agronomy

Review

Artificial Pollination Technologies: A Review

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Abstract: Pollination is critical for the production of many crops, and both insect- and wind-based pollination systems are increasingly disrupted by bloom asynchrony, weather events, and high demand for available insect pollinators. Artificial pollination systems can provide a security of yield even in poor pollination scenarios, and have been attracting increasing attention over the past decade. Here, we review pollen collection and pollen application technologies that have been employed to date. Major categories of mechanical pollination technology include: hand-pollination, handheld and backpack devices, vehicle-mounted devices, unmanned aerial vehicles (UAVs), and robotic and autonomous pollinators. The majority of the artificial pollination systems above are used to supplement natural pollination, but for some crops, these systems were found to perform adequately by themselves, including kiwifruit, olive, date palm, walnut, tomato, and hybrid maize seed. These systems often treat pollen as a system input, creating a chicken-and-egg problem in which the system is not economical without pollen and the pollen is not economical to collect without wide uptake of the system. To combat this, there has been success in developing mechanical harvesters for some crop plants (particularly almond and maize), but future work is needed for artificial pollination to be a commercial reality for the increasing number of cropping systems that are experiencing pollination deficits.

Keywords: mechanical pollination; pollination technology; pollen harvesting; pollen application; unmanned aerial vehicles; robotics; asynchrony; pollination failure

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1. Introduction

Most agricultural crops require pollination (through insects or wind) for successful production. Weather events or asynchrony in flowering between a crop and its polliniser can cause pollination failure, and insect-pollinated crops are additionally vulnerable to declines in insect pollination services. The majority of insect pollination to crops is provided by managed Western honey bees (*Apis mellifera*) and, for some crops, the regional demand for pollination services can be extreme during bloom, requiring bees to be transported over large distances to service the crop. Globally, pollinator-dependent crops represent an increasing proportion of total agricultural area [1,2], increasing demand on the supply of honey bees and pollination services. While the number of honey bee colonies has increased across the globe in response, the growth rate has not kept pace with demand [3], leading to pollination deficits [4] and increased prices for pollination services. In addition, a number of intersecting issues threaten hive supply during the pollination window, including: increasingly frequent and severe weather events (such as fires, floods, and cyclones) destroying hives as well as resources in the landscape necessary to sustain them [5]; restrictions limiting transport of hives between regions [6,7]; reduction in colony resilience due to pesticide exposure [8]; and competition for hives among crop producers [9]. Sustainable production of high-value crops may require new approaches to pollination services that supplement or substitute honey bees if, or when, there are not enough colonies available to meet demand.

Humans have tried to replace natural pollinators before, with varying degrees of success. Date palms have successfully been hand-pollinated by humans for over 4000 years—documented since at least the Code of Hammurabi [10]. Other plants have been more challenging, as most have smaller flowers, produce less pollen, and have a shorter working life for each pollen grain. Pollen from many plant species has been successfully collected and stored for breeding new varieties, but this requires a tiny fraction of the amount of pollen required to fully replace, or even supplement, insect pollinators [11]. Beyond date palm, the economics of only a handful of other crops, most notably vanilla, can support the labour-intensive cost of pollination by hand. Even in cases where manual pollination has been successful—such as the human pollinators of Maoxian County in China, where a massive force of labourers hand-pollinated vast tracts of apples with paintbrushes in 2001 [12]—they are not always sustainable. Researchers visiting Maoxian Country 10 years later found most of the apple trees had been cut down and replaced by wind-pollinated walnut and self-fertile loquat; both can be pollinated with few, or no, insects [12]. Manual pollination in Maoxian County arose because the high use of pesticides created an environment where beekeepers refused to risk their hives. It was abandoned due to labour migration into the cities.

For several decades, a handful of industries—primarily stonefruit, pipfruit, and kiwifruit—successfully collected and applied pollen using a wide array of pollination technologies, from hand applicators through to tractor-mounted spray systems. Kiwifruit is a flagship crop for artificial pollination, where its dioecious nature (male and female flowers on separate plants), lack of nectar, and high potential for fruit set led to early exploration of artificial pollination [13]. This research demonstrated that supplementing insect pollinators with artificial pollination increased both fruit set and fruit quality [14,15]. The success of early trials in New Zealand led to the development of an array of pollen delivery devices that reduced labour and made artificial pollination an important tool for many growers, and it has become the primary strategy used in Italy [16], southern China [17,18], and Korea [19]. Elsewhere, it is used as a supplemental pollination strategy, with approximately half the kiwifruit growers in New Zealand using supplemental artificial pollination. Several New Zealand companies commercially harvest and mill kiwifruit pollen, supplying it to domestic and global growers [20,21]. Tools developed for kiwifruit have been adapted for, and employed in, other cropping systems [22–24].

Field-scale artificial pollination of pipfruit, stonefruit, almonds, and date palm have also been explored in the literature, with early work also occurring in tree nuts, recently reviewed by Eyles et al. [25]. In apple, field-scale trials began early on, involving spray planes [26], broadcast tractor sprayers [27], and even explosives [26]—although often with disappointing results, showing little or no improvement in yield or quality. Recent work has favoured handheld devices, as well as sprayers and blowers mounted on vehicles, which have shown yield benefits across a number of crops [25,28]. Generally, uptake of artificial pollination has been modest to date but is accelerating as technology moves out of the lab.

Most artificial pollination technologies require a high-quality source of pollen to be successful—a chicken-and-egg situation for crop producers in places that lack existing pollen harvesting and supply infrastructure, although a number of small-scale pollen collection methodologies exist. Despite these limitations, the last decade has seen many researchers, as well as small and start-up companies, take on the pollination challenge, evidenced by the increasing numbers of patents published regarding artificial pollination devices (Figures 1 and 2; Appendix A).

