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Robotic Pollinating Tools for Actinidia Crops †

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Abstract: Pollination is a crucial reproductive process that underpins crop yield and quality as well as sustains other ecosystem services essential for our planet's life. Insects are the largest group of pollinators, particularly bees, handling the pollination of 71 of the 100 crops that contribute to 90% of the world's food supply. Nevertheless, both biotic and abiotic factors exert considerable influence on bee behaviour, which in turn affects the pollination process. Moreover, the alarming decline in bee populations and other essential insect pollinators presents a major challenge to natural pollination. This work focuses on Actinidia, a dioecious plant, i.e., with female and male flowers on separate plants, which introduces entropy into the pollination phase. In this plant, the number of pollinated seeds directly influences the size of Actinidia fruits (kiwi), so the success of the pollination phase is fundamental. However, natural pollination in Actinidia is mainly entomophilic, i.e., by insects. Hence, the exploration of alternative approaches becomes essential. To address this need, there has been a growing interest in robotic solutions for pollination, which include several tools to perform pollination. This research investigates the existing technologies for conducting artificial pollination procedures. It involves a comprehensive examination of various methods outlined in the literature, thoroughly analysing their strengths and weaknesses. The ultimate objective is to provide valuable insights and guidance to enhance the efficacy of artificial pollination processes

Keywords: kiwifruit; precision agriculture; pollination technology; yield production; sustainability

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1. Introduction

Pollination is a crucial reproductive process that underpins crop yield and quality as well as sustains other ecosystem services essential for our planet's life. Understanding and safeguarding pollination processes are essential for maintaining global ecosystems' stability [1]. Pollination is the act of transferring pollen grains from the male anther to the female stigma of a flower. However, most plants need cross pollination, so the transfer must be between different flowers. This transference can be performed by different groups of pollinating agents. Insects are the largest group of pollinators, particularly bees, handling the pollination of 71 of the 100 crops that contribute to 90% of the world's food supply [2].

Bees are considered the primary pollinator due to the large size of their colonies and their high floral constancy, i.e., they visit the same type of flower, increasing the transfer of pollen within a species [3]. Plants produce two elements of interest to bees: nectar and pollen. However, bees are only attracted to flowers primarily for their nutritious nectar.

Nevertheless, both biotic and abiotic factors exert considerable influence on bee behaviour, which in turn affects the pollination process [4]. Moreover, there is an alarming decline in bee populations and other essential insect pollinators, which is associated with widespread pollen limitation and pollination crises [5]. The extent of pollen limitation has been further compounded by ecological disruptions and ecosystem destruction, leading to shifts in the population of pollinators [5]. Consequently, the quality and quantity of pollination services these pollinators supplied have declined over time [6]. In various agricultural systems worldwide, honey bees alone have proven insufficient to deliver the optimal pollination services required [7]. Thus, there arises a necessity to supplement natural pollination efforts.

To complement natural pollination, farmers often resort to conventional artificial pollination techniques to obtain a higher percentage of fertilised flowers, greater uniformity in the shape of the fruit, and more consistent production. Artificial pollination can be performed using four different methods: (i) contact, (ii) dry, (iii) wet, or (iv) vibration.

Artificial pollination via contact consists of touching an instrument to the male organs of the flower and then to the female organs of the flower, in which case there is no need for previously collected pollen.

For dry and wet artificial pollination, the pollen must be collected and mixed with an inert dispersant or demineralised water, respectively. The advantage of dry application is that the pollen remains viable for longer. On the other hand, wet application gives the mixture of greater mass, which allows for greater control over the trajectory.

Vibration pollination only makes sense if it is used with selected, self-compatible crops (such as tomatoes), where the vibration of the flower structure causes the pollen to move, fertilising the flowers [8].

The plant species that produces kiwis is called Actinidia and has several varieties, such as *Actinidia deliciosa*, *Actinidia arguta*, and *Actinidia kolomikta*, among others. Actinidia is a dioecious plant, i.e., with female and male flowers on separate plants, which introduces entropy into the pollination phase. Female plants have pistillate flowers with long filaments, but the stamens, although numerous, do not reproduce viable pollen. Male plants have staminate flowers with short, poorly developed pistils, smaller anthers, and a rather small ovary [9].

The pollination process of Actinidia requires the transfer of pollen between different plants, usually carried out by the wind (anemophilous pollination) or by insects (entomophilous pollination). Therefore, to guarantee successful pollination and fertilisation of the flowers, it is imperative that the flowering of the female and male plants occurs simultaneously. Actinidia flowers do not have nectar, and despite the protein-rich pollen, the pollinator agents do not tend to search for nutrients in these flowers. In this crop, pollination is a critical phase of the plant's vegetative cycle that has the greatest impact on the quantitative and qualitative yield of the fruit [9–11].

Actinidia requires a fertilised ovule to form a seed, so the number of seeds in a fruit depends on transferring viable pollen from the male to the female flowers. Large quantities of seeds are needed to produce quality fruit in quantity. Seeds are obtained by doubling or tripling the pollen grains, also depending on the variety used, as the quality of the pollen is different [11].

