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Robotic Pollination in Greenhouse Farming: Current Innovations, Challenges, and Future Prospects

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ABSTRACT

Effective pollination is crucial for the production of crops, but a number of issues, including incongruous flowering periods, unfavourable weather, and a growing dependence on insect pollinators, are interfering with natural pollination processes in both insect and wind-based systems. The global decline of natural pollinators, exacerbated by climate change, habitat loss, and pesticide use, has increased the demand for alternative pollination methods in agriculture. Although greenhouses provide regulated growth conditions, they also provide unique challenges that impede conventional pollination methods. Robotic pollination appears to be a promising solution, with high precision and efficiency. In challenging pollination settings, robotic-based pollination systems have demonstrated promise as a means of guaranteeing sufficient crop yield. Alternate pollination techniques for crop production are becoming more popular as a result of weather change and persistent threats to conventional pollination machine. Artificial pollination systems offer yield security even in poor pollination conditions and have gained popularity over the past decade. This article examines current pollen collection and application technologies. The purpose of this review is to map the literature on atmospheric greenhouse machinery, highlighting important aspects.

Keywords: Pollination, Robotics, Greenhouse, Pollination mechanisms, Pollen collection.

INTRODUCTION

Honeybees depended pollination services are in high demand as pollinator-dependent crops become more prevalent worldwide (Aizen *et al.,* 2019). Although honeybee colonies have increased globally, the rate of growth has not kept up with demand (Mashilingi *et al.,* 2022), resulting in breeding deficits[4] and higher prices for breeding services (Reilly *et al.,* 2020). Over 87% of flowering plants and crops rely on pollinators for reproduction. (Brunet and Fragoso, 2024). Pollinator populations are rapidly declining globally, threatening biodiversity and food scarcity (Devkota *et al.,* 2024). Native bee populations in Northwest India have declined due to habitat degradation and pesticide use (Sihag, 2023). Similarily Loss of pollinators poses a significant threat to crop yields in the Global South (Dicks *et al.,* 2021). Pollinator decline has financial implications for worldwide food chains and trade, particularly in low-income nations that rely on pollinated crop exports. (Murphy *et al.,* 2022). Recently, researchers and organizations have projected worldwide food demand for the next 20-30 years. The FAO aslo predicts that around 50-54% increase in food demand by 2050 due to population growth. (FAO, 2018). In an era of urbanization, and more worldwide rivalry, scarce arable land, growing labor costs, and overuse of resources from nature, cultivation has difficulties in attaining a viable and economical output. (e.g. drinking water), and rising energy demand (Gogoi et al. 2020). The introduction of COVID-19 in 2020 emphasizes how crucial safety is to ensuring added value in the agri-food industry. It is essential to use technology to process products from the field to the table in order to increase their value and decrease the amount of human handling. (Fairbairn and Guthman, 2020). Additionally, the yields from greenhouse vegetable production are higher than those from open-field farming. The global greenhouse horticulture market is expected to increase at a compound annual growth rate (CAGR) of about 7.7% between 2023 and 2032, from its 2022 estimate of USD 33.6 billion to USD 66.76 billion by 2032. (Extrapolate, 2023). These days, greenhouses are essential to the production of food. From seeding to product utilizing, all agricultural operations in the agricultural goods sector incorporate mechanization and technology (Britannica, 2022). Machines should be considered not only in isolation, but also in the context of their overall processes. (Kondo *et al.,* 2011) and (Shamshiri *et al.,* 2018) drawing the attention to the importance of robotics in digital agriculture. Using this technology not only improves worker experience of life (Saiz-Rubio and Rovira, 2020), but also attracts younger generations who are more tech-savvy to agriculture. Bechar and Vigneault (2016) highlight the importance of ical innovation for those previously excluded from it. Using robotics in production can reduce costs, improve fruit quality, and eliminate hazardous and time-consuming tasks like pesticide application and harvesting. Soil preparation, handling seedlings (grafts, plant development combining), the transplant, fabricating (localized fertilization, thinning, chemical pesticides applying, cleaning up, illness and pest monitoring), while the harvest are among the responsibilities that robotic preliminary models can carry out in the greenhouses (Kondo *et al.,* 2011 and Rodriguez *et al.,* 2013). Cutting-edge technology, including deep learning and nanobots, has emerged as a viable solution for this expanding platform. The use of nanobots for pollination is being investigated through the combination of robotics and artificial intelligence, which allows for autonomous behaviour that is similar to that of natural pollinators, mimicking the effectiveness of natural pollinators. This technique can improve pollination efficiency and accuracy in confined environments, including greenhouses and isolated agricultural areas, while reducing the need for environmentally harmful chemical treatments. To address hidden hunger and maintain food chain stability, researchers are exploring alternative pollination techniques. Using a variety of pollination techniques, such as hand applicators and tractor-mounted spray systems, a small number of industries-mostly those that produce stonefruit, pip fruit, and kiwi fruit-have been effectively collecting and applying pollen for decades. Due to its high fruit set potential, lack of the nectar, which and monogamous nature (male and female flowers on different plants), kiwi fruits encouraged early investigations into synthetic pollination (Hopping and Jerram 1980). (Hopping and Jerram 1980).Using artificial pollination in addition to insect pollinators increased fruit set and quality (Hopping and Jerram 1990). High-quality pollen is necessary for artificial pollination technologies, however crop farmers in places with inadequate infrastructure for pollen gathering and supply may find this difficult. Nonetheless, there are techniques for gathering pollen on a modest scale. The number of patents for artificial pollination devices has increased over the last few decades, indicating that small businesses and researchers have taken up the pollination issue in spite of barriers. This work offers a scoping review of particular papers about robotic systems for greenhouses, addressing the broad question of their potential use. After collecting data, a study was developed to categorize robotization technologies and reclassify them based on key objectives. Complete robot design, perception, and control algorithms.