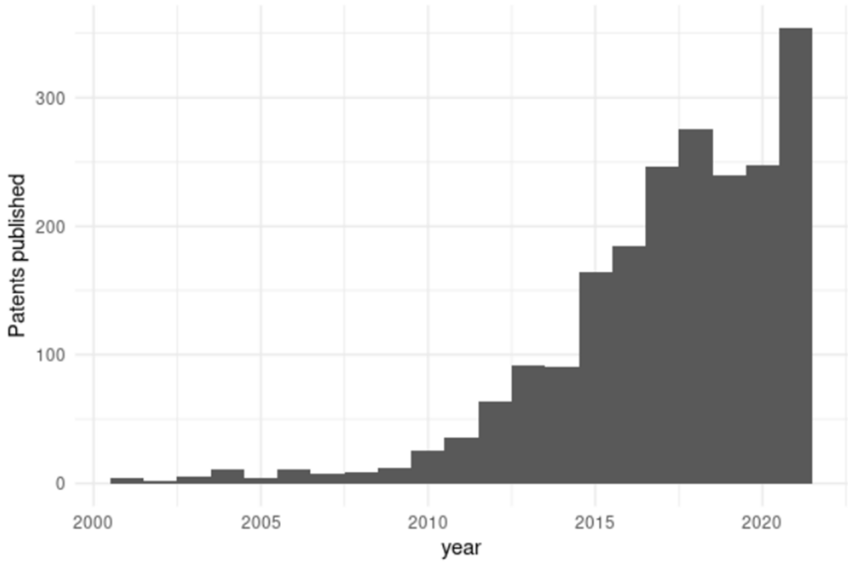

Figure 1. Number of patents published for artificial pollination devices worldwide per year between 2001 and 2021.

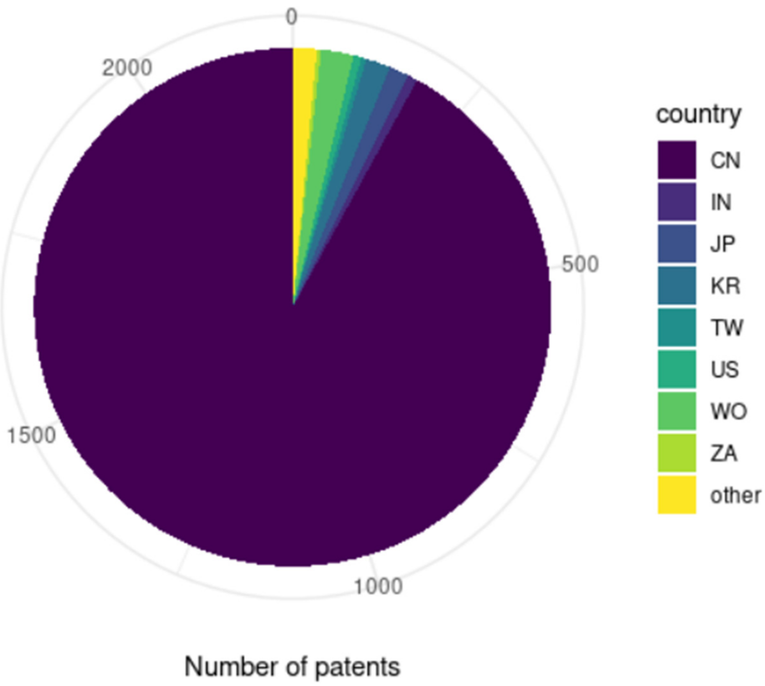

Figure 2. Filing location for patents published for artificial pollination devices worldwide per year between 2001 and 2021 for countries that had at least 5 patents. Countries are listed by their two-letter code, in order; China, India, Japan, Korea, Taiwan, United States, "WO" is worldwide patents, South Africa, and "other" represents an additional eleven countries.

2. Pollen Collection

The quantity of pollen required for artificial pollination depends on both the crop species and the device used to deliver it. Some crops, such as date palm and anemophilous (wind-pollinated) trees, produce large quantities of pollen that is relatively easy to collect. However, most crops, including almond, apple, and kiwifruit, produce a relatively small number of pollen grains per flower and require more labour [29]. This suggests two goals for practical artificial pollination: securing a supply of inexpensive, high-quality pollen, and ensuring that as little pollen as possible is wasted during application.

Pollen is typically most viable at the time of anthesis [30], just as the anthers begin to release pollen. However, collecting flowers at this stage can result in significant pollen losses, as flowers can release the majority of their pollen on the day of anthesis [15,28]. To obtain the highest quantity of pollen per flower, it is generally preferable to harvest immediately prior to anthesis to prevent pollen losses [30].

Three approaches have been taken to collecting pollen: hand-picking or mechanically harvesting flowers just prior to anthesis and extracting the pollen; vacuuming pollen directly from flowers; and using pollen traps attached to honey bee hive entrances to obtain bee-collected pollen from the crop (Figure 3).

