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Review Article

Advancements in artificial pollination of crops: from manual to autonomous

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ABSTRACT

Adequate pollination is crucial for ensuring sufficient fertilization and maximizing crop yield. However, natural pollinators are increasingly affected by multiple threats, including habitat loss and fragmentation, intensive agricultural development, and climate change, putting their sustainability at serious risk. As a complement to natural pollination services, artificial pollination plays an important role in guaranteeing food security amid the decline of natural pollinators and growing global food demand. In this study, a comprehensive review was conducted on the categories and applications of artificial pollination, along with recommendations for integrating advanced technology-driven approaches with agronomic practices to enhance targeted production. Implementation of artificial pollination is governed by the physiological characteristics of crops and employs two technical routes to determine whether the additional pollen application is required. Variety of advancements in pollination technologies and devices have been developed, with autonomous pollination systems featuring flower sensing, task planning, and precise execution gaining increasing attention. Although artificial pollination has shown increasing promise with technological advancements, the timing of pollinating, the optimal amount of pollen to be applied, and its ecological sustainability still require collaborative efforts among agronomists, technology developers and producers. Such multilateral cooperation is essential for continued development and practical application.

1. Introduction

Pollination is the process of transferring pollen from the anthers to the stigma, which is crucial for fertilization and seed formation during plant reproduction. Adequate pollination of crops can improve the yield and quality of primary agricultural products, vital as the main source of food for humans, such as grains, fruits, and vegetables (Smith et al., 2022; Toledo-Hernández et al., 2017; Brittain et al., 2014; Gonzalez et al., 1998). According to different pollination agents, natural pollination systems can be divided into biotic and abiotic, relying mainly on insects and wind for pollen transfer, respectively (Khalifa et al., 2021; Rader et al., 2020; Klein et al., 2007). Existing natural pollination systems are believed to have evolved through co-evolution among the environment, pollinators, and plants. This co-evolution has led to different plant species developing specialized floral designs to attract and compete for specific pollinators. Examples include nectar rewards that attract insects and unique floral structures that enhance pollen delivery (Johnson et al., 2022; Russell et al., 2017; Lu et al., 2011; Mayer et al., 2011; Mitchell et al., 2009). Nevertheless, the global decline of pollinators caused by human activities and ensuing ecosystem

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alterations poses a potential threat to the sustainability of natural pollination systems under the growing global food demand (Gudowska et al., 2024; Outhwaite et al., 2022).

Development of industrialization and urbanization caused by human activities has changed the properties of land resources, affecting the climate and biodiversity of corresponding areas. There is growing evidence that the decline in pollinators is primarily driven by the use of pesticides, climate change, and habitat loss, which are factors closely linked to the development of agricultural intensification and the resulting environmental degradation (Centeno-Alvarado et al., 2023; Siviter et al., 2021; Potts et al., 2016; Dixon, 2009). Apart from this, the continuously growing advanced controlled environmental agriculture (CEA), such as plant factories with controllable artificial light and relatively independent microclimates, has made natural wind pollination unfeasible and unfriendly to bees (Liu et al., 2023a; Dingley et al., 2022; Knop et al., 2017). While captive honey bees promise to be the best option for sustainable pollination in natural environments, there are restrictions on cross-regional commercialized pollination services, due to environmental fluctuations that diminish bee vitality and regional regulations (Osterman et al., 2021; Cooley and Vallejo-Marín, 2021; Hogendoorn et al., 2006). Moreover, the existing number of managed bee colonies is far from meeting the continuously growing demand for pollination, further limiting its promotion and application (Mashilingi et al., 2022; Aizen and Harder, 2009). Therefore, artificial pollination is becoming increasingly necessary as an important safeguard for productivity enhancement where natural pollination of crops is limited (Castro et al., 2021).

Various artificial pollination approaches have been developed to supplement inadequate natural pollination, considering the physiological characteristics of different crops. These diverse approaches cater to the specific needs of various crops under natural pollination conditions, covering both biotic and abiotic pollination. Artificial pollination has been applied to solve the problem of low yields caused by insufficient natural pollination and was initially carried out as a manual operation (Broussard et al., 2023; Wurz et al., 2021). While manual approaches, such as hand pollination, brush pollination, and rope pollination, have been employed for centuries to enhance crop yields, they are now mostly applied in plant breeding where parental control needs to be ensured, as well as in subsistence family farming and smallholders (Toledo-Hernández et al., 2017). In contrast, it is difficult for large-scale commercial agriculture to afford seasonal manual pollination with rising labor costs, as most primary agricultural products are far less economically viable than the same unit of germplasm (Dingley et al., 2022). This has prompted a shift in artificial pollination as commercial growers seek more cost-effective and efficient alternatives to manual labor.

Numerous research efforts have been conducted in artificial pollination with various innovative techniques to reduce and replace manual operations. Dingley et al. (2022) investigated the pollination mechanisms of tomato flowers and emerging technologies inspired by natural pollination, demonstrating that acoustic technology offers a promising approach for precise, non-contact, automated self-pollination in crops. Eyles et al. (2022) detailed the process of mechanical pollination of horticultural fruit and nut crops, covering multiple stages from pollen collection and storage to application, which indicated that gaps in pollination biology have prevented the widespread adoption of mechanized pollination. Wu et al. (2022) reviewed efficient bee pollination technologies and mechanized pollination applications for different crops, emphasizing that pollination should not be viewed as an isolated process but rather as one that requires the integration of multiple technologies. Broussard et al. (2023) discussed pollen collection and application technologies and pointed out that increasing attention was focused on drone-based and robotics solutions for commercial pollination. At present, the focus of artificial pollination research is shifting from mechanical automation to robotic autonomy, with an increasing number of technology-driven solutions being developed to address the challenges of modern agriculture. By integrating sensing, decision-making, mobility, and operation, autonomous pollination systems can adaptively respond to changing environmental conditions, optimize pollination routes, and minimize energy consumption, thereby improving the efficiency and sustainability of pollination services (Wei et al., 2024; Gao et al., 2023).

This study offers a comprehensive review of the categories, techniques, platforms, and applications of crop artificial pollination, primarily focusing on the progression from manual to autonomous operations. For this paper, artificial pollination is defined as the process of pollination that occurs through human intervention rather than natural means. According to the physiological characteristics of different crops, categories of artificial pollination were defined based on whether additional pollen supplementation is required or not. On this basis, the study analyzed the adaptability of different pollination methods to various crops, along with technological solutions used to enhance efficiency and reduce costs. In addition, the study introduces the concept of integrating advanced technology-driven approaches with agronomic practices to optimize targeted production. Finally, concrete proposals and potential risks associated with the development of artificial pollination were analyzed and discussed.

2. Review protocol

This review adopted a systematic and structured approach to comprehensively analyze advancements in artificial pollination technologies. The methodology encompasses three stages: searching, screening, and analyzing. In the searching stage, research objectives were defined, search protocols were established, and databases with targeted search strings were selected. The screening stage involved evaluating retrieved documents for relevance and excluding those that did not meet the inclusion criteria. Finally, an in-depth analysis of the selected literature was conducted to synthesize findings, identify research gaps, and propose directions for future studies.

The review primarily focused on studies addressing artificial pollination practices in major crop categories that could provide primary products, including vegetables, fruits, and grains. Three databases have been applied for desired literature searching, specifically Engineering Village (https://www.engineeringvillage.com/), Web of Science (https://apps.webofknowledge.com/), and Google Scholar (https://scholar.google.com/). Specific keywords were settled for '*(pollen OR pollinate OR pollination) AND (artificial OR assistant OR manual OR machine* OR mechan* OR drone OR unmanned aerial vehicle OR robot* OR auto*) AND (crop OR vegetable OR tree OR nut OR grain OR plant OR fruit)*'. By setting different combinations of search strings and variations, multiple retrievals were applied to each database. Additional searches were conducted using the snowball method to expand the scope by identifying relevant references from selected studies (Klerkx et al., 2019).

After finalizing the search protocols, all retrieved documents were screened based on relevance to the subject. The time frame was restricted to studies published within the last 30 years, with exceptions made for foundational works and significant innovations predating this period. Further refinement limited the document type to peer-reviewed journal articles, ensuring authenticity and objectivity. Inclusion criteria prioritized studies exploring the design, development, and application of artificial pollination methods, as well as those addressing the agronomic and biological implications of these techniques. Articles focusing exclusively on natural pollination or unrelated agricultural processes were excluded unless they provided insights relevant to artificial pollination.

3. Categories of artificial pollination

3.1. Mechanism of crops pollination

Driven by differences in plant reproduction mechanisms, pollination can be accomplished through self-pollination and cross-pollination. In self-pollination, pollen is transferred from the anthers of a flower to its own pistil stigma (autogamy) or from one flower to the pistil stigma of another flower in the same plant (geitonogamy) (Eckert, 2000). In contrast, cross-pollination involves the transfer of pollen from the anther of one plant to the stigma of another plant. In reality, achieving absolute self-pollination and cross-pollination in natural environments is challenging due to the combined influences of biotic and abiotic pollination (Wu et al., 2022). Fig. 1 illustrates the physiological characteristics and pollination mechanisms of typical crops. Self-pollination typically occurs in bisexual flowers, where both male and female reproductive organs are present within the same flower, while cross-pollination can occur in both bisexual flowers and unisexual flowers, where each flower has only one reproductive organ.

The diversity of artificial pollination methods across different crops is influenced by both physiological characteristics and the need for high revenue in commercial agricultural production. It is worth noting that due to the effects of self-incompatibility, some plants, such as Rosaceae crops like apples, pears, and almonds, exhibit low self-pollinated yields or may not bear fruit at all, despite the presence of bisexual flowers (Pardo and Borges, 2020; Wu et al., 2013; Connell, 2000). In such cases, most commercial agriculture operations cultivate specific varieties to provide pollen for cross-pollination, ensuring optimal yields and desired outcomes. A similar situation occurs with dioecious crops like kiwifruit, where individual plants produce flowers of only one sex. This necessitates the inclusion of non-fruit-bearing male plants to provide pollen for the pollination of fruit-bearing females (Gao et al., 2023; Broussard et al., 2021). Despite careful design and adaptation of plantations, natural pollination is threatened and constrained by uncontrollable weather conditions, staggered flowering, and declining pollinator populations (Sánchez-Estrada and Cuevas, 2020). Therefore, artificial pollination is recommended to achieve the high yield and quality requirements of commercial agriculture. In this study, artificial pollination was divided into two categories, depending on whether additional pollen supplementation is required as shown in Fig. 2, which also contains critical factors affecting pollination effectiveness.