There are a number of reasons why bees are less common in greenhouses than in outside settings:

- **Limited Access:** Enclosed buildings known as greenhouses offer a regulated environment for the growth of plants. Bees may have limited access to the greenhouse, hindering their ability to pollinate effectively.
- **Limited Floral Diversity:** An transformed floral landscape is the outcome of greenhouse crops, which are dependent on particular plant species selected for their compatibility and productivity in controlled circumstances. Bees may find greenhouses less enticing than their natural environments because they may have fewer flower types.
- **Pesticide Exposure:** To keep crops safe from pests and illnesses, greenhouses use a lot of pesticides. Chemical treatments and pesticides can kill bees and keep them out of greenhouses.
- **Unfavourable Microclimate:** Greenhouses offer optimal temperature and humidity conditions for plant growth. Bees prefer a natural outdoor environment, so these conditions may not be ideal for them.

For application of pollen grains artificially we have to follow two major steps those are:

Pollen grain collection and pollen application

Challenges and Strategies in Pollen Collection and Efficiency for Artificial Pollination

The amount of pollen required for artificial pollination varies based on the crop species and delivery device. Some crops, like date palm and wind-pollinated trees, produce abundant pollen that is easily collected. Most crops, such as almonds, apples, and kiwifruit, produce fewer pollen grains per flower, which requires more labour (Vaknin *et al.,* 1999). This suggests two goals for practical artificial pollination: ensuring a supply of inexpensive, high-quality pollen and minimizing waste during application. There are primarily two major goals for practical artificial application of pollen i.e., first, collecting high-quality pollen at a reasonable cost, and second, making sure that there is as little waste as possible during application. Pollen is usually at its most viable during anthesis, right before the anthers start releasing pollen, claim Pinillos and Cuevas (2008).However, as flowers may release the majority of their pollen on the day of anthesis, harvesting flowers at this stage could result in significant pollen losses. (Hopping, 1990 and Salomon-Torres *et al.,* 2021). Generally speaking, it is best to harvest as soon as possible before anthesis to optimize pollen production per flower and prevent pollen losses. (Pinillos and Cuevas, 2008). Pollen production is usually lower in entomophilous plants (plants pollinated by insects), which makes collection more difficult. Manually removing the anthers from each bloom is one artificial pollination approach that has been investigated; (Hopping, 1990) cited this method, but it is still labor-intensive and best suited for small-scale applications; However, this approach requires a lot of work and is only economical for small-scale uses (such breeding projects and the pollination of cacao and vanilla). Techniques for mechanically removing kiwifruit pollen from whole blooms (Gianni and Vania, 2018), cherimoya (Vaknin *et al.,* 1999), and date palm allowed for larger-scale pollination.

Pollen application

Numerous techniques for pollinating plants have been investigated. Pollen can be applied wet (usually suspended in an aqueous liquid, frequently with additives to ensure isotonic balance with pollen cells) or dry (perhaps diluted with a neutral carrier, like charcoal, to help manage application rates). For certain self-compatible crops, like tomatoes, there is a third option: vibrating the floral structures with a puff of air or direct contact shakes loose pollen to fertilize the flower (Peet and welles, 2005).