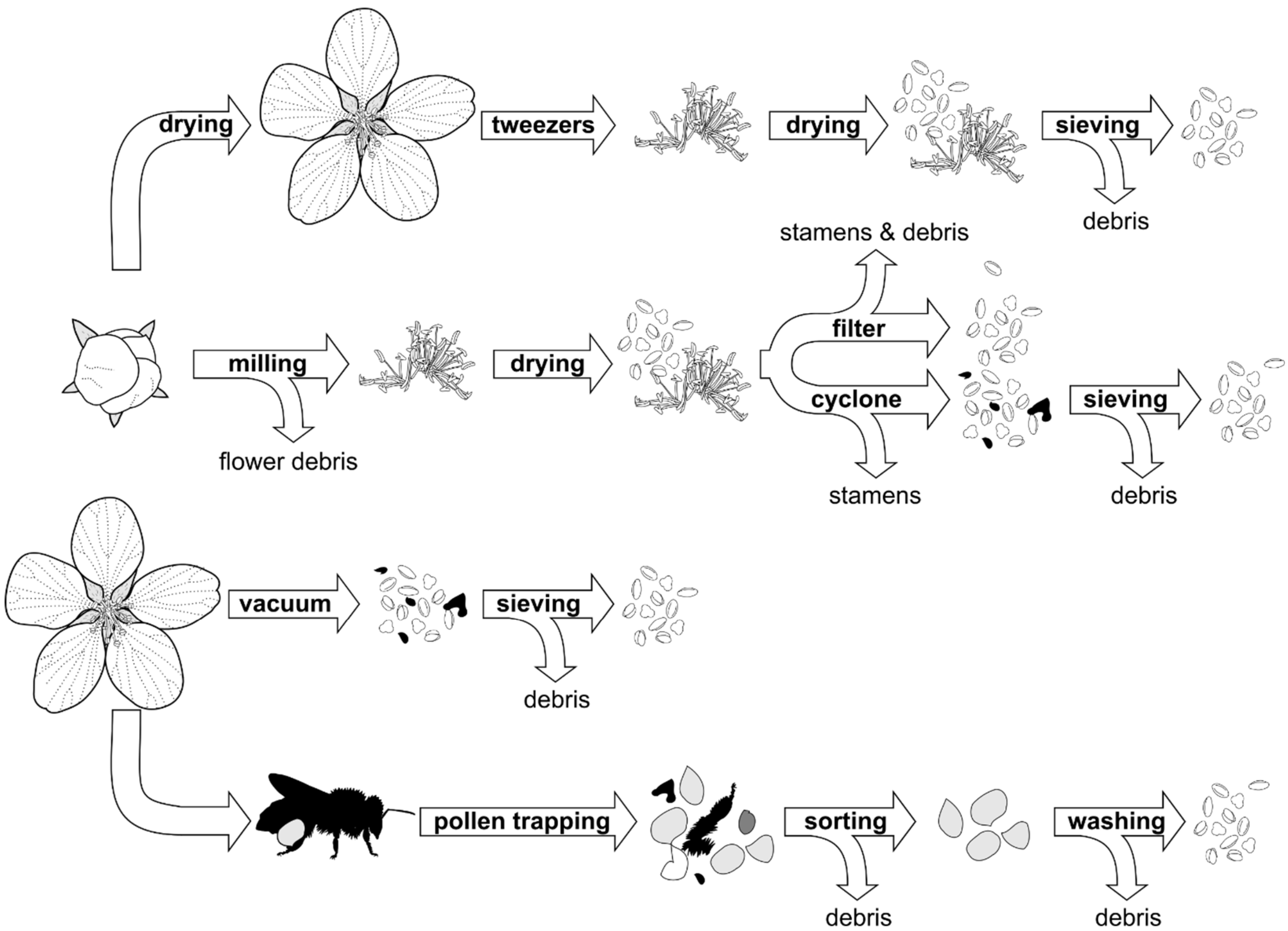

Figure 3. Different processes for extracting pollen from entomophilous flowers for artificial application. Illustration by Melissa Broussard, Plant and Food Research.

Hand-picking individual flowers, inflorescences, or panicles has been successful in plants that produce copious quantities of pollen. For date palm, entire panicles are harvested, dried, and then filtered [28]. The tassels, strobili, or catkins (male reproductive structures) of wind-pollinated plants can be handled similarly [24,31–35].

Entomophilous plants (pollinated by insects) typically produce less pollen, making collection more challenging. Anthers can be manually excised from individual flowers—an approach employed in artificial pollination research [36,37], but the method is labour-intensive and is economical only for small-scale application (e.g., breeding programmes, vanilla and cacao pollination). Larger-scale pollination was enabled by methods of mechanically separating pollen from whole flowers for kiwifruit [15,23,38,39], cherimoya [30], date palm [22,28], and almond [40]. This typically involves drying the collected flowers, milling the flowers to separate the anthers from other floral structures, allowing the anthers to dehisce under controlled conditions, and using a filter- or cyclone-type cleaning machine that extracts the anthers and pollen, which can then be dried. The pollen is then extracted using a sieve attached to a vacuum. Anther-drying has been identified as a rate-limiting step in the pollen-milling process outlined above, but attempts to reduce drying time by increasing temperature or air-flow negatively affect viability beyond a certain point [15].

Flowers are commonly sourced from growers (either to apply back to the same orchard, or sold for pollen processing), and increasingly, from orchards grown specifically to supply pollen. There are, however, several challenges with orchards dedicated to pollen production, including lower financial return than fruiting orchards and a very brief, high-labour demand for harvesting flowers. As a result, a combination of dedicated pollen production and fruiting orchards is likely to remain in use [41–43]. Anecdotally, harvest rates for manual picking vary wildly with the experience of pickers and orchard management practices. A mixed-sex kiwifruit orchard (not dedicated to pollen production), for example, could yield between 20 and 200 kg-flower/ha, with a typical yield of 30–40 kg-flower/ha from a well-trained team in a well-managed orchard. Picking rates vary from less than 1 kg-flower/day up to 40 kg-flower/day, although again this is heavily dependent on experience and orchard practice. Pollen yield for good male cultivars reportedly varies from 8.5 g/kg-flower up to 10.5 g/kg-flower with careful attention to the process. Poor-producing cultivars may yield only 4 g/kg-flower (pers. comm. Mat Johnston).

Recently, a mechanical pollen harvesting device has been developed for almond, which uses a tree shaker to dislodge flowers at full bloom, collecting them on a tarp beneath the tree [40,42]. Flowers are dislodged at various states of maturity, so pollen recovery rates are lower on a per-flower basis, but bulk harvesting significantly reduces the cost of collection. Harvesting machinery has also been developed for maize flowers, removing tassels for later milling and application in the production of hybrid maize seed [35]. More than 80 L of pollen can be collected each day with this machinery, a high yield made possible by the fact that maize is wind-pollinated and therefore produces large quantities of pollen [35].

Mechanical harvesting techniques are relatively new, so the primary driver of pollen cost is labour. In November 2022, during the pollination season, the price was NZD 8250/kg (USD 5200/kg) for kiwifruit pollen in New Zealand, and USD 7500–8500/kg for pipfruit and stonefruit pollen from the USA [44]. In contrast, date pollen is available at USD 150–225/kg in the USA and Mexico [28].

