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Innovative Technologies in the Biologization of Agriculture: A Mounted Device for Unmanned Aerial Vehicles for the use of Entomophages in Hard-to-reach Places

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Abstract

The reduction of synthetic pesticide use is an urgent priority due to their adverse impacts on human health, non-target organisms, and ecosystems. Entomophagous biological control offers an effective and environmentally benign alternative, but its large-scale adoption is constrained by labor-intensive release methods and the inaccessibility of flood-prone or obstructed terrain. Overcoming these technological barriers is essential for advancing sustainable crop protection. In this study, we designed, prototyped, and tested an automated UAV-based system for the aerial release of *Trichogramma* spp. encapsulated in biodegradable carriers. The device was developed through rapid prototyping with 3D modeling, additive manufacturing, and Raspberry Pi–driven GPS/GLONASS navigation integrated with a web-based control interface. Laboratory emergence assays confirmed 100% parasitoid emergence within six hours at 30 °C and within 24 hours at 25 °C, demonstrating that encapsulation and aerial release did not compromise biological viability. Field trials showed release accuracy within ±1 meter and identified three meters as the optimal drop height to minimize wind drift and rotor-induced turbulence. Capsule jamming, initially observed in ~10% of releases, was reduced to isolated cases following mechanical refinements. Economic assessment revealed that capsules can be produced at a cost of 31.75–36.25 KZT per unit, with designs optimized for stackability, low weight, and complete biodegradability. These findings establish the feasibility of UAV-integrated entomophage deployment as a scalable, cost-effective, and ecologically sustainable alternative to chemical pest management. By enabling precise and autonomous distribution of beneficial insects, this technology extends biological control to previously inaccessible areas, reduces labor demands, and provides a practical pathway for advancing biologized agriculture in Kazakhstan and beyond.

Keywords: Entomophages; Agricultural innovation; Unmanned aerial vehicles (UAVs); Automated bioagent application; Capsule design; Precision delivery systems.
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1. Introduction

Unmanned aerial vehicles (UAVs) are increasingly recognized as transformative tools in the advancement of intensive and sustainable agriculture. These platforms offer the potential to reduce environmental impact, enhance precision, and optimize resource use. As discussed by Andrio, UAVs enable effective pest control with minimal ecological disturbance and lower operational costs.[1] Freitas *et al*. further emphasize that UAV integration into agriculture provides extensive coverage, reduced chemical input, labor efficiency, and fast response to pest outbreaks — critical factors for timely intervention.[2] Huang *et al*. underscore that UAVs are especially promising in biological control applications, where operational efficiency must be balanced with ecological considerations.[3]

The use of UAVs for biological pest management has grown steadily in recent years, demonstrating their feasibility for entomophage distribution in both experimental and semi-commercial contexts. For example, Martel *et al*. in Canada successfully developed the “Entobot” capsule delivery system, which was capable of distributing *Trichogramma* spp. in both loose form mixed with vermicompost and as encapsulated units. This approach was applied across forest and agricultural landscapes, establishing proof of concept for UAV-enabled

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biocontrol. However, the study also revealed key limitations: the system required precise calibration and favorable weather conditions to maintain release accuracy and biological effectiveness.[4] Similarly, in Brazil, Rangel developed a lightweight, low-cost UAV distribution tool for *Trichogramma pretiosum* in soybean fields. While the system offered portability and affordability, its performance was hampered by wind-induced drift, which significantly reduced deposition accuracy in variable field environments.[5]

European trials have provided further insights into the strengths and limitations of UAV-based entomophage deployment. Razinger *et al*. conducted multi-country experiments across France, Italy, and Slovenia to release *Trichogramma brassicae*, showing that UAV-based methods could achieve satisfactory biological control under diverse agricultural contexts. Yet, these trials highlighted a persistent economic challenge: the high equipment and operational costs limited the feasibility of UAV systems in regions lacking subsidies or large-scale cooperative structures.[6] Such findings reinforce that while UAVs can facilitate precise bioagent delivery, their broad adoption requires technological and economic adaptations to local agricultural systems.

Recent technical innovations are progressively addressing these challenges. Freitas *et al*. proposed smart field partitioning algorithms to optimize distribution in irregularly shaped plots, demonstrating improved efficiency, although their approach remained dependent on highly precise flight path planning.[7] Song *et al*. introduced a rotary hammer dispenser that enabled more uniform capsule release, though its performance was still sensitive to UAV speed and flight altitude.[8] Xing *et al*. developed a sub-field modeling framework that improved delivery quality metrics in complex agricultural environments, achieving up to 97% coverage under ideal conditions.[9] Ma *et al*. further emphasized the importance of environmental interactions by using vermiculite modeling to show how wind speed and UAV velocity strongly influence dispersal outcomes. They advocated for enhanced sensor integration and adaptive hardware to counteract these effects.[10]

Commercial platforms have also emerged, with companies such as Skyinnov (France) and Soleon (Italy) employing modular, 3D-printed UAV systems for agricultural applications. While innovative in their construction, these platforms remain generalized for tasks such as spraying and do not incorporate bioagent-specific features essential for entomophage release. This highlights a broader technological gap: few current systems combine biological compatibility, mechanical precision, and economic feasibility in a manner suitable for widespread adoption, especially in transitional agricultural economies.

