Review Article

Actuation Drones in Agriculture: Advancing Precision Pest Management through Biocontrol and Modern Techniques – A Review

ABSTRACT

The impact of technology in agriculture is a positive trend, offering solutions to feed the growing population amidst environmental challenges like degradation, pollution, and water scarcity. Ensuring food security is crucial, and drones present a sustainable approach to achieving it. Drones can significantly improve agricultural efficiency, particularly in precision pest management. They can be categorized into two types: sensing drones, which detect pest hotspots, and actuation drones, which distribute solutions with precision. Together, they can create a closed-loop Integrated Pest Management (IPM) system.While much of the research has focused on drones for detecting plant stress caused by pests, this review highlights the use of actuation drones for precise releases of natural enemies, biopesticides, and advanced pest management techniques like the Sterile Insect Technique (SIT) and mating disruption. These drones offer unmatched precision and efficiency, reducing reliance on chemical pesticides and promoting sustainable pest control. However, challenges remain, including high costs, the need for specialized training, and regulatory concerns. Future research and development are essential to overcoming these obstacles and optimizing drone-assisted pest management systems. By addressing these challenges, drones can revolutionize modern agriculture, making pest management more effective, environmentally friendly, and accessible on a larger scale.

Key Words: Unmanned Aerial Vehicles**,** Actuation Drones, natural enemies, biopesticides, Sterile Insect Technique, mating disruption

Revised Abstract (with suggested additions):

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While much of the research has focused on drones for detecting plant stress caused by pests, this review highlights the use of actuation drones for precise releases of natural enemies, biopesticides, and advanced pest management techniques like the Sterile Insect Technique (SIT) and mating disruption. These drones offer unmatched precision and efficiency, reducing reliance on chemical pesticides and promoting sustainable pest control. However, challenges remain, including high costs, the need for specialized training, and regulatory concerns. Future research and development are essential to overcoming these obstacles and optimizing drone-assisted pest management systems. By addressing these challenges, drones can revolutionize modern agriculture, making pest management more effective, environmentally friendly, and accessible on a larger scale.

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INTRODUCTION

As the global population grows, technology in agriculture is becoming increasingly crucial for ensuring food security amidst challenges like environmental degradation, pollution, and water scarcity [1]. Drones, or UAVs (Unmanned Aerial Vehicles), offer a promising solution by providing precise and efficient agricultural management [2]. Equipped with advanced sensors, drones can capture real-time, detailed data that goes beyond human visual capabilities, allowing for more accurate and reliable information [3].

Drones are used in many fields, including military, cinematography, and disaster management. In agriculture, they are emerging as a key technology for precision farming and sustainable agriculture. They help address issues like labor shortages and health risks from chemicals [4]. By utilizing various sensors, drones contribute to precision pest management in two main ways: detecting pest hotspots and delivering solutions[5].

Sensing drones identify areas with high pest populations using remote sensing technologies. While aircraft have long been used for pesticide application, they often result in significant pesticide drift and environmental harm [6,7]. Drones offer a more precise alternative, potentially reducing the area and quantity of pesticide use[8]. Moreover, drones can enhance biological control by efficiently distributing natural enemies in specific locations, increasing their efficacy and reducing costs[9].

In contrast, actuation drones are designed to release natural enemies, such as predatory insects or parasitoids, exactly where they are needed. This targeted approach improves the effectiveness of biological control and reduces reliance on chemical pesticides[10] . Combining these drones in a closed-loop system can provide a cost-effective and environmentally friendly pest management solution.

Biological control involves using one organism to manage another, with many commercially available options like parasitoids and entomopathogenic nematodes [10]. Drones could improve the application of these agents, which are often dispersed manually or using other equipment [11]. While the use of drones for distributing natural enemies is still developing, they promise to make biological control more accessible and effective compared to traditional methods[12,13].

This review will delve into the capabilities of actuation drones for the precision distribution of natural enemies, explore their role in modern pest management, and discuss the challenges and opportunities for their broader adoption in agriculture.

Actuation Drones for Precision Releases of Natural Enemies

Drones have emerged as versatile tools in various sectors, including agriculture, where they hold promise for augmentative biological control[14]. Augmentative biological control relies on the large-scale release of natural enemies for immediate pest management [10]. These natural enemies, such as predators, parasitoids, and pathogens, help in managing pest populations without the need for chemical pesticides[15]. The application of drones in this field could revolutionize biological control methods by increasing the efficiency of distributing natural enemies precisely where they are needed[16].

The ability of drones to distribute natural enemies across large areas offers significant advantages[16]. Unlike manual distribution methods, drones can cover extensive fields quickly, reducing the time and labor involved[17]. Furthermore, targeted delivery of biological control agents may enhance their efficacy by placing them directly in pest hotspots. This precision could reduce overall application costs and improve the success rates of biological control programs[18].