In Actinidia, farmers often resort to conventional artificial pollination techniques to obtain a higher percentage of fertilised flowers, higher uniformity in the shape of the fruit, and more consistent production. Artificial pollination can be conducted either dry or wet, using pollen that has been previously collected and preserved.

This work aims to study the available technologies to perform artificial pollination processes. A study of the different options in the literature is conducted, analysing the advantages and disadvantages of each method to support the artificial pollination process.

2. Advancing Artificial Pollination with Digital Farming Technologies

This article categorises the diverse types of artificial pollination found in the literature into four specific approaches: (i) manual pollination, (ii) handheld pollination devices, (iii) vehicle-mounted pollination devices, and (iv) robotic pollination [12]. This article analyses the instruments used in the different types and methods of artificial pollination.

The most basic form is manual pollination, requiring human operators to manually transfer pollen to each flower. Although manual pollination is a precise and effective practice, it is very time consuming and labour intensive and, therefore, quite expensive.

This type of artificial pollination can be profitable in three different cases: (i) self-compatible crops, (ii) crops where the cost of pollen is low, and (iii) the market value of the crop is very high.

Table 1 summarises the information found in the literature on manual pollination. Manual pollination is usually carried out via the contact of an instrument between the male and female organs of the flower. The tools used are soft so as not to damage the flower (which could interfere with the development of the fruit) [13,14]. In manual pollination, it is also common to use the anthers or the male flower as a tool so that no pollen is wasted [15–17]. On the other hand, there is also dry application using basic tools such as squeeze bulbs, cloth bags, and puffers [13,18].

Table 1. Summary of the literature on manual artificial pollination.

Method	Tool	Crop	Applicability	Reference
contact	anteras	cocoa	flowering plant	[15]
contact	anteras	yam	flowering plant	[16]
contact	male flower	cucumber	flowering plant	[17]
contact	party ballon	date palm	date palm species	[19]
contact	sponge strips	date palm	flowering plant	[20]
contact	male strands	date palm	date palm species	[13]
contact	cotton	date palm	flowering plant	[13]
contact	brush	apple	flowering plant	[14]
dry application	cloth bag and puffer	date palm	flowering plant	[13]
dry application	squeeze bulb	date palm	flowering plant	[18]

The development of portable pollination devices makes the artificial pollination process more efficient. However, this strategy still relies on human operators and reduces the precision of the process compared to manual pollination.

Table 2 summarises the information found in the literature on handheld devices developed for pollination. Most of the handheld devices developed for artificial pollination use dry or wet application methods [21–30]. Portable devices use tools, such as air pressure, sprayers, and equivalent tools to spread the pollen. However, these approaches spread the pollen through the air, so some precision is lost in the pollination process, and some pollen is wasted. On the other hand, some devices use the vibration method, which is only successful with self-compatible plants [31,32].

Table 2. Summary of the literature on handheld devices for artificial pollination.

Method	Tool	Crop	Applicability	Commercial	Reference
dry application	ducted fan	date palm	flowering plant	✗	[21]
dry application	sprayer	pistachio	flowering plant	✗	[22]
dry application	air pressure	kiwi	flowering plant	✗	[23]
dry application	sprayer	kiwi	flowering plant	✓	[24]
dry application	sprayer	kiwi	flowering plant	✓	[25]
dry application	air blower	kiwi + olive	flowering plant	✓	[26]
wet application	sprayer	kiwi	flowering plant	✗	[27]
wet application	pollination gun	kiwi	flowering plant	✗	[28]
wet application	pressure sprayer	kiwi	flowering plant	✓	[29]
wet application	fogger	kiwi + olive	flowering plant	✓	[30]
vibration	electrostatic	tomato	self-compatible plants	✗	[31]
vibration	air pressure	cacao	self-compatible plants	✗	[32]

Vehicle-mounted pollination devices have been developed to carry out artificial pollination on a large scale, requiring fewer human operators and less working time. However, this strategy lacks precision in the pollination process, which significantly increases pollen wastage and its associated costs.

Table 3 summarises the information found in the literature on vehicle-mounted pollination devices. Most vehicle-mounted devices use air pressures or sprayers designed to spread the pollen on a large scale [33–39]. On the other hand, Khatawkar et al. [40] developed an electrostatic mechanism to disperse pollen. However, large-scale systems do not pollinate precisely, which causes much pollen to be wasted. Only the pollen grains that land on the petals of the flowers can be redistributed by the bees and pollinate flowers. Many of the references found developed techniques to pollinate the kiwi crop, given the interest in developing advantageous techniques for artificially pollinating kiwi and regarding the mentioned characteristics of this crop [34–39].

Table 3. Summary of the literature on vehicle-mounted devices for artificial pollination.