In the pursuit of less-expensive material for artificial pollination, there has been considerable interest in pollen collected by honey bees, despite its variable viability and purity. The impurities stem from two sources: honey bees mix pollen with nectar to form pollen pellets on their legs, and additionally may not be foraging exclusively on the target crop. Trials have successfully demonstrated fruit set using bee-collected pollen in kiwifruit [45–47], peach [48], apple [48,49], pear [48,50], almond [51,52], and canola [53]. Researchers found, however, that fruit drop was higher and fruit weight lower in flowers fertilised with bee-collected pollen instead of pure pollen. Consequently, higher application rates are required. Several studies have noted lower fruit set from bee-collected pollen, which was improved by washing it and formulating it to remove excess sugars, which otherwise appear to inhibit pollen germination [30,49,53]. A recent study found that pollen on bees' bodies is much more able to achieve fruit set than that stored on their corbiculae; bees that do not pack their pollen with sugars (e.g., *Megachile rotundata*, Megachilidae; *Halictus* spp., Halictidae) do not show the same detrimental effect on pollination potential [53], but it has not yet been possible to collect pollen from these species at sufficient scale. More research into the handling and processing of bee-collected pollen is needed before it can be used for large-scale pollination.

Pollen can also be vacuumed directly from some flowers, catkins, or strobili. The viability of pollen collected in this way is generally much higher than that with other methodologies [30,38]. Furthermore, in some designs, the vacuum may be reversed to apply collected pollen immediately without further processing or storage. Vacuum collection has successfully been employed to collect quantities of larch [54], Douglas fir [55], olive (manual [23], mechanised [30]), kiwifruit [23,38,56], and cannabis [57] pollen. Pollen yield varies with plant species, with yields 500 cc/h being reported for Douglas fir [55], 140 g/h being reported in kiwifruit [38] and 100–200 g/h in olive (cultivar-dependent [23]). A handful of prototype mechanical pollen-harvesting systems have been developed to vacuum pollen from trees. These rely on surrounding the tree with a vacuum and filtration system, while using a tree shaker to release the pollen (olive [30], larch [54]). These mechanised systems can harvest up to ten times the quantity of pollen as handheld vacuum devices can, although the pollen tends to be of somewhat lower quality [54].

Different processes are explored in Figure 3.

After collection and processing, binucleate pollen can be put into cold storage and kept viable, often for several years. Storage conditions for particular species have been explored thoroughly in the literature on germplasm maintenance and plant breeding (recently reviewed by [58]). As long as the cold chain is maintained, it is not uncommon to be able to store pollen at −20 °C for 1–6 years with little loss of viability [23,28,58], giving producers flexibility to apply pollen from one year to the next, helping to mitigate synchronicity and production risks.

3. Pollen Application

Many methods to pollinate plants have been explored. Broadly, there are two main approaches: pollen can be applied dry (possibly diluted with a neutral carrier, such as charcoal, to help manage application rates), or wet (generally suspended in an aqueous liquid, often with additives to ensure isotonic balance with pollen cells) (Figure 4). A third option is available for selected, self-compatible crops—such as tomato—where vibrating the floral structures, either through direct contact or with a puff of air, shakes loose pollen to fertilize the flower [59].

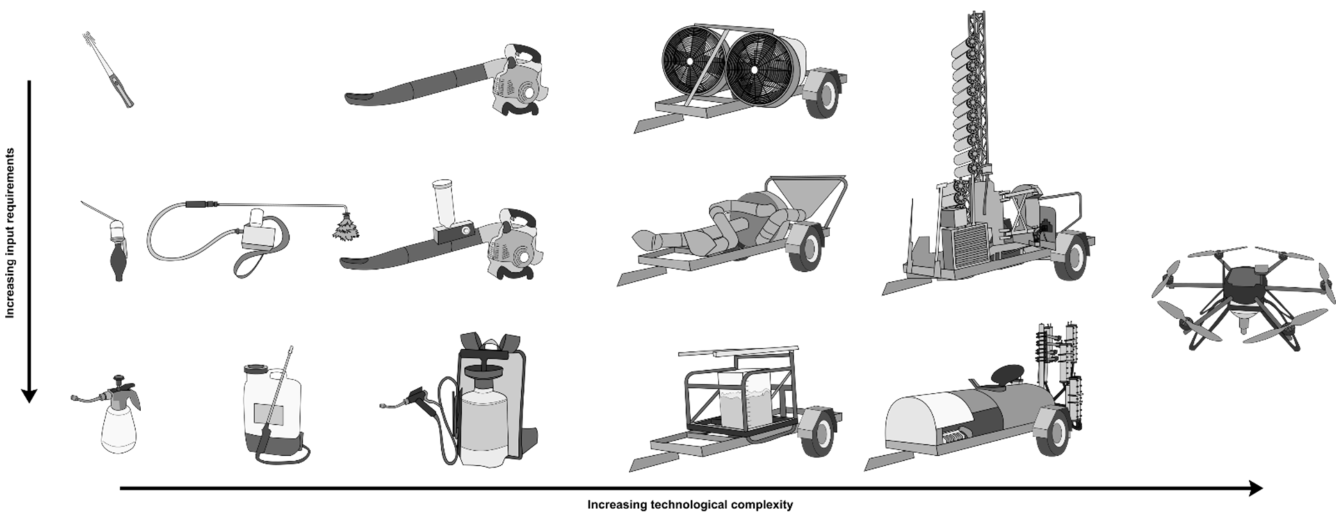

Figure 4. Diagrams of examples of commercially available pollination technologies. Top row: vibratory technologies requiring no external pollen. Middle row: dry-application technologies requiring pure pollen and (optionally) diluent powder. Bottom row: wet-application technologies requiring pollen and a compatible carrier solution. Illustration by Melissa Broussard, Plant and Food Research.

Most application literature measures results directly in terms of fruit or seed set, as pollen requirements have been characterized for relatively few crops [60–63]. Research has shown that liquid-carrier (or dry diluent composition) formulation, temperature, time of day, weather, stigma receptivity, and flower age all influence pollination efficacy [41,61,64–68]. These factors are largely ignored in much of the work published on alternative pollination systems.

Dry application has two important advantages over wet pollen application:

- Dry pollen delivered to non-target areas (e.g., petals, leaves) often remains viable and can be redistributed to the stigmas by bees [69], while pollen remains viable only for a short time once it becomes wet (30–100 min; [15,70]);

- Suitable aqueous carrier solutions have been demonstrated for kiwifruit [36], cherry [70], pear [71,72], pistachio [32], and date palm [28], but new solutions must be created, or customized, and validated for each crop.