3.2. Non-pollen supplementation artificial pollination

Non-pollen supplementation artificial pollination (NPS-AP) is proposed for self-pollinating crops with short pollen transport paths. The goal is to enhance the efficiency and effectiveness of pollen release and transfer, ensuring sufficient pollination to achieve higher yields.

Although some crops have evolved mechanisms to ensure self-pollination through long-term natural selection, it is difficult to get satisfactory revenue in commercial agriculture with these adaptions alone. In the case of a typical self-pollinating crop, for example, tomato pollination requires specific stimulus to dislodge pollen from the sporocarp, which is usually accomplished with the assistance of wind or specific insect agents. Greenleaf and Kremen (2006) provided evidence that wild bees can enhance the production of field-grown tomatoes by increasing self-pollination through floral sonication. However, these agents are less effective in CEA systems, which are largely isolated from external insects and natural environmental. Studies have reported that, without interference, only about 30 % of tomato flowers can bear fruit by self-pollination in a greenhouse environment (Detar et al., 1968). In this case, various artificial strategies have been used for many years to simulate or enhance the effects of natural pollinators. Depending on the method of implementation, NPS-AP can be divided into contact-based mechanical vibration and non-cont1-act approaches such as air and acoustic vibration.

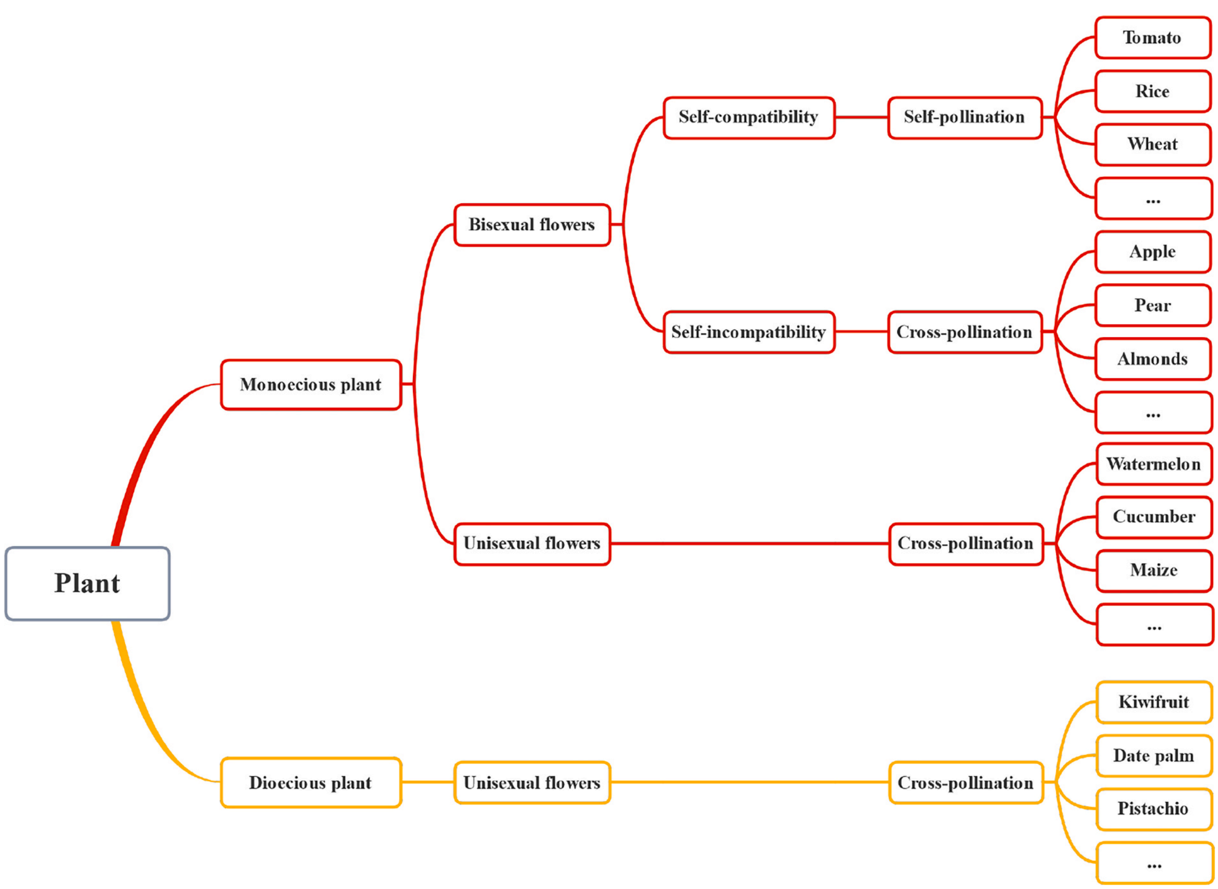

Fig. 1. Physiological characteristics and pollination mechanism with different crops.

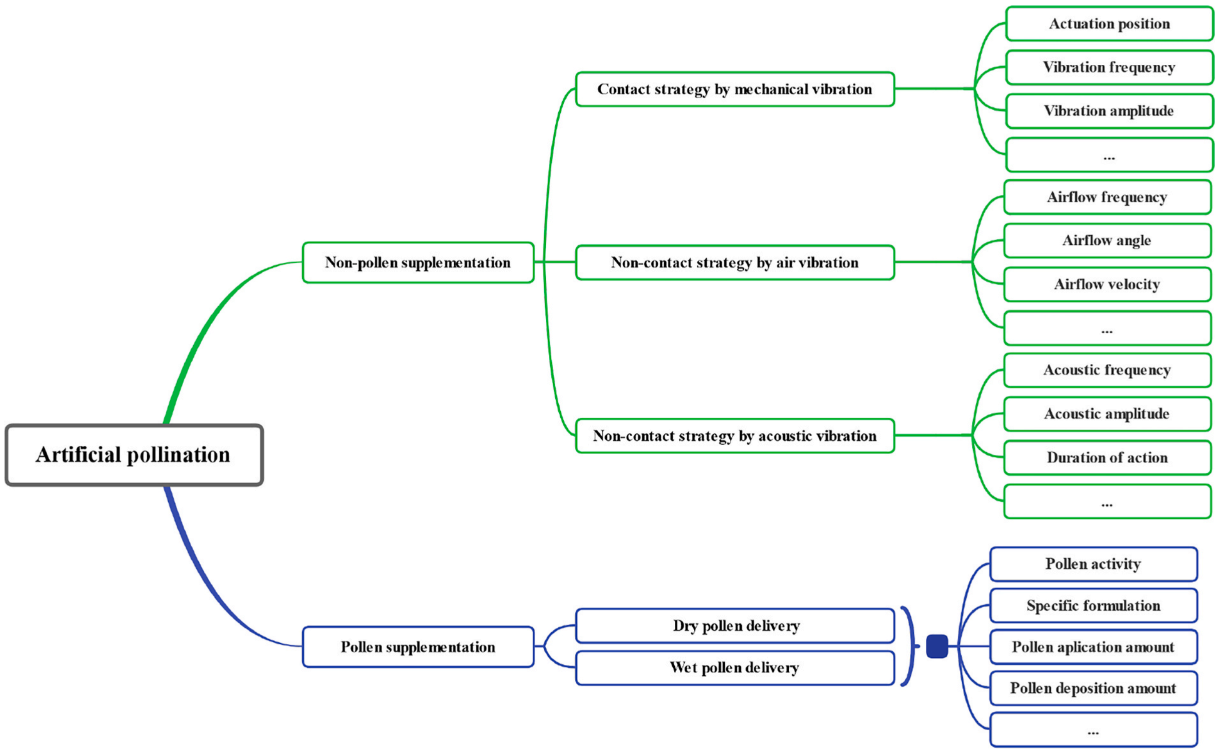

Fig. 2. Categories of artificial pollination with critical factors affecting effectiveness.

3.2.1. Contact strategy by mechanical vibration

The process of contact mechanical vibration typically involves dynamic shock, friction, and vibration, which promote pollen delivery by interacting with the stems, branches, and flower clusters of crops. Contemporary approaches utilized by commercial growers include trellis shaking, vine knocking, and inflorescence impacting, among others (Freitas et al., 2015; Hanna, 2004; DeTar et al., 1968). These techniques are employed to increase crop production, especially where natural pollination is restricted. However, while most of these techniques are superior to no-treatment methods, they are not as efficient as natural pollination by bees (Palma et al., 2008; Pressman et al., 1999; Cribb et al., 1993). Consequently, in order to achieve adequate pollination and ensure stable crop outputs, researchers have investigated the mechanisms behind contact vibratory pollination.

Contact vibratory pollination varies across crops and is influenced by the location and parameters of the vibratory action, leading to differences in pollen release characteristics. Jiang et al. (2021) developed a mechanical model for hybrid rice pollination using a reciprocating lead screw mechanism, which analyzed the effects of different impact heights, impact speeds, and harvesting speeds on the amount of pollen shed. The results indicated that the amount of pollen released was most affected by the impact height (position of impact) and increased with higher impact speeds. Liu et al. (2022) developed a motion simulation model that combined discrete elements and hydrodynamics techniques to investigate the release process and motion properties of pollen during tomato pollination by mechanical vibration. Their findings revealed that the angle of pollen distribution increases with vibration amplitude, while the influence of amplitude on pollen speed is minimal. Similar conclusions regarding the impact of vibration amplitude on pollen release have been observed in biotic pollination by bees (Kemp and Vallejo-Marín, 2021; De Luca et al., 2013).

