conditions play a vital part in supporting pollen viability by bringing down temperatures important for protecting pollen viability. The metaxenic impacts of various pollen sources fundamentally influence the produce yield and quality, underscoring the requirement for choosing high-viability pollen for improved farming. Coordinating these cutting-edge innovations, for example, drone-assisted pollination, biotechnological mediations, and assortment procedures, holds huge guarantee for improving pollination proficiency, diminishing work costs, and expanding harvest resilience to natural pressure. By improving these components, date palm drives higher natural yields and improved general harvest quality. In addition, developing biotechnological procedures, for example, hereditary alteration, could possibly reinforce palm characteristics against contagious infections and atmospheric changes. Future research will undoubtedly refine storage methods to protract pollen viability for more prolonged periods under fluctuating environmental conditions. The evolution of more effective drone-assisted pollination frameworks that can function in diverse climates and agricultural settings should be further investigated. The progressions in genetic engineering and transcriptomics could be exploited to boost pollen quality and its resilience to environmental stress. In addition, breeding programs should persist in focusing on genetic diversity, incorporating marker-assisted selection to improve pollination efficiency and optimise fruit yield and quality. The role of metaxenic impacts in pollination could also be studied in more detail to comprehend the systems through which diverse pollen sources sway fruit progression. Overall, incorporating these

state-of-the-art techniques will be crucial for maintaining and bettering date palm output in the face of global agricultural challenges.

Declaration of competing interests

The author declares no conflict of interest.

Author contribution statement

Maryam: Conceptualization, Writing original draft and submission.

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