Insect pollinators take advantage of naturally occurring electrostatic forces, which help transfer pollen from bee to flower [73]. Research and commercial application have demonstrated that electrostatically charging dry pollen can improve the proportion captured by the flower by 5- to 10-fold [70,74–76]. However, droplets in aqueous systems generally have larger mass, making it more difficult to attach a sufficient charge to the pollen to affect its trajectory.

The main advantages of aqueous systems are:

- Enabling more targeted delivery, efficacy during damp conditions where insect pollinators may be scarce [15,23,38];
- The additional liquid mass increases momentum for targeted delivery, reducing the risk the pollen is dispersed by wind.

The majority of the artificial pollination systems in Figure 4 are used to supplement available bees, but for some crops, these systems perform adequately by themselves, including kiwifruit [16,19,23,77–80], olive [23], date palm [28], walnut [33,81], tomato [59], and hybrid maize seed [35].

In cases where insect pollinators are abundant, bees perform equivalently or better than artificial pollination for kiwifruit [56,82,83] and kiwiberry [84,85], but when conditions are not optimal, particularly in years where local conditions limit pollinator activity, correctly applied supplemental pollination can increase seed number and fruit size [16,19,23,78–80]. Pollen is typically applied in two or more passes through the orchard [86], but a single pass at petal fall has been effective in Italian kiwifruit orchards [23].

3.1. Hand-Pollination

Manual pollination with a paintbrush, stick, or pole tipped with a feather-brush is labour-intensive [12,23,41,87]. This cost can be sustained by some high-value crops (Table 1) [11], particularly when pollen does not need to be collected (e.g., tomato), the pollen is produced in abundance and collection costs are low (e.g., date), or the market value of the crop is very high (e.g., vanilla). Where mechanisation is available (even if only in the form of a vibratory wand), it is often more effective and economical than manual pollination [23,59,72,86,87].

Table 1. Summary of artificial pollination methods used in global cropping systems.

Pollination Method	Example Technologies	Applicability	Crop Types (Commercial/ *Prototype*)	References
hand-pollination	paintbrush, feather, velvet, tuning fork, stick, brushing flowers together	most plant species	cacao, cherimoya, date palm, dragon fruit, vanilla, indoor tomato (regions without bumble bees)	[11,28]
handheld devices	vibrating rods, electric toothbrush, leafblowers	self-compatible plants	cacao, indoor tomato, capsicum, eggplant	[59,88,89]
	puffers, pneumatic applicators, sprayers	open-flowered plants where pollen is available	kiwifruit, cherimoya, stonefruit, pipfruit, pistachio, date palm, larch (timber breeding)	[23,28,31,41,72,90–92]
vehicle-mounted devices	mobile fans	self-compatible plants	kiwifruit, olive	[23]
	mobile pollen sprayers and blowers	open-flowered plants where pollen is available	kiwifruit, pipfruit, stonefruit, date palm	[23,27,28,93]
vehicle-mounted devices with electrostatic charge	mobile electrostatic pollen sprayers and blowers	open-flowered plants where pollen is available	*kiwifruit*, almond, pistachio, pipfruit, stonefruit, *larch* (timber breeding)	[54,94,95]
unmanned aerial vehicles (UAVs)	drones	wind-pollinated	almond, pipfruit, stonefruit, date palm, walnut	[33,51,81]
robotics	autonomous vehicles, mobile robotic arms	to date, each technology has focused on a single crop	hybrid maize, *kiwifruit*, *caneberries*, *strawberry*, *indoor tomato*	[35,77,96–100]

3.2. Handheld Devices

Handheld devices, such as blowers, sprayers, and vibratory wands, are quicker and easier to use for applying pollen than simple hand tools, such as paintbrushes, significantly reducing labour costs. Within these technologies is a constellation of inventive processes, but we found that four general categories of applicators are commonly used in commercial settings: vibratory wands (particularly for indoor tomato production); pneumatic devices tipped with a brush or feather-brush (for orchard crops); handheld blowers (often utilising commercial leaf blowers as a base component); and modified agricultural sprayers (Table 2). Directed broadcast of pollen using a handheld leaf blower has been estimated to deliver only 1% of pollen to stigmatic surfaces [101]; for dry application, some of the remaining 99% may then be redistributed by bees [69]. Other approaches have been explored, including a bubble gun [102], and a handheld electrostatic pollinator that can both collect and apply pollen [103]. However, both require further research to overcome the technical challenges (e.g., poor targeting and damage to floral structures from coronal discharge) before they could become commercial realities. A different handheld electrostatic pollinator was used successfully for the indoor cultivation of hybrid larch seed, but requires an external pollen supply [31].

Table 2. Types of handheld devices used for artificial pollination.

Mode	General Type	Description	Examples	References
Vibration	Vibrating wands	battery-powered vibrating devices to pollinate self-compatible solanaceous crops	electric toothbrush	
			Vibri-Vario, Royal Brinkman, ‘s-Gravenzande, The Netherlands	[104]
			off-label use of vibrators and sex toys	[105]
	Blowers	often an unmodified leaf blower; used to vibrate plants or move airborne pollen	leaf blowers, handheld dusters	[88,89]
Dry	Puffers	rubber diaphragm, receptacle and tube	“Columbus” (コロンブス), Japan	[90,91]
	Pollination guns	handheld battery powered device with a pollen receptacle/vortex chamber for applying targeted dry pollen	handheld pollen duster, USA	[28,86,106]
	Pneumatic dusters	pole tipped with feather brush or fan with pneumatic pollen supply; designed to reach into orchard canopy	“Love Touch” (ラブタチ), Japan	[28,91]
	Handheld blower device with pollen reservoir	motorised devices with a pollen reservoir to disperse dry pollen over a large area; often a modified leafblower	KiwiPollen Duster, KiwiPollen, New Zealand PollenPlus Pollen Blower, PollenPlus, New Zealand Soffi@PollineZ, Biotac, Verona, Italy “Speedy” Dall’Agata, Forlì, Italy Backpack AirShear, KiwiPollen, New Zealand	[21,23,28,34,41,107]
Wet	Handheld wet applicator	handheld bottles or pressurised backpack sprayers	Cambrium, KiwiPollen, New Zealand ElettroEASY, Volpi, Mantova, Italy	[23,24,28,41,52,92]