Certain natural enemies, such as insect-killing fungi and nematodes, can already be applied using conventional spray equipment [5,11]. As drones are increasingly used for pesticide application[19], the integration of these biocontrol agents with drone technology could follow a similar path. The automation and programmability of drones allow for tailored applications based on specific environmental conditions, further optimizing the release process[20].

However, not all natural enemies can be applied as easily as fungi or nematodes. The release of larger predators or parasitoids, for instance, is often more complex, time-consuming, and costly. Various mechanical distribution systems have been developed to facilitate the dispersal of predators, but their application remains a challenge[21]. Despite this, the versatility of drones could still provide a solution. By adapting drones with appropriate release mechanisms, they could be used to deploy a wider range of natural enemies in diverse environments[14].

Historically, the idea of using aircraft to distribute biological control agents was explored in the 1980s [22,23]. While these early efforts demonstrated potential, the high cost and limited technology available at the time restricted widespread adoption(Table - 1). Modern drones, on the other hand, are smaller, more affordable, and capable of accessing areas that are difficult for larger aircraft to reach[24]. This opens up a myriad of possibilities for enhancing biological control efforts on both small and large scales.

Drones represent a promising tool for augmentative biological control, offering precision, efficiency, and reduced costs. By enabling the targeted release of natural enemies, drones could increase the adoption of biological control methods, potentially reducing reliance on chemical pesticides[25]. As technology continues to advance, drones may play a crucial role in sustainable pest management practices, bridging the gap between traditional methods and modern innovations. However, further research and development are needed to overcome challenges related to the deployment of certain natural enemies and to optimize drone-assisted biological control systems[26].

Actuation Drones for Precision Releases of Biopesticides

Actuation drones are used in agriculture to apply biopesticides directly and precisely to targeted areas within fields. These drones use advanced technology to control the release of biopesticides based on real-time data, making them especially useful for managing pest outbreaks in large farms where traditional methods may be less effective[19].

Biopesticides include various types, such as microbial agents (bacteria, fungi, viruses), plant extracts, and biochemical substances. Drones can be equipped to handle different forms of biopesticides, including liquid sprays and dry powders, ensuring they are applied effectively [5,11].

One major advantage of using drones for biopesticide application is the reduction of pesticide drift, which is the spread of pesticides beyond the intended target. Traditional methods can cause harm to beneficial insects, wildlife, and ecosystems due to drift, but drones allow for more precise application, reducing the amount of biopesticide needed and minimizing harm to non-target organisms[27,28,14].

Drones also improve labor and operational efficiency by automating the application process, reducing the need for manual labor, and lowering costs. They can access hard-to-reach areas within fields, ensuring complete coverage for pest control [26,12,13].

However, there are challenges in adopting drone technology for biopesticide application, including the high cost of drones, the need for specialized training, and regulatory concerns. Despite these challenges, advances in drone technology and decreasing costs are making this method more accessible to farmers[31] .

Recent developments in drone technology have opened new possibilities for more efficient pest management. While some progress has been made in using drones to apply biological control agents, there is still limited information on drone application parameters and the effectiveness of these agents when delivered by drones. Some studies have shown success with specific organisms, like the bacterium Bacillus thuringiensis, but more research is needed, especially with entomopathogenic fungi(Table - 3). For example, a study on spraying the fungus Metarhiziumacridum by drone showed that factors like flight configuration, weather, and vegetation type significantly affected the deposition of the fungus. Despite some drift during dusting, spraying biopesticides with drones was found to be more uniform and effective [32,33,34].

Reducing Pest Populations with Drones: Sterile Insect Technique and Mating Disruption

Drones are emerging as innovative tools for pest management, particularly in enhancing techniques like the Sterile Insect Technique (SIT) and mating disruption[35]. These environmentally friendly, species-specific methods offer sustainable alternatives to chemical pesticides and can be seamlessly integrated into broader Integrated Pest Management (IPM) strategies.

Sterile Insect Technique (SIT)

The Sterile Insect Technique (SIT) involves mass-rearing and sterilizing insects, typically through irradiation, and releasing them into the wild. When these sterile insects mate with wild counterparts, the resulting offspring are either sterile or non-existent, leading to a gradual reduction in pest populations[36]. SIT has been widely recognized as a valuable tool in IPM due to its precision, minimal environmental impact, and compatibility with other management methods [37].

Traditionally, sterile insects have been released through ground-based methods such as all-terrain vehicles (ATVs) or by manned aircraft [38]. However, these methods can be expensive, labor-intensive, and less precise, limiting the wider adoption of SIT. Drones offer a promising alternative. By enabling aerial releases at targeted locations, drones can increase the effectiveness of sterile insect dispersal while reducing the costs associated with ground releases.The cost-effectiveness and precision of drones may help expand the use of SIT to new regions and crops, making it more accessible to growers[39].