While contact mechanical vibration is a viable option for crops under controlled environments, its efficiency remains limited by mechanical constraints and plant-specific factors. Advancements in modeling and parameter optimization could bridge the gap between contact-based and biotic pollination efficacy.

3.2.2. Non-contact strategy by air vibration

Air vibration pollination is inspired by natural wind, which involves creating conditions that allow pollen to be dislodged by vibration and transferred utilizing airflow. Compared to mechanical vibration, it could reduce the potential risk of damage and physical harm to plants associated with direct contact methods (Tang et al., 2012). This method is specifically valuable in CEA systems, such as greenhouses and indoor farms, where natural wind is absent and traditional pollinators are not viable. In addition, it is well-suites for certain specialized field crops, such as hybrid rice, that require much stronger airflow than natural conditions for effective pollination, particularly when the parents are planted at intervals. Air vibration can be generated through various devices, such as fans, blowers, or specifically designed air jets, to create controlled airflows (Mahadik et al., 2021; Hanna, 1999). Despite the benefits of air vibration pollination, it requires precise control with careful calibration of airflow patterns to meet actual pollination needs (Wang et al., 2012a).

To provide a theoretical foundation for commercial applications, researchers focused to understand the mechanism behind airflow vibration pollination. Wang et al. (2012b) investigated the principles of air vibration in pollination, demonstrating that airflow can generate vibratory forces on plants, as affecting structures like stems and leaves, as well as transport forces that act on the pollen. The effects of these forces are mainly influenced by airflow velocity, with a positive correlation observed between velocity and force. When the airflow is not strong enough, it is difficult for pollen to be dislodged from the flowers. As the airflow reaches a certain threshold (which varies depending on the crops and growing conditions), it will dislodge and disperse the pollen. However, if the generated airflow is too strong and exceeds a certain range, pollen will spread to non-target pollination areas, thereby reducing the effectiveness of pollination. Considering the requirements of pollen shedding and dispersal, Wang et al. (2015) proposed a hybrid rice pollination method combining vibration impact and airflow delivery, and used computational fluid dynamics (CFD) technology to analyze the flow field characteristics of designed pollination tubes and airflow outlets, enabling optimization of operation parameters. Li et al.

(2015a) analyzed and validated an airflow field model with a superposition of parallel jets, and showed that the jet pole angle directly affected the coverage of airflow field and was positively correlated with pollination uniformity. Liu et al. (2024a,b) presented a simulation model of pollen movement for tomato pollination combining vibratory release induction and airflow movement guidance, noting that the coupled approach outperformed vibratory and airflow pollination alone, with pollen grains covering improved by 85.5 % and 100.63 %, respectively.

Effectiveness of air vibration pollination can be optimized by adjusting the intensity, direction, and frequency of the air currents generated, tailored to the specific requirements of different crops and environmental conditions. Nahir et al. (1984) developed a pulsating air jet as a vibration energy carrier for artificial pollination experiments on both field-grown and greenhouse-grown tomatoes, which revealed that pollination efficiency and flower acceleration varied unimodally with pulse frequency, peaking around 25 Hz. Xi et al. (2023a) evaluated the response characteristics of rice panicles to airflow impact to optimize the operating parameters of pneumatic pollinators. Their study highlighted that both velocity and point of airflow application significantly influence pollen distribution and panicle movement. To further improve pollination efficiency, Xi et al. (2023b) analyzed the effects of various airflow combinations on pollen distribution in hybrid rice, which indicated that a single airflow directed at multiple rows of male parents simultaneously can lead to uneven pollination. To improve the breadth and uniformity of pollen distribution, it is essential to understand and optimize the interference caused by multiple airflow combinations. Air vibration represents a promising alternative to traditional methods, but its success depends on precise calibration to crop-specific requirements. Future research should focus on integrating advanced modeling tools, such as CFD, to refine airflow dynamics and ensure uniform pollen distribution.

3.2.3. Non-contact strategy by acoustic vibration

Acoustic vibration pollination was inspired by observing natural bee behavior, known as buzz-pollination, which mainly involves physical vibrations and high-frequency acoustic stimulation. Acoustic vibration employs sound waves to induce resonance in the plant, causing it to release pollen from the flowers, providing a gentler alternative approach in artificial pollination. The amount of pollen released during buzz-pollination is influenced by the frequency of the generated vibrations and the thorax displacement of bees. Similarly, the effectiveness of acoustic vibratory pollination is determined by parameters such as frequency and amplitude (Jankauski et al., 2022; De Luca et al., 2019). While acoustic vibratory pollination can promote pollen release across a wide range of frequencies, using a specific frequency, known as the natural frequency for particular crops, can maximize the effect while requiring lower intensity (De Luca et al., 2013; Detar et al., 1968). Due to the heterogeneity of the composition and structure of biological tissues in flowers, the amplitude of vibrations experienced varies (Vallejo-Marín et al., 2022). A study by King and Buchmann (1996) found that pollen-producing anthers may experience vibration amplitudes hundreds of times greater than the receptacle due to variability in the vibrational propagation in tomato flowers. Shimizu and Sato (2018) developed a prototype ultrasonic pollinator designed to deliver vibratory force at frequencies between 20 and 30 Hz, which were modulated to match the characteristic frequency of strawberry flowers and achieved a marketable fruit rate of 91.7 %, surpassing the results of both manual brush pollination and no intervention. In addition, it has been shown that the duration of acoustic wave exposure and the specific characteristics of the flowers also influence the amount of pollen released (Tayal and Kariyat 2021; De Luca et al., 2020; Vallejo-Marín, 2019).

Acoustic methods present a gentle, scalable alternative to mechanical and air vibration strategies. Research should prioritize refining frequency modulation technologies to improve their cost-effectiveness and adaptability for broader agricultural applications.

3.3. Pollen supplementation artificial pollination

Pollen supplementation artificial pollination (PS-AP) is conducted on crops that either cannot produce sufficient pollen or require cross-pollination. This technique involves directly applying collected pollen to the targeted plants or flowers. It has been used for many years to enhance production and quality, evolving from hand pollination to the use of auxiliary devices and automated equipment. The most extensive application through PS-AP is in dioecious crops, such as kiwifruit and date palm, which depend on cross-pollination for fruiting due to their unisexual flowers produced by separated male and female plants. These crops face challenges from the asynchronous flowering periods of male and female plants, making PS-AP crucial for successful pollination (Alyafei et al., 2022; Munir et al., 2020; Howpage et al., 2001). Although natural pollination for these crops can be achieved, to a certain extent, by wind and insects, inadequate pollination can result in fruit set rates and average quality that fall short of meeting commercial demands (Akhavan et al., 2021). In this case, supplementing the female plants with pollen during the flowering period is essential to ensure successful pollination and high yields. In addition, PS-AP also plays a role in self-incompatible crops (e.g., apple or pear), especially when limited pollen production and reduced insect activity due to adverse weather threaten pollination (Millard et al., 2023). According to different forms of pollen application, PS-AP can be categorized into dry pollen delivery and wet pollen delivery.

3.3.1. Dry pollen delivery

Dry pollen delivery is a method of artificial pollination in which dry powdered pollen is applied directly to the flower or its pistil. It can be accomplished by spraying pollen using a device that generates airflows, or by contact-point pollination using a specific tool. High-quality pollen for commercial use is often expensive due to the complexity of its production, which requires strict control over multiple steps, including collection, drying, purification, and storage, to ensure its viability and quality (Eyles et al., 2022). For a combination of economic as well as feasibility considerations, the pollen is usually used in mixtures with special carriers (e.g., charcoal, flour, and lycopodium spore) in specific ratios to pollinate different crops (Akhavan et al., 2021; Castro et al., 2021; Sakamoto et al., 2009).

Effectiveness of dry pollination delivery is influenced by both the amount of pollen applied and specific operations. Due to its light weight and small size, pollen is susceptible to being carried away by natural winds or obstructed by the canopy or other structures during application. As a result, not all pollen reaches stigma, which can hinder the effectiveness of pollination. Sánchez-Estrada and Cuevas (2020) investigated the effects of dry pollen delivery in varying quantities (measured as the number of pollination events) to the canopy of olive trees during flowering period, and results showed that increased pollen application led to higher yields. Dahab et al. (2020) found that using high-pressure airflow to spray pollen onto the bloom area of date palms allowed for a better coverage of flowers and resulted in higher yields with less pollen usage compared to manual pollination, by inserting a male spadix into a female spadix. Most of these studies highlight the feasibility of dry pollen delivery for ensuring crop pollination. However, there are large differences in the final yield compared to natural pollination, likely due to substantial losses during pollen transfer that are often overlooked (Abbate et al., 2023, 2021; Castro et al., 2021; Sáez et al., 2019).

Electrostatic force attachment systems modeled from biotic pollination have shown promise for improving dry pollen delivery by enhancing pollen adsorption to the stigma and reducing its loss during application. Khatawkar et al. (2021) reviewed the concept of electrostatics along with examples of device design and application for crop pollination, showing that electrostatic pollination holds promise for commercial use by reducing pollen consumption and improving fruit setting. Numerous studies and commercial applications have demonstrated that incorporating electrostatic force improves dry pollination in crops such as almond, kiwifruit, date palm, pear, and pistachio. Improvements have been observed across various aspects, including pollen consumption, fruit setting and total yield (Murakami et al., 2020; Murakami and Yamaguchi, 2017; Gan-Mor et al., 2009; Gan-Mor et al., 2003a; Vaknin et al., 2001).