3.3. Vehicle-Mounted Devices

Sprayers, blowers, and fans of various kinds have been developed for large-scale pollination (Table 3). These devices require far fewer person-hours than equivalent handheld devices [28,86]. Early trials with apples used spray planes [26], and broadcast tractor sprayers [27]). In kiwifruit, broadcast systems were developed in the 1980s and had significant uptake by growers in the USA, Italy, and New Zealand for supplementing insect pollinators (replacing them in Italy, southern China, and Korea [16–19]) owing to their lower labour costs than hand application. In the Middle East, several inventions, including directed high-pressure sprayers drawn by tractors [28], have also performed as well as or better than the standard practice of manually pollinating date palm. Most of these devices are made to be towed behind a tractor, but some are also able to be mounted on farm ATVs for increased manoeuvrability, or on autonomous robotic platforms to reduce operator costs (e.g., XAG's R150, Guangzhou, Guangdong, China, a small, multipurpose autonomous spraying and mowing robot). XAG's ground-based pollen sprayer traversed a row of an apple orchard in 10 min, while hand pollination would take more than 2 h; however, pollination efficacy was not reported [93]. Broadcast wet sprayers are considered a last resort for pollination, and have lower efficiency in kiwifruit than dry applicators unless high rates of pollen are used [23], and also failed to deposit any pollen on the stigma of the much smaller Japanese plum flowers [14].

By their nature, non-targeted systems are wasteful, as pollen grains that settle on leaves, orchard structures, and branches do not fertilise the flower (pollen grains that land on petals, which can be redistributed by bees, are in the minority). To address this, researchers have investigated directed broadcast of electrostatically charged pollen, primarily for almonds, but also for apple, pear, sweet cherry, kiwifruit, and pistachio. Directing the pollen into the canopy reduces the amount of pollen lost to the wider environment, while positively charging the pollen increases attraction to pointed structures (such as styles), increasing pollen deposition [108]. Most of the work investigating electrostatic charge in pollination has involved an Israeli group led by Gan-Mor [74,75,108], and two US groups [109,110]. The application of electrostatic charge has increased pollen deposition on stigmas and improved the fruit set of almond, pistachio, date, apple, cherry, and pear under poor pollination conditions [70,94,110]. In general, for insect-pollinated crops other than kiwifruit and date palm, broadcast pollination is applied in addition to bee pollination, where it may improve fruit or nut set in years where pollination is poor [70,110]. However, there have been few studies on the effects of electrostatically charged pollen application on insect-pollinated crops without the assistance of bees; a trial from the grey literature suggests that the systems are no substitute for insect pollinators—almond yields were 1.3% without pollination, 17% with electrostatic pollination, and over 50% with insect pollination [111].

Table 3. Representative pollination devices mounted to tractors with and without electrostatic charge capability.

Mode	General Type	Examples	References
Vibration	Fan	Ventola, Italy	[23,41]
Dry	Pollen blowers	QuadDuster, KiwiPollen, New Zealand	
		AirShear, KiwiPollen, New Zealand	[107]
		PollenSmart, PollenSmart, New Zealand	[41]
		ATV Applicator, PollenPro, USA	[113]
		Scumby, Firman Pollen, USA [112]	[112]
		Palm Tree Pollination Machine, AgroPalms Machinery, Spain	[28,114,115]
	Electrostatic pollen blowers	Home-made devices	[116]
		Edete	[95]

Table 3. *Cont.*

Mode	General Type	Examples	References
Wet	High-pressure sprayers	Palm Tree Pollination Machine, Agrom Agro Machinery, IL	[28]
	Fogger/fine mist sprayers	Kiwi Pollen Boom Sprayer, KiwiPollen, New Zealand Spruzz@Polline TR, Gerbaudo, Cuneo, Italy XAG R150, China	[38] [23,93]
	Electrostatic sprayers	Electrostatic Spraying Systems, Inc., USA OnTarget, On Target Spray Systems, USA Fruit Tower, LectroBlast, USA	[111] [117] [116] [93]

3.4. Unmanned Aerial Vehicles (UAVs)

Drone-based pollination technology has received considerable attention (Table 4). The use of drones to pollinate crops is an attractive proposition both because drones have a good aesthetic fit for the job—they are airborne pollinators, like bees—and because drone technology has a lower barrier to entry than other forms of robotics [118]. These devices are either directly controlled by a pilot, follow a set path defined by the layout of orchard rows, or utilise a 3-D model of the environment built from an earlier pass by scouting drones [119]. Many drone pollinators are modifications of commercially available drones, particularly those designed for agrichemical sprays (e.g., [51,81,120]), but a number are also being custom-designed for pollination. Several pollination modes are being explored, including aerial broadcast distribution of pollen (Table 4), as well as utilising the drone's air vortices for pollination directly for hybrid grain production and glasshouse-grown self-compatible crops such as strawberry, tomato, pepper, and eggplant [121,122]. Other approaches have also been prototyped, including a microdrone with a fur pad for direct contact pollination [123], and a drone equipped with a bubble gun [102], but the drawbacks to both approaches—time in the first case and accuracy in the second—may limit their applicability in field situations. Indeed, contact-style drones have been criticised for trying to emulate bees too closely: it is neither practicable nor desirable to create tens of thousands of microdrones to replace a single honey bee colony [124,125], let alone the thousands of colonies used each year for intensive commercial cropping. Aerial broadcast approaches are likely to have the same limitations as ground-based broadcasts, with only a small portion of the pollen dispensed reaching the stigma where it can contribute to pollination.

Table 4. Representative drone-based artificial pollination technologies and their efficacies versus standard pollination practices.