Mating Disruption

In addition to SIT, drones can play a pivotal role in implementing mating disruption techniques. Mating disruption relies on the strategic release of pheromones that interfere with pests' ability to find mates, effectively reducing their reproduction rates [40]. One common product used in mating disruption is SPLAT (Specialized Pheromone & Lure Application Technology), an inert matrix that can be infused with pheromones or pesticides and applied as dollops[41] .

Drones provide an efficient and precise method for deploying mating disruptors across large commercial fields[42]. Their ability to navigate difficult terrains and apply disruptors at specific locations ensures more effective coverage compared to manual application methods. Additionally, drones can be used for attract-and-kill strategies, which combine pheromones with a killing agent, drawing pests in and eliminating them[43]. The combination of these methods has proven to be effective in managing a variety of pests across different cropping systems.

The integration of drones into pest management strategies like SIT and mating disruption represents a significant advancement in sustainable agriculture[44]. Drones offer precision, cost efficiency, and the ability to cover large areas quickly, making them ideal for the release of sterile insects and the deployment of pheromone-based disruptors[45]. As these technologies continue to evolve, they hold the potential to reduce the reliance on chemical pesticides and increase the adoption of environmentally friendly pest control methods[14]. By bridging the gap between traditional techniques and modern innovations, drones are set to play an increasingly important role in IPM and the future of pest management(Table - 2).

Table .1 Actuation Drones for Precision Releases of Natural Enemies

Sl no	Natural Enemies	Scientific name	Family and Order	Insect pest	Scientific name	Family and Order	References
	Egg parasitoid	*Trichogrammaostriniae*	Hymenoptera: Trichogrammatidae	European corn Borer	*Ostrinianubilalis*Hübner	Lepidoptera: Crambidae)	[46]
	Egg parasitoid	*Trichogrammaminutum*	Hymenoptera: Trichogrammatidae	Eastern spruce budworm,	*Choristoneurafumiferana*Clemens	Lepidoptera: Tortricidae	[46]
	Mile-a-minute weevil	*RhinoncomimuslatipesKorotyaev*	Coleoptera: Curculionidae	Mile-a-minute weed	*Persicariaperfoliata*(L.) *H. Gross*	Caryophyllales: Polygonaceae	[47]
	Lacewings	*Chrysoperlarufilabris*(Burmeister)	Neuroptera: Chrysopidae	Lettuce aphid,	*Nasonoviaribisnigri* (Mosley)	Hemiptera: Aphididae	[48]
	defoliating moth	Neomusotimaconspurcatalis Warren	Lepidoptera: Crambidae	Old World climbing fern,	Lygodium microphyllum	Lygodiaceae	[49]
	Egg parasitoid	*Trichogrammaostriniae*	Hymenoptera: Trichogrammatidae	Corn Borer	*Ostriniafurnacalis*(Guenée)	Lepidoptera: Crambidae	[50]
	ectoparasitoid	*Tamarixiaradiata Waterston*	Hymenoptera: Eulophidae	Asian citrus psyllid	*DiaphorinacitriKuwayama*	Hemiptera: Psyllidae	[51]

Table .2 Reducing Pest Populations :Sterile Insect Technique and Mating Disruption

	Common Name	**Scientific name**	**Family and Order**	**Mechanism**	**References**
1.	Sterile Mexican fruit fly	*Anastrephaludens(Loew)*	(Diptera: Tephritidae)	Designed a conveyor belt mechanism underneath a straight walled insect compartment to meter and expel insects Release device	[52]
2.	Sterile Codling Moth	*Cydia Pomonella (Linnaeus)*	(Lepidoptera: Tortricidae)	Comparing Deliveries of Sterile Codling Moth by Two Types of Unmanned Aerial Systems and from the Ground	[26]
3.	Cranberry fruitworm	Acrobasis Vaccinii (Riley)	Lepidoptera: Pyralidae)	Mating disruption extruder system that effectively delivered one gram droplets of mating disruption over cranberry beds	[53]
4.	Sterile Codling Moth	*Cydia Pomonella (Linnaeus)*	(Lepidoptera: Tortricidae)	Combined Effects of Mating Disruption, Insecticides,	[35]
5.	sterile male	Aedes aegypti	(Diptera: Culicidae)	Release of Sterile Mosquitoes with Drones in Urban and Rural Environments	[54]
6.	Male Mosquitoes	Aedes aegypti	(Diptera: Culicidae)	The Effect of Storage Conditions on Survival of Male Mosquitoes During Transport	[55]

Table .3 Actuation Drones for Precision Releases of Biopesticides

Biopesticide	Insect pest	References
Metarhizium rileyi	Fall armyworm and soybean looper	[56]
Bacillus thuringiensis var. israelensis	*Aedesvigilax* (Skuse)	[32]
Bacillus thuringiensis	Bagworm, *Metisaplana* WALKER	[33]
liquid formulation (conidia+diesel) of *Metarhziumacridum* (Farlow) Kepler, Rehner and Humber	Desert locust, *Schistocercagregaria* (Forsk.)	[34]