Role of aerial robots for pollination

There are different robotics helps in artificial pollination majorly divided in to two groups of aerial pollination robots: first is Unmanned Aerial Vehicles

(UAVs), which vary in size from microscopic to huge drones and are mostly used for disseminating pollen clouds, and second is insect-scale Aerial Robots, which are tiny robots made to resemble natural insect pollinators. While UAVs adopt a more comprehensive strategy, employing drone technology to disperse pollen over agricultural regions, insect size robots are especially made to coexist peacefully with the environment by mimicking the way actual insects pollinate plants. (Sapkota *et al.,* 2024)

Unmanned aerial vehicles (uavs)

There has been a lot of interest in drone-based pollination technology. The idea of using drones to fertilize crops is appealing because, like bees, they are aerial pollinators and since drone technology is less expensive than other robotics approaches (Wikifactory, 2020). These devices can be pilot-controlled,either employ a 3D model of the area produced from a prior pass by scouting drones, or adhere to a predetermined route established by the arrangement of orchard rows (Alkhamis, 2022).Some flying insect pollinators are designed specifically for pollination, although many are modifications of commercial drones, especially those used for agrichemical spraying. Aerial broadcasting pollen redistribution and personal pollination using drone air waves are two pollination methods on the research agenda for hybridization the production of grains and glasshouse-grown self-compatible products such as eggplant, tomato, pepper, and strawberry (Sur, 2021). There have also been prototypes for other techniques, like a micro drone with a fur pad for close interaction in fertilization (Chechetka *et al.,* 2017) and a drone equipped with a bubble gun (Yang and Miyako, 2020). However, the limitations of both methods accuracy in the second case and time in the first may restrict their use in field settings. Building tens of thousands of micro drones to replace a single honey bee colony is not desirable nor feasible given the hundreds of thousands of colonies used annually for heavy industrial agriculture (Gleadow *et al.,* 2019). In fact, contact-style robots have drawn criticism for their overly similar resemblance to bees. Given that only a tiny percentage of the dispersed pollen reaches the stigma, where it can aid in fertilization, airborne broadcasting techniques are probably going to have the same drawbacks as ground-based dissemination.

Date palm pollination, which was previously done by hand with people climbing the palm trees, has seen some commercial success with drone pollinators. Since these trees yield large amounts of pollen, there is minimal worry regarding waste from dissemination (Gan maor *et al.,* 2003), and fewer people climbing trees results in significant time savings and increased safety. Another developing field is walnut pollination, which has shown promising early results in several nations and yields walnut kernels that are comparable to those from wind-pollinated controls (Schroeder, 1943). The most well-known company in this area is Drop copter. Compared to growers using conventional methods, they offer pollination services to a number of crops, including apple, cherry, and almond, which have fruit sets that are 53%, 40%, and 94% greater, respectively. Nevertheless, there is currently a dearth of independent data regarding the effectiveness of this system (as well as the majority of commercial drone offerings). Because drones can disperse pollen above the canopy, they hold great promise for tall tree crops. Conifer breeding (De and Wood, 2020) and wind-pollinated nut crops (Hazelnut, Pistachio, and Walnut; Nitin, 2021) that have shown potential in artificial pollination trials may benefit from their utilization.

INSECT scale aerial robots

More than 20 years ago, the concept of using tiny flying robots that mimic pollinating insects began to gain traction as a way to combat declining bee numbers. Beginning in 1998, the UC Berkeley Insect Scale Millisystems Lab developed biologically inspired flapping wing aerial systems as part of a Micromechanical Flying Insect (MFI) project automobiles with flexible hinges composed of fiber-reinforced composites known as smart composite microstructures (SCM) with piezoelectric actuation (Wood *et al.,* 2008). When subjected to mechanical stress, piezoelectric materials can generate electric charges and vice versa (Uchino, 2017).

In their finished prototype, a slider-crank transmission system connected four piezoelectric actuators distributed over two wings. The project laid the foundation for future research even if it was unable to produce a robot with sufficient propulsion to lift its own weight. For instance, the Robert Wood team at Harvard University's Wyss Institute designed the RoboBee using piezoelectric bending actuators created by the MFI team at the centimetre scale (Wood, 2008). An insect-inspired MAV with possible applications in flower pollination is the RoboBee. The researchers carefully fabricated the mechanical and electromechanical parts required for its operation using the laser-micro-machining process. Smart composite microstructures (SCM) were used to create a piezoelectric clamped-free bending cantilever that effectively delivers mechanical power. Even though the Robo bee has shown controlled flying in laboratory conditions, its usefulness in actual pollination has not yet been evaluated, As a result, this field still needs more study and advancement.