Method	Tool	Crop	Applicability	Commercial	Reference
dry application	electrostatic	date palm	flowering plant	✗	[40]
dry application	air pressure	date palm	flowering plant	✓	[33]
dry application	air blower	kiwi	flowering plant	✓	[34]
dry application	air pressure	kiwi	flowering plant	✓	[35]
wet application	sprayer	kiwi	flowering plant	✓	[36]
wet application	sprayer	kiwi	flowering plant	✓	[37]
dry application	air pressure	kiwi + olive	flowering plant	✓	[38]
dry application	fans	kiwi	flowering plant	✗	[39]
wet application	sprayer	kiwi	flowering plant	✗	[39]

Robotic pollination mimics the behaviour of natural pollinators, accomplishing the pollination task with great precision, and does not require a human operator. This type of solution enables efficient and effective artificial pollination on a large scale.

Table 4 summarises the information found in the literature on robots for artificial pollination. The types of robots used for this task can be divided into three main groups: (i) drones, (ii) ground robots with manipulators, and (iii) ground robots with implements. Edete [41] has developed an autonomous vehicle with multiple nozzles that generate controlled air vectors with a precise pressure and flow rate to disperse the electrostatically charged dry pollen. This solution substantially reduces pollen waste. Various manipulators have been developed to approach flowers or inflorescences and pollinate them via wet application. This solution allows for great precision but may have an inefficient operating time on a large scale [42–45]. Chechetka et al. [46] puts animal hair filled with ionised gel into the drone, which then comes into contact with the flower's female organs. Other drones have been developed, yet they are not precise, and waste pollen [47–50].

Table 4. Summary of the literature on robotic pollination.

Method	Tool	Crop	Applicability	Robot	Commercial	Reference
dry application	electrostatic	almond + pistachio	flowering plant	ground robot with implements	✓	[41]
wet application	sprayer	kiwi	flowering plant	ground robot with implements	✗	[51]
vibration	air-pressure	tomate	self-compatible plants	ground robot with implements	✓	[52]
contact	cotton	blackberries	self-compatible plants	ground robot with manipulator	✗	[53]
wet application	sprayer	tomate	flowering plant	ground robot with manipulator	✗	[42]
wet application	sprayer	kiwi	flowering plant	ground robot with manipulator	✗	[43]
wet application	sprayer	kiwi	flowering plant	ground robot with manipulator	✗	[44]
wet application	sprayer	kiwi	flowering plant	ground robot with manipulator	✗	[45]
wet application	animal hair	lily	flowering plant	drone	✗	[46]
wet application	sprayer	date palm	flowering plant	drone	✗	[47]
wet application	soap bubble	lily	flowering plant	drone	✗	[48]
wet application	sprayer	walnut	flowering plant	drone	✗	[49]
dry application	dispenser	multiple	flowering plant	drone	✓	[50]
vibration	ultrasonic	strawberry	self-compatible plants	drone	✗	[54]

Table 5 summarises some details of the most relevant articles found in the literature about robotic pollination solutions. Most of the articles present a perception system that acquires images using a camera and utilises machine or deep learning methods to recognise and locate the flowers to be pollinated. However, the articles presented that detect flowers using neural networks do not share the dataset they used for training. The most complex perception system uses an RGB-D camera for mapping and inflorescence detection, the LiDAR sensor for localisation, as well as mapping and obstacle avoidance and the GNSS system for raw inertial measurements. In the case of the manipulators, the authors plan the route from the arm of the manipulator to the stigma of a flower. The success rates shown are very promising, although the operating time to perform pollination is still quite long, given the number of flowers per tree and the number of hectares to be pollinated.

Table 5. Recognition approaches for target flowers used in robotic pollination.

Robot	Perception System	Recognition	Success Rate	Operating Time	Conditions	Reference
ground robot with implements	stereo camera + LiDAR	CNN	-	-	outdoor	[51]
ground robot with manipulator	RGB-D camera + LiDAR + GNSS	Inception-v3	-	-	greenhouse	[53]
ground robot with manipulator	RGB cameras	HSV	69.6%	15 s / inflorescence	greenhouse	[42]
ground robot with manipulator	RGB-D camera	YOLOv5l	99.5%	2 s / flower	outdoor	[43]
ground robot with manipulator	binocular RGB camera	YOLOv4	89.59%	6 s / flower	outdoor	[44]
ground robot with manipulator	binocular RGB camera	YOLOv4	85%	5 s / flower	outdoor	[45]
drone	-	-	90%	-	outdoor	[48]
drone	3D RGB camera	SVM	-	-	greenhouse	[54]

3. Conclusions

Artificial pollination is currently used to complement pollinating agents in many crops to obtain a higher number of fertilised flowers, greater uniformity in the shape of the fruit, and more regular production.

In this article, we bring together the latest developments in the field of artificial pollination, from manual to robotic pollination, analysing the tools used in detail. Several devices for crop pollination are already used commercially, and others are being developed, with an increasing emphasis on robotic-based solutions. Some devices have already been developed and tested in the Actinidia crop since it is a nectar-poor dioecious plant.

However, the right balance between pollination precision and running time has yet to be found. The greater the precision, the less pollen is wasted and the better the yield. The shorter the running time, the greater the possibility of large-scale reproduction.

Nevertheless, the increase in research and the development of commercial solutions signals a growing recognition of the vital role of pollination in agricultural food production.

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