3.3.2. Wet pollen delivery

In contrast to dry pollen delivery, wet pollen delivery involves suspending pollen in a liquid medium before applying it to the flowers for pollination. Additional liquid mass allows for increased momentum during pollen application and reduces the effects of wind disturbances. The liquid medium typically contains water and some nutritional composition that supports pollen viability and activity, potentially enhancing the attachment of pollen to the stigma (Soliman et al., 2017). Notably, the viability of pollen in prepared solutions gradually diminishes over time, imposing stricter application time constraints compared to dry pollen. These constraints vary depending on the specific formulations of the pollen liquid and the species involved (Liu et al., 2023b). Although existing studies have developed and tested the feasibility of several liquid formulations for crops like kiwifruit, date palm, pistachio, and pear, large-scale validations of application parameters needed to ensure their commercial viability remain limited (Salomón-Torres et al., 2021; Ascari et al., 2018; Karimi et al., 2017; Zeraatkar et al., 2013; Sakamoto et al., 2009).

Most wet pollen delivery systems for crop pollination utilize liquid atomization, achieved through hydraulic or pneumatic assistance. These approaches involve converting the pollen solution suspension into droplets that can be evenly distributed over the flowers. The results of hydraulic pollination have been inconsistent due to the uneven distribution of pollen particles in suspension and the lack of homogeneity in the droplets. This variability makes it difficult to maintain consistent quality throughout the continuous pollination process (Shi et al., 2019; Mu et al., 2018). Pneumatic pollination, whether through internal or external mixing forms of pressure assistance, has been demonstrated to reduce the size of spray droplets and improve their uniformity, as evidenced by studies aiming to optimize droplet coverage and deposition (Hao et al., 2023; Williams et al., 2021; Williams et al., 2020; Musiu et al., 2019).

PS-AP offers a robust solution for increasing yields in challenging pollination conditions. However, optimizing pollen usage efficiency and delivery precision remains critical for commercial scalability. Integrating supplementary methods, such as electrostatic forces in dry delivery, advanced formulations in wet delivery, and optimized pollen movement trajectory that enhance pollen deposition in the pistil, could further enhance outcomes.

4. Applications of artificial pollination

4.1. Hand-held pollination

Hand-held pollination represents the most traditional and widely practiced approach to artificial pollination, which involves the manual transfer of pollen to crops or female parts of flowers using simple or especially designed tools. These tools can range from basic brushes, blowers, and vibratory wands (as shown in Fig. 3a) to more sophisticated devices designed to mimic the natural pollination process (Hiraguri et al., 2023a; Zhang et al., 2022). The primary advantage of hand-held pollination is its flexibility, allowing experienced operators to tailor the process to specific agronomic requirements, which enables targeted pollination of individual flowers or specific plant varieties (Razeto et al., 2006). The development of this application has evolved from purely manual operations to semi-mechanized processes, though human assistance remains essential (Haffar, 1999). A summary of research on hand-held pollination, including backpack equipment with manual operations, is presented in Table 1.

A variety of hand-held tools, as well as commercial dusters and sprayers, have been applied to validate the feasibility of artificial pollination across different species. In order to verify the effectiveness of a developed pollen suspension, Sakamoto et al. (2009) utilized a commercial electric sprayer for pear pollination and showed that the fruit setting rate achieved with spray pollination was comparable to that of hand-dry pollination using a feathered stick, while offering superior pollen consumption and pollination effectiveness. Ellena et al. (2014) applied a commercial hand ventilator to pollinate female hazelnut flowers directly with a mixture of pollen and lycopodium spore, which showed that supplementary pollination can significantly improve yield in hazelnut under adverse weather conditions. Sánchez-Estrada and Cuevas (2020) conducted a pollination experiment using a commercial electrical powder duster on the canopy of olive trees, which indicated that artificial cross-pollination increased fruit setting, yield, and overall profits. Abbate et al. (2021) evaluated the performance of artificial pollination in kiwifruit using dry pollen delivery, which demonstrated that this method resulted in higher percentages of fruit setting and marketable fruits compared to natural pollination by wind or insects. In addition, hand-held tools designed to generate vibratory forces have been shown to promote self-pollination in tomatoes (Hiraguri et al., 2023a). Similar studies that rely on general tools or commercial devices are summarized in Table 1, detailing the pollination approaches employed along with their corresponding performance.

To further reduce pollen waste and improve pollination efficiency, several specialized pollination devices have been developed and optimized for specific crops. Following laboratory simulation and field verification of electrostatic pollination (Vaknin et al., 2001; Bechar et al., 1999), Gan-Mor et al. (2003a) developed an electrostatic blowing pollinator powered by two levels of direct current potentials. This device was used to investigate the effects of various pollination parameters on

(a) (b) (c)

Fig. 3. Applications of hand-held pollination. (a) Mechanical vibration pollination for tomato by hand-held vibrator (Hiraguri et al., 2023a); (b) Electrostatic pollination for almond by backpack device (Gan-Mor et al., 2003b); (c) Air vibration pollination for hybrid rice by backpack device (Wang et al., 2015).

Table 1
Summary of hand-held pollination.

Applied Crops	Categories of artificial pollination	Pollination approaches	Adopted tools	Pollination performance	References
Date palm	PS-AP	Dry pollen delivery	Manual pollination by hand	Maximum fruit retention rate of 83 % (±9%)	Mesnoua et al. (2024)
		Dry pollen delivery	Self-designed hand-held duster	Average fruit weight of 234.47 g	Akhavan et al. (2021)
		Dry pollen delivery	Manual pollination by hand	Average speed of 18 trees per hour	Dahab et al. (2020)
		Dry pollen delivery	Hand-held soft foam duster	Average fruit setting rate of 82.07 % (±3.66 %)	Munir et al. (2020)
		Wet pollen delivery	Handheld sprayer	Average fruit setting rate of 85.71 % (±1.02 %)	
		Wet pollen delivery	Handheld sprayer	Average fruit retention rate of 31.75 %	Soliman et al. (2017)
		Dry pollen delivery	Manual pollination by hand	Average fruit retention rate of 26.15 %	
		Dry pollen delivery	Self-designed hand-held duster	Live pollen rate of 87.2 % (±4.9 %)	Haffar (1999)
Olive	PS-AP	Dry pollen delivery	Commercial hand-held powder duster (Dustin mizer model 1212)	Maximum fruit setting rate of 38.00 %	Sánchez-Estrada and Cuevas (2020)
Cacao	PS-AP	Dry pollen delivery	Commercial hand-held misting pump (Cifarelli M1200 EIMA)	No statistical differences to natural pollination	Vera-Chang et al. (2016)
Kiwifruit	PS-AP	Dry pollen delivery	Commercial hand-held spray applicator (PS-100)	Maximum fruit weight of 98.0 ± 0.7 g	Oh et al. (2022)
		Wet pollen delivery	Commercial hand-held misting pump	Maximum fruit weight of 96.7 ± 0.4 g	
		Dry pollen delivery	Manual pollination by hand	Average fruit setting rate of 78.64 %	Castro et al. (2021)
		Dry pollen delivery	Commercial Hand-held puffer	Average fruit weight of 128.23 g	Abbate et al. (2021)
		Wet pollen delivery	–	Average fruit setting rate of 65 % (±5%)	Sáez et al. (2019)
		Dry pollen delivery	Manual pollination by a duster Commercial backpack dry distributer (Dell'Agata Speedy) Commercial backpack dry distributor (Biotac SoffiaPollin)	Pollination speed of 25 h/ha Average fruit weight of 97.4 g Pollination speed of 5——7 h/ha	Tacconi et al. (2016)
		Wet pollen delivery	Commercial backpack liquid distributer (Ravello Professional)	Average fruit weight of 88.5 g	
		Wet pollen delivery	Hand-held fine brush	Pollination speed of 1 h/ha	Naik and Rana (2013)
		Dry pollen delivery	Hand-held fine auotomizer	Average fruit weight of 99.6 g	
		Dry pollen delivery	Manual pollination by hand Hand-held duster Commercial portable duster (Dall'Agata Danielle)	Pollination speed of 5——7 h/ha Average fruit weight of 91.5 g Average fruit setting rate of 85.07 %	Razeto et al. (2006)
		Dry pollen delivery	Self-designed hand-held air-assisted device	Maximum fruit weight of 89.63 %	Ding et al. (2015)
		Dry pollen delivery	Self-designed hand-held air-assisted device	Average fruit setting rate of 100 %	Ding et al. (2014)
		Dry pollen delivery	Manual pollination by hand Commercial hand-held powder duster (Southern Pacific International airflow pollinator)	Average fruit setting rate of 96.60 % Average fruit setting rate of 88.75 %	Gonzalez et al. (1998)
Hazelnut	PS-AP	Wet pollen delivery	Backpack device	Pollen coverage of 67.11 %	Ascari et al. (2018)
		Dry pollen delivery	Hand-held ventilator	Pollen coverage of 57.66 %	Ellena et al. (2014)
Pear	PS-AP	Dry pollen delivery Wet pollen delivery	Hand-held feathered stick Commercial hand-held sprayer	Average fruit setting rate of 97 % Average fruit weight of 114 g	Sakamoto et al. (2009)
Almond	PS-AP	Dry pollen delivery with electrostatic	Self-designed electrostatic pollen applicator	Average fruit setting rate of 87 %	Gan-Mor et al. (2003a)
Oil tree peony	PS-AP	Dry pollen delivery	Manual pollination by soft-tip brush	Average fruit weight of 77 g	Zhang et al. (2022)
Pistachio	PS-AP	Wet pollen delivery	Hand-held sprayer	50 % fruit setting rate increase compared to hand pollination	Karimi et al. (2017)

(continued on next page)

Table 1 (*continued*)

Applied Crops	Categories of artificial pollination	Pollination approaches	Adopted tools	Pollination performance	References
		Wet pollen delivery	Hand-held sprayer	37.3 % yield increase compared to natural pollination	Zeraatkar et al. (2013)
Hybrid rice	NPS-AP	Air vibration	Self-designed backpack device	Average fruit weight of 374.8 g	Xi et al. (2023b)
		Air vibration	Self-designed backpack device	Pollen consumption of 252 g/ha	Wang et al. (2015)
		Air vibration	Hand-held blower	Average fruit weight of 388.2 g	Wang et al. (2012a)

its performance across different areas of the canopy, validating pollination deposition in commercial almond orchards. Other studies explored the performance of this pollinator in field experiments across different crop types, including date palm, almond (as shown in Fig. 3b), kiwifruit, and pistachio, using various bearing modes (Gan-Mor et al., 2003b). Ding et al. (2014) proposed a hand-held pneumatic pollinator powered by a variable-speed centrifugal fan and analyzed the effect of outlet wind speed on pollen distribution through CFD. Further field experiments validated the coverage and amount of pollen delivered at different parameter settings of a constructed pollination pipeline for kiwifruit flowers (Ding et al., 2015). Wang et al. (2015) designed a backpack pollinator combining collision and air-blowing methods for hybrid rice pollination, leading to superior pollen uniformity and operational efficiency compared to manual pole pollination in field experiments (as shown in Fig. 3c). Akhavan et al. (2021) developed a portable lightweight electric pollinator equipped with a 6.5 m boom, capable of blowing collected pollen onto date palm trees at a height of 9 m for pollination.