Further developments in simulating the intricate flying patterns of bees, such as vertical lift and wing articulation, have been accomplished at Harvard, building on these pioneering work (Karpelson, 2009). However, the ongoing problem of on board power still prevents these gadgets from being autonomous, even with current advancements in imitating bee flying dynamics. Advanced technological advancements like as lightweight power electronics and integrated systems-on-chip (SoC) have enhanced overall functionality and control over wing movement. However, because of unsolved power management concerns, these robots have not yet achieved completely autonomous flight (Zhang *et al.,* 2017). By combining solar power with a biplane wing design, the RoboBee X-Wing achieves autonomous flying and achieves an impressive lift-to-weight ratio. Nevertheless, its performance is susceptible to changes in wind patterns, temperature swings, and harsh lighting conditions including direct sunshine and shadow transitions, all of which can have a major effect on its aerodynamics and operating efficiency (Mc gill *et al.,* 2021). An adaptive control method advanced this step toward autonomous operation, which is essential for field operations in pollination. However, practical use is still limited to laboratory trials, highlighting the disconnect between lab-based breakthroughs and field-ready applications. A range of flapping-wing MAVs are shown in comparative studies in the field, each with unique successes and difficulties. For example, while Colmenares and colleagues' work on resonance-based wings and Carnegie Mellon University's small robot designs provide fascinating potential, they are unable to produce enough lift (Colmenares *et al.,* 2015). Although Toyota's direct piezoelectric actuation and switchable electro-adhesive forces for landing are exciting experimental technologies, their need on external power sources remains a major drawback.[52–54] Although problems with power and onboard sensing capabilities continue to plague MAV designs, the use of four-winged configurations[55] and inventions like the Bee+ (Yang *et al.,* 2019) and a multi-terrain robot from the University of Washington[55] demonstrate the variety of MAV designs. Because of their lower operating voltages, electromagnetic actuators have been proposed as a possible substitute for piezoelectric mechanisms. However, they have drawbacks of their own, such as high energy consumption, which makes them less appropriate for self-sustaining MAV (Zou *et al.,* 2016). As the subject develops, research on insect-scale airborne robots is becoming more and more multidisciplinary, including elements of biology, control theory, energy systems, and machine design (Wang *et al.,* 2021).

Practical issues, including their delicate mechanical construction, intricate manufacturing requirements, high energy needs, and limited payload capacities, make it difficult to apply these robotic technologies in actual, commercial agricultural contexts (Tanaka *et al.,* 2022). Additionally, farming's extreme variability and unpredictability make its practical use difficult conditions (such as crop traits and weather patterns). Micro-electromechanical systems (MEMS) and insect size robotics have recently made significant strides, particularly with the introduction of MEMS-based LiDAR scanners, which may pave the way for the integration of sophisticated vision systems in micro-robots (Wang *et al.,* 2021). At the same time, swarm robotic systems are improving MAVs' collective control, increasing their potential applications in agriculture (Singh *et al.,* 2021). Even with these developments, it is still quite difficult to make these robots imitate the dexterity and mobility of wild pollinators. The design of next MAV (Ajanic *et al.,* 2020) may benefit from the insightful information provided by research on avian flight dynamics. Additionally, wearable sensors enable in-depth research on bee behaviour, providing vital information on movement patterns and interactions with the environment (Iyer *et al.,* 2019). Even though these advancements are important first steps, research is still being done to determine how to close the gap between lab results and real-world agricultural applications in order to deploy Robo bees and other similar MAVs as viable pollinators in agricultural systems.

Automation and self-sustained pollination

With the goal to reduce waste, automated robotic drones frequently target specific blooms. The most common approach is to detect a bloom that needs pollination using machine vision. Generally speaking, two methods of pollen administration have been researched: spraying pollen from a distance or transporting an end-effector close to the bloom. There have been numerous approaches to using an end result to disseminate pollen, such as brushing the blossom with a machine arm, contacting the bloom with a vibrating rod, and using an air explosion or a tuned oscillation. These techniques only work with self-fertile crops (like tomatoes), except from brushing pollen. Remotely sprayed pollen might arrive either wet or dry.