Mode	Technology	Country [1]	Description	Crop	Development [2]	Pollen [3]	Efficacy [4]	Reference
Vibration	Polybee	SG	A multipurpose fee-for-service microdrone, pollinating self-compatible plants by air currents; indoor only	indoor strawberry, tomato, peppers, eggplant	commercial trials	-	n.d.	[122]

Table 4. *Cont.*

Mode	Technology	Country [1]	Description	Crop	Development [2]	Pollen [3]	Efficacy [4]	Reference
Dry	Dropcopter	US	A fee-for-service drone pollinator	almond, pistachio, pipfruit, stonefruit, date palm	commercial	+	=/+	[116] [126]
	Blue White Robotics	IL	A multipurpose agricultural drone originating from military drone designs	date palm	commercial	+	+	[127]
	Dro Bee	TN	A drone with machine vision capability to distinguish between receptive and unreceptive date palm panicles	date palm	prototype	+	=	[128]
	CODE Three Fourteen	AE	A fee-for-service drone pollinator; field-capable, 25–100× faster than human pollination	date palm	commercial trials	+	n.d.	[119]
	Aermatica 3D-Bly-A	IT/TR	A multipurpose agricultural drone capable of dispensing dry powder	walnut	commercial	+	+	[33,81]
Dry or wet	Wakan Tech	OM	Fee-for-service drone pollinator, 20–30× faster than human pollination	date palm	commercial	+	=	[120]
Wet	XAG "Electronic Bees"	CN	A multipurpose agricultural drone capable of dispensing atomised droplets	almond, pears	commercial	+	n.d.	[51]

[1] Two-letter country code abbreviations: AE: Arab Emirates, CN: China, IL: Israel, IT: Italy, OM: Oman, SG: Singapore, TN: Tunisia, TR: Türkiye, US: United States. [2] Stage of development: "commercial" means the product is available for use in commercial orchards, "commercial trials" means that an advanced prototype has been developed and field trials have been conducted or are underway, and "prototype" means that a working test model has been constructed. [3] Whether a device requires (+) or doesn't require (-) external pollen. [4] Efficacy compared with industry standard practice. This is self-reported for all drone technologies, except for one study using Aermatica's drone to pollinate walnut. n.d. = not disclosed.

Drone pollinators have seen a degree of commercial success in date palm pollination, historically pollinated by hand, by humans scaling the palm trees. As these trees produce copious quantities of pollen, there is little concern about waste from broadcast application [108], and the increase in time savings and improved safety from reducing tree climbing are significant [28,119,120]. Walnut pollination is another emerging area, with positive initial results in multiple countries, producing walnut kernels equivalent to those from wind-pollinated controls [33,81]. Dropcopter is the most well-known organization in this field. They provide pollination services to several crops (Table 4), including apple, cherry, and almond, reporting 53%, 40%, and 94% higher fruit set, respectively, over grower standard methods. However, little independent information about this system's efficacy (and those of most commercial drone offerings) is available to date.

Drones have considerable promise in tall tree crops where their ability to dispense pollen above the canopy is an advantage, with potential applications in conifer breeding [129] as well as wind-pollinated nut crops, which have shown promise in artificial pollination trials, including hazelnut, pistachio, and walnut [25,33,81].

3.5. Robotics and Autonomous Pollination

Autonomous robotic pollinators are often designed to target individual flowers for to minimize waste. Generally, machine vision is used to identify a flower that requires pollination. Broadly, two approaches to delivering pollen have been explored: moving an end-effector close to the flower, or spraying pollen from a distance. Several methods to apply pollen with an end-effector have been explored, including using a robot arm to brush the flower with pollen, touching the flower with a vibrating rod, and delivering a tuned vibration or air-blast to distribute pollen. Aside from brushing pollen, these methods apply only to crops that are self-fertile (e.g., tomato). Pollen sprayed from a distance can be delivered wet or dry.

Machine-vision systems employing deep learning can locate objects in images with 90%, or higher, accuracy, and with processing rates of up to 100 frames/s [97,130–133]. Systems employing robotic arms tend to be relatively slow. For example, research on a tomato pollination robot reported pollination speeds of 15–20 s per flower, rates that are not practical for pollination of commercial-scale crops [134–136]. Several systems that have already been commercialised are quicker—achieving application rates of about 2–5 s per flower cluster [137]—using several arms to pollinate multiple flowers at once and air-jets to reduce the fine motor control required to position end-effectors directly on a flower. For example, Arugga AI incorporate four sets of nozzles to pollinate high-wire tomato [98]. However, systems employing arms to move an end-effector close to the flower have been used only in greenhouse applications to date (Table 5). Field applications tend to favour spraying systems, delivering a dose of pollen from a vehicle moving through the crop. For example, PowerPollen are running commercial trials with a tractor-mounted boom holding 16 parallel autonomous pollinators for maize. The system mechanically funnels maize silks into the autonomous pollinator's spray region and deliveries a dose of electrostatically charged dry pollen as the tractor traverses the crop rows [35].

Table 5. Robotic artificial pollination devices.

Mode	Technology	Country [1]	Description	Crop	Development [2]	Pollen [3]	Efficacy [4]	Reference
Air jets	Arugga AI	IL	multipurpose autonomous platform with multiple targeted air jets	high-wire tomato	commercial trials	-	n.d.	WO2020095290A1 [98]
	Ultrasonic strawberry pollinator	JP	stationary platform using bursts of ultrasonic vibration to pollinate strawberry	strawberry	prototype	-	+	[99]
	Jiangsu University strawberry pollinator	CN	autonomous platform using targeted blowers to deliver heated air to strawberries	strawberry	prototype	-	n.d.	CN109588305B
Contact	BrambleBee	US	autonomous platform with single arm; did not pollinate real flowers	cane-berries	Early prototype	-	n.d.	[97]
	Stickbug	US	next iteration of BrambleBee; autonomous platform with six arms	cane-berries	Early prototype	-	n.d.	[138]
	Singrow strawberry pollinator	SG	UR3 robotic arm using an Augmentus platform developed for indoor strawberry pollination	strawberry	prototype	-	n.d.	[96]
	HarvestX	JP	autonomous platform with robotic arm tipped with a pom-pom for pollinating individual flowers	strawberry	commercial trials	-	n.d.	JP2019177764 [100]
	Iseki pollination robot	JP	autonomous platform with a robotic arm for vibrating tomato flowers	tomato	patented	-	n.d.	JP2011200196A