Hand-held pollination has proven its feasibility in supplementing natural pollination through a combination of specialized tools and semi-mechanized devices with human expertise. However, it is challenging for hand-held pollination to become a mainstream solution for large-scale planting scenarios, not only owing to the continuously growing demand for pollination services but also due to the declining number of agricultural practitioners (Khatawkar et al., 2021). More efficient approaches must be adopted to address large-scale pollination needs, considering both economic and commercial requirements.

4.2. *Vehicle-mounted pollination*

Vehicle-mounted pollination represents an advancement in artificial pollination technology, designed to address the limitations of hand-held methods by incorporating mechanized processes, especially in large-scale planting scenarios. This approach utilizes vehicles equipped with specialized pollinators, enabling consistent pollination while reducing labor intensity. The equipment used for vehicle-mounted pollination can be either monolithic or detachable, with vehicles serving as platforms for pollination, ranging from specialized transporters to general agricultural platforms like tractors. More details on this technology are provided in Table 2, which also contains their pollination performance in practical planting conditions.

Tractors and other agricultural vehicles are commonly used as motorized platforms to expedite complementary pollination and cover larger areas, providing a wide working range. To enhance ease of operation and increase work speed in large areas, Gan-Mor et al. (2003b) mounted a custom-designed electrostatic blowing pollinator on selected off-road vehicles (as shown in Fig. 4a) for field pollination in pistachio and kiwifruit orchards. Tacconi et al. (2016) compared two forms of pollen delivery (dry and wet) for kiwifruit pollination using six different types of application equipment, ranging from backpack to tractor-mounted platforms in field experiments, and indicated that the flowering stage is fundamental for maximizing pollination benefits (as shown in Fig. 4b). Similar conclusions were drawn by Asteggiano et al. (2011), which pointed out that the optimal application time might differ between dry and wet pollen delivery methods for kiwifruit. Dahab et al. (2020) designed a mechanical pollinator powered by an air compressor and an air vacuum device to generate airflow for dispersing dry pollen,

Table 2
Summary of vehicle-mounted pollination.

Applied Crops	Categories of artificial pollination	Pollination approaches	Types of vehicle	Pollination performance	References
Date palm	PS-AP	Dry pollen delivery	Tractor	Average speed of 18 trees per hour Pollen consumption of 0.5—1 g per tree	Dahab et al. (2020)
		Dry pollen delivery	Vehicle-mounted lifting platform	Pollen consumption of 5 g per tree Fruit setting rate of 56 %	Gan-Mor et al., (2009)
		Dry pollen delivery with electrostatic	Vehicle-mounted lifting platform	Pollen consumption of 0.125 g per tree Fruit setting rate of 60 %	
Pistachio	PS-AP	Dry pollen delivery with electrostatic	All-terrain vehicle	12.7 % yield increase compared to open pollination	Gan-Mor et al., (2003b)
Kiwifruit	PS-AP	Dry pollen delivery	Tractor	Pollination speed of 0.5 h/ha Average fruit weight of 91.0 g	Tacconi et al. (2016)
		Wet pollen delivery	Tractor	Pollination speed of 2 h/ha Average fruit weight of 93.2 g	
		Dry pollen delivery with electrostatic	All-terrain vehicle	13.2 % seeds number increase per fruit compared to open pollination	Gan-Mor et al., (2003b)
Hybrid rice	NPS-AP	Contact vibration combine with airflow	Hand power chassis	Average setting rate of 14.9 % higher than that of 10.9 % by rope pollination	Jiang et al. (2021)
		Layer embedded airflow vibration	High ground clearance power chassis	96.02 % pollen release increase compared to setting required	Wang et al. (2021)
		Airflow vibration	High ground clearance power chassis	Average setting rate of 44.2 %	Zhou et al. (2019)

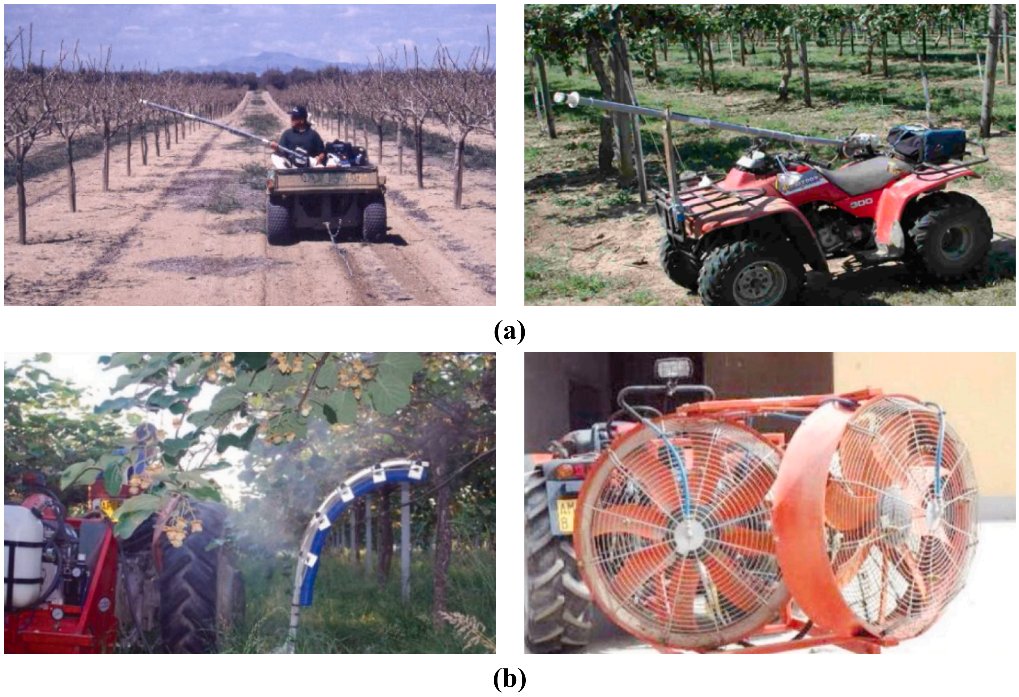

Fig. 4. Examples of vehicle-mounted pollination. (a) Vehicle-mounted pollination equipped with self-designed electrostatic pollen applicator for pistachio (left) and kiwifruit (right) (Gan-Mor et al., 2003b); (b) Vehicle-mounted pollination for kiwifruit by wet pollen delivery (left) and dry pollen delivery (right) (Tacconi et al., 2016).

which was mounted behind a tractor, with aluminum pipes used to pollinate date palms at an average height of 8–10 m. In another study, a high-pressure system was used to deliver liquid pollen suspension, which mounted on tractors for pollinating date palms in high floral zones (Salomón-Torres et al., 2021). Although tractors and other similar carriers are convenient for large-scale pollination, they can be impractical in situations with limited working space. A typical scenario is mechanized pollination for intensively grown hybrid rice, where different parental plants are spaced at intervals, leaving insufficient room for large vehicles like tractors to maneuver. This constraint necessitates the use of more compact or adaptable equipment.

Various studies have developed airflow-driven hybrid rice pollinators using small power chassis as carrier vehicles. These pollinators achieve pollen transfer through different mechanisms, including

Table 3
Summary of drone-mounted pollination.

Applied Crops	Categories of artificial pollination	Pollination approaches	Types of UAV	Pollination performance	References
Pear	PS-AP	Wet pollen delivery	Multi-rotor UAV (DJI MG-1S)	Fruit setting rate of 49.70 % Inflorescence setting rate of 85.83 %	Xu et al. (2023)
		Wet pollen delivery	Multi-rotor UAV (DJI T20)	–	Liu et al. (2023b)
		Wet pollen delivery with bubble as carrier	Multi-rotor UAV	Maximum fruit setting rate of 90.00 %	Yang and Miyako (2020)
Walnut	PS-AP	Dry pollen delivery	Self-designed quadrotor UAV	134.70 % production increase compared to manual pollination	Mazinani et al. (2023)
Camellia	PS-AP	Wet pollen delivery	Multi-rotor UAV (DJI T20)	Fruit setting rate of 42.67 % in upper canopy Fruit setting rate of 36.00 % in lower canopy	Hu et al. (2023)
Date palm	PS-AP	Wet pollen delivery	Multi-rotor UAV (DJI Agras T16)	Maximum fruit setting rate of 100 % Minimum fruit setting rate > 62.00 %	Alyafei et al. (2022)
Hybrid rice	NPS-AP	Airflow vibration	Multi-rotor UAV (XAG P20)	Released pollen was increased	Zhang et al. (2021a)
		Airflow vibration	Multi-rotor UAV (SUMA18)	–	Li et al. (2015b)
		Airflow vibration	Multi-rotor UAV	–	Li et al. (2014a)
		Airflow vibration	Uniaxial single-rotor UAV (YUREN SCAU-2)	–	Li et al. (2014b)

Note. –, not specified.

mechanical impact, pipeline airflow supplying the panicle layer, combined ducted airflow supplying, and ducted-fan airflow supplying (Jiang et al., 2021; Wang et al., 2021; Yao et al., 2020; Zhou et al., 2019). The impact of the carrier travelling speed on pollination consistency was also highlighted in the study by Xi et al. (2023a), which pointed out that walking speed is closely related to the duration of airflow action on the plant and affects the acceleration of the panicle caused by the airflow.