Potential and Limits of UAS for Trichogramma Releases

- ✓ The Trichocards offer some protection against both abiotic conditions and predation
- ✓ While Trichocards can be installed under any weather conditions, UAS have some constraints regarding mainly winds and their flight duration is limited by the battery autonomy.
- ✓ The regulations surrounding the use of UAS can also have an impact on its use for biological control applications.
- ✓ A tight timing of the UAS bulk release right before parasitoid emergence could offer a good solution, although the costs of parasitoids emerging too early would be even more detrimental.
- ✓ Releasing capsules containing the biocontrol agents could also offer parasitoids a protection.
- ✓ Bulk releases allow the dispersion of parasitoids during release while capsules act more like Trichocards where the parasitoid dispersal comes from punctual points instead of spreading in the field/forest.
- ✓ Trichocards and capsules also require more work, which of course adds to costs. However, preparing capsules is faster than preparing Trichocards, given that the proper installations are available.
- ✓ Of course, UAS also carry operation costs, that may vary based on whether they are done by producers, forest managers, or by service providers.
- ✓ UAS also brings the benefit of being potentially coupled with imagery that could detect the presence of the pest, and more precisely release biocontrol agents only on the specific part of the field/forests that need them, avoiding non-host or healthy plants.

Advantages

1. Precision Application: Drones enable precise distribution of biological control agents, biopesticides, and pheromones, reducing wastage and ensuring targeted application in pest hotspots.

2. Cost and Time Efficiency: Drone-assisted releases reduce labor costs and time spent on manual distribution methods, especially in large or difficult-to-access fields.

3. Environmental Benefits: By promoting the use of biological control and reducing reliance on chemical pesticides, drones contribute to environmentally sustainable pest management.

4. Coverage of Large Areas: Drones can cover extensive fields quickly and efficiently, making them suitable for large-scale agricultural operations.

5. Adaptability: Drones can be programmed for specific tasks and adjusted based on real-time data, making them versatile for different pest management scenarios.

6. Reduction in Pesticide Drift: The precision of drones reduces the risk of pesticide drift, minimizing harm to non-target organisms and ecosystems.

Disadvantages

1. High Initial Costs: The acquisition of drones and related equipment can be expensive, posing a barrier for small-scale farmers.

2. Specialized Training: Operating drones for pest management requires specialized training, which may not be readily available to all users.

3. Regulatory Challenges: Compliance with regulations governing drone use in agriculture varies by region and can be complex, potentially limiting widespread adoption.

4. Technical Limitations: Factors such as weather conditions, flight endurance, and payload capacity may restrict the effectiveness of drone applications in certain environments.

5. Limited Research: While some progress has been made, more research is needed on drone application parameters, particularly for certain biological agents like entomopathogenic fungi.

6. Maintenance and Upkeep: Regular maintenance and technical support are required to ensure drones operate effectively, adding to operational costs.

Conclusion

The integration of drones into pest management practices represents a significant advancement in sustainable agriculture. Drones provide precision, cost efficiency, and environmental benefits, making them ideal for tasks such as the release of natural enemies, biopesticide application, and mating disruption. By addressing the challenges associated with drone technology, including costs, training, and regulations, the agricultural sector can unlock the full potential of drones for pest management. As research continues to evolve, drones are likely to play an increasingly important role in reducing the reliance on chemical pesticides and enhancing the effectiveness of IPM strategies.

Future Prospects

1. Advancements in Drone Technology: Future developments in drone technology, including increased payload capacity, longer flight times, and enhanced automation, will improve the efficiency of drone-assisted pest management systems.

2. Cost Reduction: As drone technology becomes more widespread, the cost of acquiring and operating drones is expected to decrease, making them more accessible to a broader range of farmers.

3. Integration with AI and Data Analytics: The combination of drones with artificial intelligence (AI) and data analytics could enable real-time monitoring and decision-making, further optimizing pest management practices.

4. Expansion of Biocontrol Research: Continued research on the application of various biocontrol agents using drones will provide insights into best practices and improve the effectiveness of these agents.

5. Sustainability and Ecosystem Impact: Drones will contribute to more sustainable agricultural practices by minimizing the environmental impact of pest management and promoting biodiversity conservation.

6. Policy and Regulatory Frameworks: As the use of drones in agriculture expands, more streamlined and supportive regulatory frameworks will be necessary to facilitate their adoption while ensuring safety and environmental protection.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AItechnologies such as Large Language Models(ChatGPT, COPILOT, etc) and text-to-imagegenerators have been used during writing orediting of manuscripts.

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