The adoption of UAV-based systems carries particular promise for Kazakhstan's agricultural sector.[11] The country's vast and heterogeneous landscapes, which include remote and flood-prone areas, demand solutions that are not only precise and biologically compatible but also robust, affordable, and adaptable to local conditions. However, most UAV dispersal devices developed internationally are not tailored for the regional requirements of Central Asian agriculture, where operational reliability and cost efficiency are as important as technical sophistication.

Despite notable advances in UAV applications for agriculture, entomophage distribution remains underdeveloped. Current systems frequently exhibit limitations in dispersal precision, suffer from operational complexity, or prove too costly for widespread adoption. Zhan *et al*. demonstrated that UAV-based deployment of *Trichogramma* could be highly effective but emphasized that adaptability and cost remain persistent challenges.[12] Likewise, Cui *et al*. reported that release precision is highly sensitive to environmental factors such as wind speed and to the specific configuration of UAV equipment, underscoring the necessity for hardware-level innovations that can stabilize performance under real-world conditions.[13]

Taken together, the literature reveals a clear research gap in the development of UAV platforms specifically adapted for biological pest control in challenging agricultural environments. There is an urgent need for systems that integrate biological compatibility, low-cost manufacturing, and mechanical precision while maintaining consistent release accuracy under diverse conditions.

To address this gap, the present study aims to develop and field-test a UAV-mounted capsule dispersal device designed for the release of entomophages under Kazakhstan's agricultural conditions. The system integrates biodegradable capsule carriers, GPS/GLONASS-guided navigation, and algorithmic control logic to achieve precise spatial release of *Trichogramma* spp. eggs. By enabling bioagent deployment in hard-to-reach areas and ensuring compatibility with domestic UAV platforms, this work advances both the technological and ecological dimensions of biologized pest management, providing a scalable pathway toward more sustainable agricultural practices.

2. Materials and methods

In developing the device, established methodologies in engineering (Pahl *et al.*) and plant protection (Grinberg *et al.*) were applied.[14,15] The design process followed systems engineering principles and modern design methods,[16] with rapid prototyping (Rosen *et al.*) employed to define technical requirements, create 3D models in Autodesk Fusion 360, visualize in Blender, and iteratively refine prototypes through 3D printing.[17–19]

Device control was implemented using object-oriented

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programming on a Raspberry Pi 4 microcomputer. Positioning relied on a NEO-6M GPS/GLONASS module, with coordinates collected via the NMEA protocol.[20,21] Routes were defined as waypoints from KML files or manual input, and algorithms corrected deviations in real time. Stepper motor actuation was controlled by the microcomputer based on GPS data.[22]

Capsule design was informed by existing entomological practices, which traditionally used cardboard envelopes containing *Trichogramma* eggs embedded in biogel. The new capsules were fabricated from biodegradable materials available in Kazakhstan, selected to ensure complete degradation within five years under field conditions. Capsule release was optimized using bioglues such as bioliposam, biolipostim, and bioprimers.[23]

Laboratory assays were conducted in a thermostat with four replicates, each capsule containing ten *Sitotroga* moth eggs parasitized by *Trichogramma* spp.[24,25] Emergence of adults was assessed on days 3, 5, and 7. Field trials were performed on a 0.1 ha site with a designated UAV base point (H), testing GPS accuracy, communication systems, and timed capsule release.[26]

Environmental considerations guided material choice, as degradation rates of paper, cardboard, and polymers such as PLA vary with soil pH and moisture. Cardboard typically decomposes within months under favorable conditions, whereas PLA may persist for several years in extreme soils. To ensure sustainability, a criterion was adopted requiring full degradation of capsule materials within five years. Terrain-following and mission-planning software enabled UAVs to autonomously adjust altitude, ensuring consistent release height and accurate capsule placement across variable topography.

2.1 Mechanical design and prototyping

The device design was based on rapid prototyping principles, beginning with the formulation of technical requirements, solid modeling in Autodesk Fusion 360, and visualization in Blender. Components were fabricated using additive manufacturing, with models exported in *.stl format and processed in Cura and Prusa Slicer.[27]

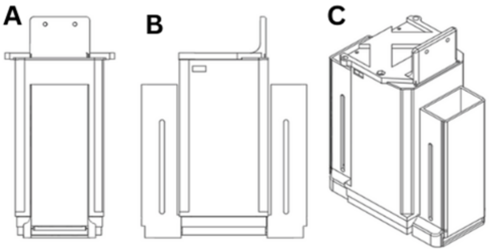

Fig. 1: Technical drawings of the UAV-mounted capsule dispersal device for automated release of entomophages. (A) Front view showing the external frame and capsule slot. (B) Side view illustrating the capsule compartment and mounting structure. (C) Isometric view displaying the assembled device with capsule storage unit.