4.3. Drone-mounted pollination

Drone-mounted pollination is another innovation in artificial pollination, offering the ability to perform a broader range of pollination tasks from the air. This method is less restricted by terrain and workspace limitations, making it particularly effective in diverse planting patterns among crops. Pollination implementations can be accomplished by equipping drones with specialized sprayers for pollen delivery or by utilizing the airflow fluctuations generated during flight. These methods can be applied ranging from NPS-AP to PS-AP and cover multi-species from tree crops to grains, as shown in Table 3. Several applications have been explored, including the modeling and analysis of airflow fields generated by different types of unmanned aerial vehicles (UAVs), such as multi-rotor UAVs and uniaxial single-rotor electric

unmanned helicopters (as shown in Fig. 5a). These studies have examined the effects of various flight parameters on cross-pollination uniformity and pollen release in hybrid rice (Li et al., 2015b; Li et al., 2014a; Li et al., 2014b). Zhang et al. (2021a) analyzed the three-dimensional airflow field distribution of a quadrotor UAV and the trajectory of hybrid oilseed rape plants under rotor airflow, concluding that flying perpendicular to the male parent maximizes pollination effectiveness.

In drone-mounted pollination applications, both dry and wet pollen delivery have been applied to supplement pollination across various crops. Mazinani et al. (2021a,b,2023) used CFD to simulate the airflow field beneath a selected quadrotor UAV, analyzing the movement trajectory of pollen in the air. Their study demonstrated a significant yield improvement of 134.7 % compared to conventional hand pollination, achieved by using the UAV for dry powder application in a field trial for walnut pollination. Alyafei et al. (2022) compared the effects of different pollination methods on date palms and confirmed the feasibility of UAV pollination for commercial application by using drones to spray water-suspended pollen. Xu et al. (2023) developed a liquid spray pollination system based on a multi-rotor UAV for pear trees grown in a horizontal scaffolded pattern, which verified the effects of different flight parameter combinations on pollen drop coverage and deposition (as shown in Fig. 5b). Hu et al. (2023) investigated the effects of UAV flight parameters on pollen droplet distribution during camellia pollination, concluding that the heterogeneity of canopy structure can lead to differences in fruit setting rates within the same fruit tree. Yang and Miyako (2020) introduced an innovative pollination method using soap bubbles as pollen carriers by formulating a special solution, which resulted in a fruit-setting rate comparable to hand pollination in field experiments with pears and explored its feasibility for use with UAVs.

4.4. Autonomous intelligent pollination

While artificial pollination has progressed from manual operations to mechanized processes over the years, a gap remains in improving the accuracy of pollination and the utilization rate of pollen to enhance both economic viability and practical effectiveness. Generally, successful pollination occurs when pollen reaches the pistil of target flowers. However, vehicle-mounted or drone-mounted pollination, often employed in wide-area patterns, can lead to significant pollen waste. Manual pollination, characterized by its fixed-point precision and flexible approach, allows for targeted application. However, it fails to meet the increasing demands for pollination services and certainly cannot serve as the dominant method in large-scale operations. Autonomous pollination is positioned at the forefront of artificial pollination technology, integrating advanced robotics, artificial intelligence (AI), and sensor systems to execute accurate and efficient pollination tasks without human intervention. These systems are designed to minimize pollen waste and maximize pollination efficiency, ultimately increasing crop yields and reducing costs.

Different from manual and mechanized methods, autonomous pollination is designed to sense and interact with flowers or desired targets without human intervention. Inspired by the biology of natural pollinators, Chen and Li (2019) outlined autonomous pollination as a series of sequential steps, including details about operational area delineation, flower perception, pollination execution, and effectiveness evaluation, and so on. Machine vision systems play an important role in this process as the preliminary stage, functioning with sensors and perception algorithms for canopy or flower recognition and spatial positioning. Many studies have employed RGB (Red, Green, Blue) or RGB-D (Red, Green, Blue − Depth) sensors to capture plant or floral areas at various scales, integrating these with increasingly performing convolutional neural networks (CNNs) for flower detection and localization (Duc Tai et al., 2024; Li et al., 2022a). Since not all flowers bloom simultaneously or become suitable for pollination at the same stage, researchers have explored prior agronomic information to distinguish the phenological stages of individual flowers. This approach involves applying multi-class labeling and detection to identify different flowering stages of kiwifruit, apple, and tomato (Gong et al., 2023; Hiraguri et al., 2023b; Li et al., 2022b; Yuan and Choi, 2021). In continued exploration, Li et al. (2022c) mapped the spatial distribution of flowers and their clusters within the canopy by using You Only Look Once version 5 large (YOLOv5l) network to detect flowers and branch nodes of kiwifruit, coupled with Euclidean distance matching. Li et al. (2023) introduced a deep learning-based method to predict the positions and orientations of kiwifruit flower clusters, which combined SOLOv2 for

(a) **(b)**

Fig. 5. Examples of drone-mounted pollination. (a) Drone-mounted pollination for hybrid rice by airflow vibration (Li et al., 2014b); (b) Drone-mounted pollination for pear by wet pollen delivery (Xu et al., 2023).

flower segmentation with MobileNetV2 for detecting key points at the center of each flower. The orientation of the entire cluster was then determined by averaging the orientations of individual flowers within the cluster.

The feasibility of intelligent pollination services that directly target flowers has been demonstrated by prototype robotic pollinators. Li et al. (2022d) proposed an automatic kiwifruit pollinator scheme consisting of a mobile chassis, a robotic arm, and a binocular vision system, which simulated the trajectory planning of the utilized lightweight robotic arm, achieving a pollination speed of 5 s per single flower in field experiments. Yang et al. (2023) developed a prototype robot with visual servoing techniques to guide the manipulation of a robotic arm by detecting the orientation and area of rotated pistils, which obtained a success rate of 86.19 % for small pistils pollination in forsythia flower models under laboratory environment (as shown in Fig. 6a). Ahmad et al. (2024) developed a mobile robotic arm platform equipped with an intelligence-guided visual servoing system for watermelon pollination, which adapted YOLOv8n to distinguish between male and female flowers, achieving an average pollination speed of 8 s per flower and an average target localization accuracy of 1.03 cm (as shown in Fig. 6b).

As the technology for autonomous pollination continues to improve and innovate, significant progress has been made in field testing. Williams et al. (2020) reported a robotic kiwifruit pollination system that consisted of a machine vision system for flower detection and localization and a self-designed manifold air-assisted spray system for effective pollen application, reaching a pollination rate of 79.5 % at 3.5 km/h. Gao et al. (2023) developed an air–liquid spray pollination robot for kiwifruit that employs a selective pollination strategy based on multi-class flower detection and distribution identification, achieving an average fruit setting rate of 88.5 % (as shown in Fig. 6c). To address the challenge of sequence planning in movement-based pollination, Wei et al. (2024) introduced a redundant cooperative control strategy for planning optimized pollination paths while simultaneously managing mobile task processing by leveraging the available redundancy of mobile platforms and the operating end-effector, which acquired an average pollination rate of 7.5 s per flower in a tomato greenhouse by contact vibrating. Hiraguri et al. (2023a) proposed an autonomous pollination system through a cluster of small drones working in collaboration, allowing search drones equipped with machine vision systems to detect and locate flowers, while pollination drones equipped with vibrators for contact vibration pollination under the designed separation of functions, which achieved a fruit setting rate comparable to natural pollination by bumblebees in tomato (as shown in Fig. 6d). More details about this part were summarized and presented in Table 4 with their pollination performance in different experimental conditions.