Table 5. *Cont.*

Mode	Technology	Country [1]	Description	Crop	Development [2]	Pollen [3]	Efficacy [4]	Reference
Dry	PowerPollen	US	tractor-drawn autonomous spray system capable of targeting individual maize silks; uses electrostatic charge; field-capable	maize	commercial trials	+	+	US10905060B2 [35]
	Pioneer Hi-Bred maize pollinator	US	tractor-drawn autonomous spray system capable of targeting individual maize silks; uses electrostatic charge; field-capable	maize	patented	+	n.d.	US9433161B2
	Monsanto maize pollinator	US	tractor-drawn autonomous spray system capable of targeting individual maize silks; uses electrostatic charge; field-capable	maize	patented	+	n.d.	WO2022046811A1
Wet	Autonomous kiwifruit pollinator	NZ	autonomous platform with nozzles capable of individual targeting; field-capable	kiwifruit	prototype	+	=/-	[77]
	Autonomous kiwifruit pollinator	CN	autonomous platform fitted with a robotic arm and nozzle, capable of individual targeting; field-capable	kiwifruit	prototype	+	=/-	[139]
	Autonomous tomato pollinator	CN	autonomous platform with nozzles capable of individual targeting	high-wire tomato	prototype	-	-	[134]
	Verdant Robotics	US	multipurpose autonomous platform capable of targeting apple flowers for pollination and thinning; field-capable	apple	patented	+	n.d.	US11308323B2

[1] Two-letter country code abbreviations: CN: China, IL: Israel, JP: Japan, NZ: New Zealand, SG: Singapore, US: United States. [2] Stage of development: "commercial" means the product is available for use in commercial orchards, "commercial trials" means that an advanced prototype has been developed and field trials have been conducted or are underway, and "prototype" means that a working test model has been constructed, "early prototype" means that a model which works on QR codes or similar proxies is being developed, "patented" means a patent for the device exists but the development stage is otherwise unknown. [3] Whether a device requires (+) or doesn't require (-) external pollen. [4] Efficacy compared with industry standard practice. This is self-reported for all available technologies. n.d. = not disclosed.

Autonomous robotic pollinators equipped with expert-informed targeting systems could identify and target flowers that produce the best fruit, enabling intelligent pollination services—a possibility suggested by Verdant Robotics' patented apple pollinator and flower thinner (US11308323B2). Unfortunately, very few data are available about the pollination efficacies of the above devices. The prototype ultrasonic strawberry pollinator was able to perform better than hand pollination [99], while the prototype tomato pollinator performed substantially worse [134]. PowerPollen reported success in hybrid maize production, with a 20% boost in seed yield over current practice [35].

Pollen delivered in an aqueous suspension, sprayed from a moving platform, has demonstrated speeds more practical for intensive commercial cropping [77]. In 2019, during field trials of the autonomous research prototype robot, the machine fully pollinated >670 export-quality "Hayward" kiwifruit, without contribution from insect pollinators, from a platform moving at 2.5 km/h. Key metrics (fruit set, seed count, fruit weight) were comparable to those of insect-pollinated control samples [77]. However, the authors cited high pollen usage (3–5 kg/ha), the associated labour cost to collect the pollen, and relatively slow speed as some of the challenges to be overcome before practical commercial application.

4. Conclusions

Artificial pollination is currently used to supplement insect pollinators for a variety of cropping systems. The rare cases where artificial pollination is used instead of insect pollinators are generally characterized by particular features that make natural pollination difficult, such as a lack of natural pollinators (vanilla, cherimoya, date palm) or dioecy combined with abundant pollen (e.g., kiwifruit, pistachio), or, conversely, are those that are easily self-pollinated by agitation alone (e.g., tomato, strawberry). A variety of devices are being developed and are used commercially to pollinate crops, with increasing focus on drone- and robotics-based solutions.

However, many challenges remain. Insects are full-service pollinators collecting, transporting and delivering a portion of the pollen they collect while foraging. They reproduce quickly, easily producing thousands of “workers” each year, and thus provide the scale needed for intensive commercial cropping systems. Yet, like many ecosystem services, their contribution to food production is threatened. Most artificial pollination research to date treats pollen as a system input and its delivery as the final output. Pollen is available at commercial scale for a limited number of crops globally, and its availability is driven largely by quantified benefits for supplementing natural pollinators. Little research has been found on the collection, processing and management of pollen for artificial pollination in many crops. Perhaps because of the lack of clear commercial benefit and practical methods for application, harvesting pollen is of limited value for all but the highest-value crops. Nevertheless, the increased activity in research and commercial applications over the last decade signals growing appreciation for the vital role pollination services play in agricultural food production systems.

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Appendix A

Patent search query:

CTB = (hand-held NEAR3 device OR handheld NEAR3 Device OR handheld NEAR3 pollinat * OR hand-held NEAR3 pollinat * OR pollination near3 device OR pollination NEAR3 apparatus OR tractor OR sprayer OR drone * OR “robotic platform” OR autonomous OR “precision technolog *” OR “micro air vehicle *” OR MPr * OR UAV OR “unmanned aerial vehicle” OR mechanical NEAR3 pollinat * OR artificial NEAR3 pollinat *) AND CTB = (Nozzle * OR vibration OR “machine vision” OR “computer vision” OR sensor * OR “artificial intelligence” OR AI OR bubblegun * OR “soap bubble” OR Blow * OR puff * OR coat * OR “liquid membrane” OR brush * OR squirt * OR air-assisted OR air-liquid OR spray * OR propellant * OR applicator) AND CTB = (pollinat * OR pollen near3 deliver * OR pollen NEAR3 dispens * OR pollen NEAR3 applicat * OR pollen near3 distribut *) AND AD > = (20000102);

After review of the initial results, text matching was used to remove irrelevant patents on growing methods, plant hormone application, embryogenesis, transgenic plants, honey bee hive products, cancer, cold storage, and printing patents.

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