Deep learning-based machine vision systems can process up to 100 frames per second and find objects in pictures with 90% accuracy or better (Ohio *et al.,* 2018). Systems using robotic arms are frequently somewhat slow. For instance, studies on a tomato pollination robot have shown that pollination speeds of 15–20 per flower are impractical for commercial-scale crop pollination (Yuan *et al.,* 2016). With application rates of approximately 2 to 5 seconds per flower cluster, several commercially available devices are faster (Arugga *et al.,* 2022). The precision control of movement needed to position end-effectors directly on a flower and many arms to pollinate multiple flowers simultaneously is lessened by these devices' usage of air jets. For instance, Arugga AI pollinates high-wire tomato products using four sets of injectors (Arugga, 2022). Only greenhouse applications, however, have used systems that use arms to move an end-effector near to the bloom thus far. Spreading methods, which deliver a dosage of pollen from a automobile moving across the cultivation, are often preferred for field applications. Power Pollen, for example, is doing commercial trials with a boom mounted on a tractor that can hold 16 autonomous pollinators for maize at once. As the tractor moves between the crop rows, the device delivers an electrostatically charged dosage of dry pollen by manually funneling maize silks into the autonomous pollinator's spray zone (Schilling, 2021). Independent robotic pollinating insects with highly developed targeting computational methods may be able to identify and aim for the plants that yield the best fruit, enabling knowledgeable pollination services, according to Verdant Robotics' published apple pollinator and flower less thick (US11308323B2). Regretfully, Information regarding the efficacy of the aforementioned technologies in pollination is scarce. The prototype ultrasonic strawberry pollinator surpassed manual pollination, while the tomato pollinator performed noticeably worse (Yuan *et al.,* 2016), (Shimizu and Sato, 2018). Hybrid maize production was successful, according to Power Pollen, with a 20% increase in seed output over conventional methods (Schilling, 2021).

According to Williams *et al.,* (2020), there is proof that pollen sprayed from a moving platform in an aqueous solution can travel at speeds more appropriate for intensive commercial cropping. During field tests in 2019, the autonomous research prototype robot successfully pollinated over 670 export-quality "Hayward" kiwifruit from a platform traveling at 2.5 km/h without the assistance of insect pollinators. Fruit weight, seed count, and fruit set-all important metrics-matched those of control samples pollinated by insects (Williams *et al.,* 2020). However, the authors noted that some of the obstacles to be addressed before a realistic commercial use include the relatively sluggish pace, the high usage of pollen which is around (3–5 kg/ha), and the accompanying mankind expense in the collection of the pollen.

CONCLUSION

In further days in the green house production systems, robotic-based pollination will become an essential way to augment insect pollinators. Robotic pollinators are necessary because greenhouses' regulated conditions make it difficult for bees to survive. This report offers a comprehensive overview of the potential of robots in pollination for the advancement of new technologies used in intensive farming. Furthermore, even if it seems unduly ambitious, it helps the scientific community by gathering the data and giving the authors a framework that has allowed them to create a lexicon and a set of rules for categorizing the technologies associated with greenhouse robotization. It can help researchers and companies make technological and financial decisions about the incorporation of robots in greenhouses. Evidently, developing the robotization process of tasks performed within a greenhouse requires taking into account factors other than technological viability. For example, a feasibility study of the economic, social, environmental, and legal challenges is necessary to ensure industry accepts technology. Additionally, these reviews are reliable and helpful enough to assist envision future study areas, such as sensors, end-effectors, data fusion, novel applications, or interaction with Internet of Things systems for the creation of artificial pollinators.

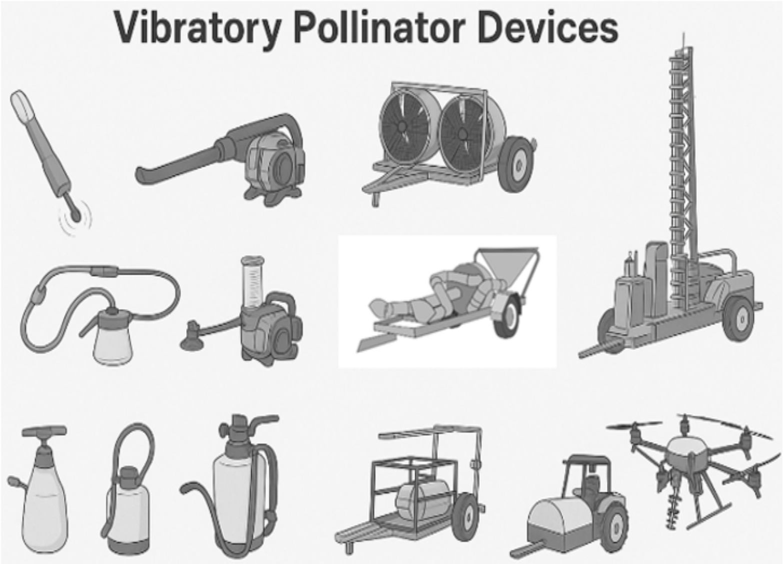

Fig. 1. List of examples for commercially available pollination technologies

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Conflict of interest

The author declare that we have no conflict of interest.

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