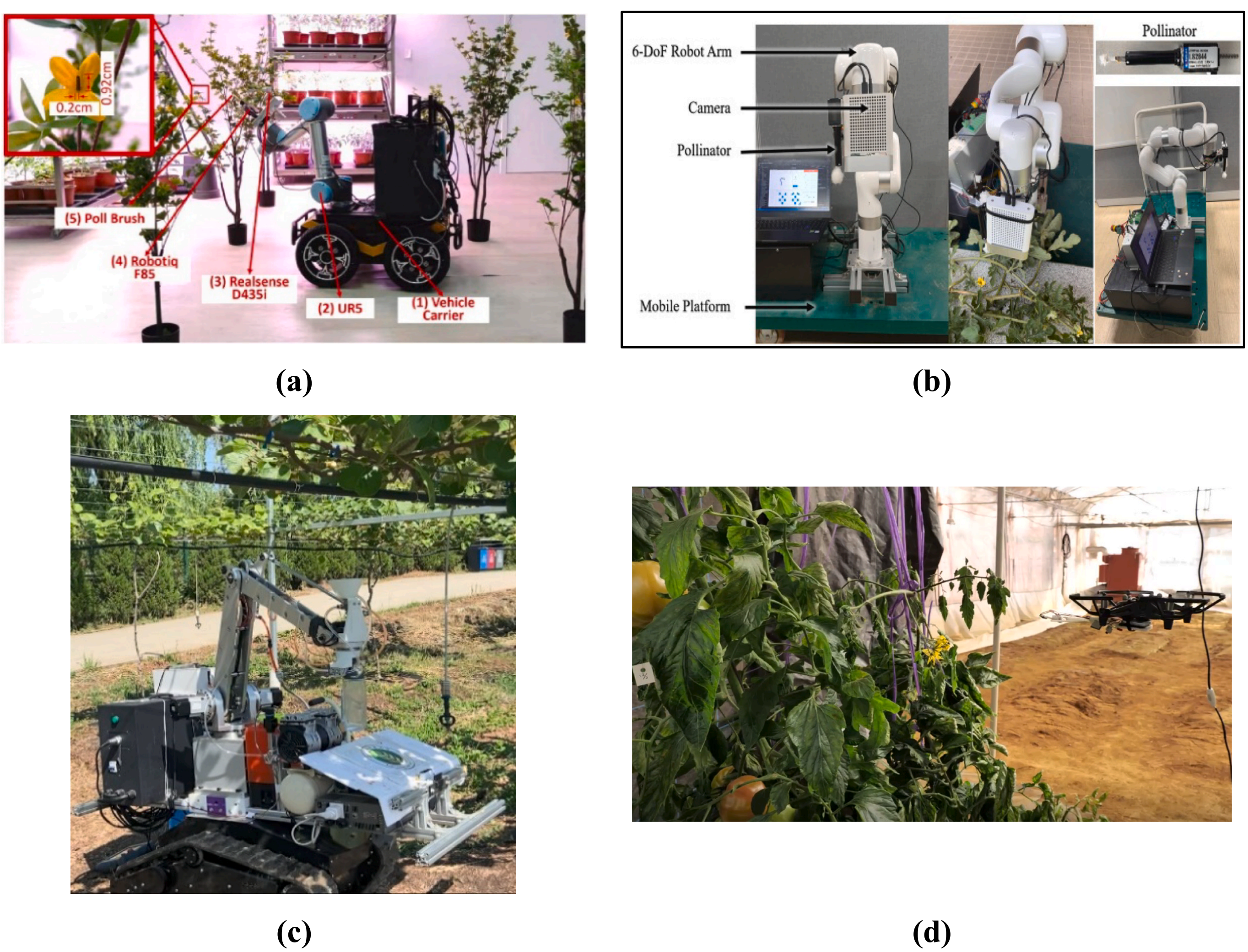

Fig. 6. Progress in autonomous pollination. (a) Robotic pollinator for forsythia with flower model in laboratory (Yang et al., 2023); (b) Robotic arm pollination platform for watermelon in laboratory (Ahmad et al., 2024); (c) Robotic pollinator for kiwifruit in field orchard (Gao et al., 2023); (d) UAV based pollinator for tomato in greenhouse (Hiraguri et al., 2023a).

Table 4
Summary of autonomous pollination.

Applied Crops	Categories	Actuators	Operation conditions	Perception system for flower detection and localization				Pollination performance	References
				Sensors	Detection Method	DetectionPerformance	LocalizationPerformance		
Watermelon	PS-AP	Robotic arm equipped with a linear pollinator	Laboratory	RGB-D(Azure Kinect)	YOLOv8	mAP = 90.30%	mAE = 1.7 cm	Average speed of 8 s per flower	Ahmad et al. (2024)
Forsythia	PS-AP	Robotic arm equipped with a brush	Laboratory	RGB-D (Realsense D435i)	Improved YOLOv5	Accuracy = 91.08%	Maximum errors = 3.8mm	Success rate of 86.19%	Yang et al. (2023)
Kiwifruit	PS-AP	Robotic arm equipped with an air-liquid nozzle	Field orchard	RGB-D (Realsense D435)	YOLOv5l	mAP = 93.23%	-	Average fruit setting rate of 88.5%Pollen consumption of 0.15 g for 60 flowers	Gao et al. (2023)
		Robotic arm equipped with a liquid sprayer	Field orchard	Binocular camera	YOLOv4	Average accuracy = 92.00%	-	Average success rate of 85% Average speed of 5 s per flower	Li et al. (2022d)
		Robotic arm equipped with conical two-fluid spray nozzle	Field orchard	Binocular camera (KS1A552-D)	YOLOv4	Average accuracy = 95.27%	-	Average success rate of 86.59% Average speed of 6 s per flower	Li et al. (2022a)
		Independently controlled air-assisted multi-nozzle for fixed installations	Field orchard	Stereo cameras	FCN	-	-	Average success rate of 60 ± 3% Pollen consumption of 4.6 kg/ha	Williams et al. (2021)
		Independently controlled air-assisted multi-nozzle for fixed installations	Field orchard	Two RGB(Baslar ac1920-40uc)	Faster-RCNN	Average F1 score = 0.85	-	Average success rate of 79.50%	Williams et al. (2020)
Tomato	NPS-AP	Robotic arm equipped with contact vibratory	Greenhouse	RGB-D(Orbbec Gemini2)	YOLOv5	Success rate = 95.27%	-	Average speed of 7.5 s per flower	Wei et al. (2024)
		Micro UAVs equipped with contact vibrator	Greenhouse	RGB	CNN	Accuracy = 87.3%	Error within 30 mm is about 80%	Fruit setting rate > 50%	Hiraguri et al. (2023a)

Note. −, not specified; FCN, Fully Convolutional Networks; mAP, mean Average Precision; mAE, mean Absolute Error.

5. Directions and challenges

5.1. Timing determination for artificial pollination

Successful pollination is crucial for ensuring sufficient fertilization and maximizing yields, and it typically must occur within the limited flowering period of crops. This process largely depends on the timing of pollen application or pollination operation, which should align with the reproductive phase of the targeted crops and their flowers (Brantley et al., 2019). Unlike natural pollination, which involves biotic and abiotic factors operating in a repeated and multiple-pollination process, artificial pollination is primarily conducted through a single or very limited number of operations due to economic and operational efficiency considerations (Oh et al., 2022; Pressman et al., 1999). Experiments of artificial pollination conducted by Asteggiano et al. (2011) and Tacconi et al. (2016) revealed that the receptivity of flowers at different phenological stages varies across pollination systems, which indicated that the optimal flowering stages for dry and liquid pollen delivery in kiwifruit, in terms of maximizing fruit weight are the petals fall stage and early petal fall stage, respectively. Therefore, key stages such as bud development, flowering, and fruit setting, influenced by the specific crop species, environmental conditions, and the physiological state of flowers, must be closely monitored to ensure pollination occurs when the flowers are most receptive (Dang et al., 2025). Conventional agronomic practices offer a comprehensive approach to pollination, relying on regular field observations and manual assessments conducted by experienced agronomists. However, this delicate and repetitive method requires a significant amount of skilled labor, making it impractical and cumbersome in large-scale commercial agriculture.

With the advancements in image processing and AI technologies, machine vision systems now offer an automated approach for estimating the flowering stages of plants. Machine learning and deep learning models, especially CNNs, have been successful in image recognition tasks by extracting detailed features about petal color, shape, and size. This makes them particularly well-suited for detecting and classifying different stages of flower development. These technologies, successfully applied to crops ranging from tree fruits to vegetables, allow for the determination of both the various flowering stages of individual flowers and the overall degree of flowering in a plant, with data collected either from low-altitude drones or ground-based near-end equipment (Mhamed et al., 2024; Lei et al., 2023; Song et al., 2023; Gonzales et al., 2022). These predictive models are continuously refined with new data and technological advancements, leading to improved accuracy and reliability over time. Moreover, remote sensing technologies, including satellite imagery and drones equipped with multispectral and hyperspectral cameras, enable the identification of crop growth periods and flowering patterns, as well as the assessment of flower receptivity across large fields and orchards (Liu et al., 2023c; Zhang et al., 2022; Zhang et al., 2021b; Wan et al., 2018). However, only a few studies have proposed automated flowering stage detection specifically for artificial pollination applications in crops such as tomato (Bataduwaarachchi et al., 2023; Hiraguri et al., 2023a; Hiraguri et al., 2023b; Liu et al., 2023a) and kiwifruit (Gao et al., 2023; Gong et al., 2023; Li et al., 2022b; Li et al., 2022c). Other studies either did not address this aspect or relied on manual discrimination methods.

After assessing flowering periods, determining the optimal pollination time requires careful consideration of environmental factors. The physiological state of a plant dynamically adjusts to environmental changes, which can lead to variations in the effectiveness of pollination depending on the timing chosen within the full flowering periods. A clear example of this is that low humidity combined with high temperatures can cause the stigma of flowers to dry out, making it difficult for pollen to adhere and deposit (Dingley et al., 2022). Research has also shown that temperature directly affects pollen germination and the development of pollen tubes after pollination, which in turn affects the growth and quality of the final fruit and its seeds (Gonzalez et al., 1995; Jansson and Warrington 1988). Similar conclusions about the impact of environmental conditions on pollination outcomes have been reported, such as the ineffectiveness of applying vibrations to tomato flowers in dark and cloudy weather to promote pollen release and achieve effective pollination (DeTar et al., 1968).

This suggests that technical feasibility must be continuously optimized through the enhancement of agronomic knowledge and further exploration. Existing methods for automated floral assessment should incorporate the influence of environmental factors to refine pollination timing from feasible to optimal. Advanced data analysis techniques are crucial for this refinement, utilizing multi-year historical data on pollination success, environmental conditions, management assessment, and crop yields to continuously improve the accuracy and reliability of pollination operations (Manthos et al., 2024). With its capabilities in resource management and multi-sensor interoperability, Internet of Things technology offers a viable platform for continuous data collection at a multimodal scale. Through comprehensive information aggregation, producers could achieve real-time monitoring of environmental conditions, flowering stages, and pollinator activity, enabling timely and precise decision-making for manual pollination interventions. Future research should focus on integrating engineering techniques with pollination biology, agronomy, and plant physiological analyses, while also addressing the specific needs of technicians and producers in order to maximize pollination benefits (Eyles et al. 2022; Kleijn et al., 2019).

5.2. Optimization of pollen application strategies

The overarching goal of PS-AP is to achieve high yields and high-quality produce with minimal waste. This requires an understanding of the specific needs of crops and their varieties, ensuring they receive sufficient pollen at the right time by employing tailored pollen application strategies. The correct dosage varies between different crops and even between different varieties within the same crop. Broussard et al. (2021) conducted artificial pollination experiments on kiwifruits, revealing that the full seed rate of different varieties ('Hayward' and 'Zesy002') was not significantly influenced by the timing of pollen application but was highly correlated with pollen dosage. Inadequate pollination can result in low crop bearing, prompting many studies to investigate the impact of supplemental pollination on improving crop productivity, leading to recommendations for increasing pollen application to enhance pollination benefits (Mesnoua et al., 2024; Xu et al., 2023). However, exceeding a certain threshold of pollen loading may cause overall yields to stabilize or even decline. While maximizing fruit set have potential to enhance production, it may also reduce the quality and marketability of individual produce (Akhavan et al., 2021; Snelgar et al., 1998). Excessive crop loads also increase the demands of orchard management, such as the need for more intensive thinning and higher resource consumption, including water and fertilizer. This overburdening of resources can also heighten the risk of biennial bearing in perennial crops. The drawbacks of excessive supplemental pollination have also been observed in nut crops like pistachios and walnuts, where overloading stigmas with pollen can increase competition between pollen grains and potentially reduce final yield (Mazinani et al., 2023; Vaknin et al., 2002).

Wide dispersal of pollen can be achieved through mechanized methods, such as vehicle-mounted or drone-mounted pollination systems. These are effective for crops with consistent cropping patterns, dense inflorescences, and easy access to pollen. The objective is to blanket the entire area of plants with pollen, ensuring that every viable flower has the opportunity to be fertilized. Despite the long-standing implementation of standardized cropping patterns in commercial orchards and large-scale fields, growth differences between plants are inevitable. These differences manifest in variations in canopy structure, size, flowering volume, and other factors (Mao et al., 2024). Crops with differing canopy density and blooming performance place varying demands on pollination, requiring tailored approaches to ensure effective fertilization (Sánchez-Estrada and Cuevas, 2020; Vera-Chang et al., 2016). In this case, variable pollination, which adjusts pollen load and spray rate based on the specific needs of crops and individual growth differences, appears to be a feasible approach. Sensor-based variable-rate spraying systems, equipped with widely-used stereo vision and laser scanning technologies, offer a solid foundation for variable-rate pollination through canopy recognition and geometric classification (Taseer and Han 2024; Wei et al., 2023; Abbas et al., 2020). In addition, a review by Eyles et al. (2022) on mechanical pollination in tree fruit and nut crops highlighted the potential of considering structural, phenological, and physiological processes at the tree scale to inform canopy management practices, ultimately maximizing pollen transfer and pollination benefits. When combined with advanced evaluations of flowering volume, the application prospects of this solution are very promising.

Precision pollination, which targets flowers or inflorescences directly using robots or micro air vehicles, offers a finer-grained approach compared to traditional methods. This technique focuses on delivering pollen specifically to flowers or their pistils rather than broadly dispersing it over a wide area, which can be particularly beneficial for high-value crops with individually growing inflorescences. Advanced technologies, such as machine vision and AI, are employed as analytical tools to accurately identify stages of flower development and selectively target flowers for pollination (Gao et al., 2023). This approach has demonstrated the potential to minimize the need for fruit thinning by ensuring that only the desired number of flowers is pollinated, thus achieving ideal fruit loads on each plant. However, despite the promise of this technology, producers often prioritize operational costs over the feasibility highlighted by researchers (He et al., 2022). Challenges such as limited pollination speed and unexpected equipment investment must be addressed before precision pollination can be practically implemented on a commercial scale.

5.3. *Efficiency improvement for autonomous pollination*

At the forefront of technological advancements in artificial pollination, autonomous pollination systems are emerging as a promising and scalable alternative to traditional methods. Equipped with advanced sensors and AI-driven algorithms, these systems can perform precise and consistent pollination tasks without human intervention. Among these new ideas, robotic arms that align flowers close to each other are gaining momentum as a way to improve the accuracy and efficiency of pollen delivery. These robotic arms, which feature multiple degrees of freedom, are particularly adept at navigating and avoiding obstacles in complex environments. However, many prototypes adopt an intermittent pollination strategy, where the pollination task is not synchronized with the movement of the mobile chassis, thereby reducing overall efficiency.

Some researchers have focused on improving the efficiency of autonomous pollination through mobile pollination strategies. By coordinating and strategically planning the motion of the robotic arm, the movement path of the actuator during pollination can be minimized, thereby increasing efficiency during task intervals. Wei et al. (2024) demonstrated that a mobile pollination approach using a redundant cooperative control strategy, which takes into account the redundant motion capabilities of both robotic arm and chassis, achieved a 94 % success rate and improved efficiency by 36.4 % compared to intermittent strategies in greenhouse tomato pollination (Fig. 7a). In fact, similar task planning and solutions can be adapted to other agricultural scenarios, such as harvesting and pruning.

Incorporating multiple actuators into autonomous pollination systems provides another option for enhancing efficiency. Multiple actuators enable the system to simultaneously perform pollination on several flowers, reducing the time required and expanding the coverage area. In a study on kiwifruit pollination, Williams et al. (2020) addressed the dynamic delays of the actuator-sensor system and developed a simplified spray control model for mobile pollination, which achieved a pollination rate of 79.5 % at a travel speed of 3.5 km/h by a self-designed multi-nozzle spraying actuator during field orchard experiments (Fig. 7b). Compared to structured greenhouse environments, uncontrollable field conditions present additional challenges such as ambient winds and uneven terrain, which can reduce the accuracy of pollination. Despite these challenges, the potential for multi-machine collaboration holds promise for further efficiency improvements. By deploying multiple machines that work in concert, the pollination process can cover larger areas more quickly and accurately, making this approach particularly viable for commercial applications.

6. Potential risks of applying artificial pollination

Artificial pollination is implemented as an important support in addressing the global decline of pollinators and meeting the growing demand for food. This technology encompasses a wide range of methods, from manual pollination using hand-held tools to mechanized devices and advanced autonomous systems driven by AI. While manual operations offer significant benefits, including enhanced control over pollination timing and improved productivity, they are gradually being replaced by mechanized pollination that offers greater efficiency. Despite the promising results of these advancements, potential risks associated with its widespread adoption must be considered.

One of the main issues with artificial pollination is related to the safety and security of humans during operation. As current artificial

(a) (b)

Fig. 7. Examples of mobile operation in autonomous pollination. (a) Pollination for tomato in facility greenhouse by target contact vibration (Wei et al., 2024); (b) Pollination for kiwifruit in field orchard by target pollen spraying (Williams et al., 2020).

pollination services for actual production are often designed for large-scale operations using strategies in NPS-AP and PS-AP, this could lead to unintended pollen dispersal, temporarily increasing airborne pollen concentrations in pollinated areas. This has the potential to cause severe allergic reactions and respiratory illnesses among farm workers and nearby residents who are sensitive to pollen, a group that accounts for more than 20 % of the population (Guryanova et al., 2022; Ravindra et al., 2022; Singh and Kumar, 2022). In addition, a review by Dingley et al. (2022) highlighted the dangers of prolonged exposure to artificial acoustic or airborne vibration methods used to promote self-pollination, including harmful effects from specific sound frequencies and cumulative damage from excessive sound intensity. Therefore, establishing and strictly enforcing compliant operating standards and providing adequate protection for workers are essential steps towards minimizing these risks as much as possible.

The impact of artificial pollination on the broader ecosystem also raises significant concerns, particularly regarding pollinator biodiversity. Natural pollinators, such as bees, butterflies, and other animals, play a vital role in maintaining biodiversity through the cross-pollination of a wide range of plant species (Katumo et al., 2022). Increased reliance on artificial pollination could lead to a decline in natural pollinator populations as their ecological role diminishes (Potts et al., 2018). This reduction in pollinator biodiversity may intensify plant competition, leading to a chain reaction on plant diversity and on the animals that depend on these plants for food and habitat (Wei et al., 2021). Artificial pollination has been developed and implemented as a supplement to natural pollination, focusing on the economic efficiency of specific commercial crops. However, this approach often overlooks the broader ecological implications, with the potential risk of causing imbalances in local ecosystems and weakening their resilience and adaptability to environmental change.

To mitigate these potential impacts, achieving a sustainable balance between artificial and natural pollination practices is crucial. This balanced approach would involve preserving habitats, implementing pollinator-friendly farming practices, and responsibly using artificial pollination to ensure it supports rather than replaces natural pollinators. Through these integrated strategies, advances in pollination technology can align with ecological sustainability, contributing to both agricultural productivity and ecosystem health.

7. Conclusions

In this paper, a comprehensive review of artificial pollination was conducted, exploring its various categories and applications. As global food demand continues to rise and natural pollination services face increasing threats from habitat loss, intensive agriculture, and climate change, artificial pollination emerges as an essential supplement to ensure food security. To achieve effective artificial pollination, it must be meticulously tailored to the physiological needs of specific crops, ensuring that each plant or flower receives adequate pollen at the optimal time. Despite the growing interest in autonomous pollination systems, current applications still face challenges related to operational efficiency due to their relatively slow speed. These systems, which integrate advanced sensors and AI-driven algorithms, hold the potential to perform precise and consistent pollination tasks without human intervention. In addition, this refined approach allows for selective pollination, targeting only desired flowers to manage crop loads and reduce the additional costs associated with thinning, which is specifically valuable for high-value crops with low physiological fruit dropping. It is also important to recognize that artificial pollination should not be viewed as a substitute for natural pollination but rather as a complementary tool. Natural pollinators play an irreplaceable role in maintaining biodiversity and ecosystem health. Therefore, efforts to advance artificial pollination should be coupled with initiatives to protect and restore natural pollinator habitats. There is a need to strengthen collaboration between agronomists, technology developers, and producers to further promote the development of artificial pollination technologies and systems while minimizing potential risks.

CRediT authorship contribution statement

Leilei He: Writing – original draft, Methodology, Investigation, Data curation. **Xiaojuan Liu:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Yusong Ding:** Writing – review & editing, Methodology, Conceptualization. **Xudong Jing:** Writing – review & editing, Methodology. **Haojie Dang:** Writing – review & editing, Methodology, Conceptualization. **Bryan Gilbert Murengami:** Writing – review & editing, Methodology. **Lamin L. Janneh:** Writing – review & editing, Methodology. **Rui Li:** Writing – review & editing, Methodology, Conceptualization. **Spyros Fountas:** Writing – review & editing, Methodology, Conceptualization. **Jayme Garcia Arnal Barbedo:** Writing – review & editing, Methodology, Conceptualization. **Longsheng Fu:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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