Parts were printed in PLA and PETG, with mechanical elements designed in accordance with ISO 6336 standards for gear transmissions and GOST guidelines for material selection, tolerances, and mechanical strength. Figs. 1 and 2 present the technical drawings and cross-sectional schematics of the device, illustrating the arrangement of the frame, GPS sensor, microcomputer, motor, gearbox, pusher, and capsule storage unit.

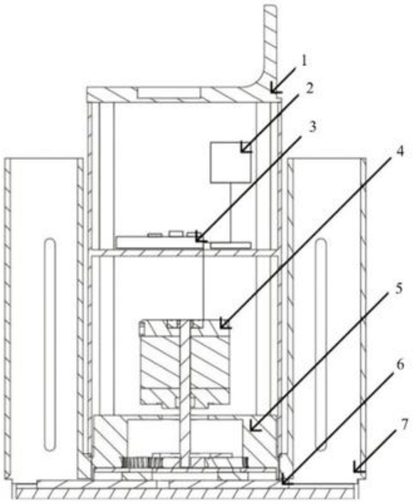

Fig. 2: Cross-sectional schematic of the UAV-mounted capsule dispersal device showing key components: 1 – frame, 2 – GPS sensor, 3 – control unit (microcomputer), 4 – electric motor, 5 – gearbox, 6 – pusher, 7 – capsule store.

2.2 System architecture and control

The control architecture was implemented on a Raspberry Pi 4 microcomputer, using object-oriented programming to coordinate navigation and capsule release. Positioning relied on a NEO-6M GPS/GLONASS module, with coordinates acquired via the NMEA protocol. Flight paths were defined as sequences of waypoints from pre-prepared KML files or manual input, with algorithms correcting deviations from the route in real time. Stepper motor actuation was managed through the RpiMotorLib interface and an A4988 microcontroller. To improve positional accuracy, raw GPS data (±2 m error) were filtered using the Exponentially Weighted Moving Average (EWMA) algorithm,[28] while short-term trajectory prediction employed linear regression based on a two-second sliding window.[29] These methods reduced noise and improved synchronization of capsule release with UAV movement. Fig. 3 illustrates the GPS error correction process and regression-based trajectory prediction.

A custom web-based interface, implemented in HTML5, JavaScript, and Flask, allowed operators to manage the device through mobile or desktop connections to the Raspberry Pi's access point. The interface displayed real-time UAV position, mission progress, and device operation, while log files were automatically generated in *.json, *.csv, and *.xml formats for subsequent analysis.

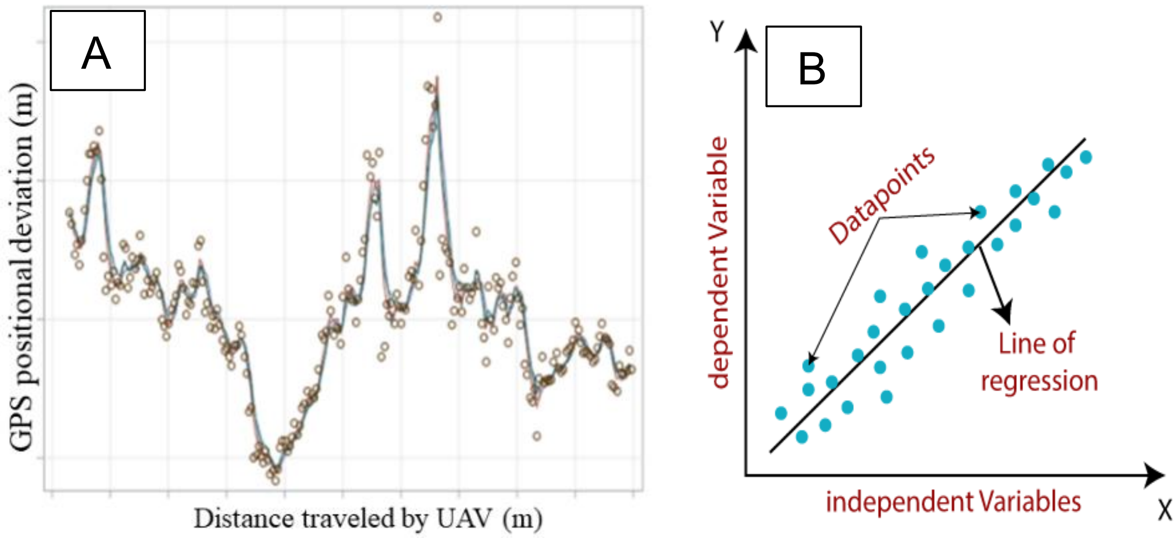

Fig. 3: (A) Output data of the UAV-mounted capsule dispersal device showing raw GPS positional deviations (dots) and smoothed trajectory using the Exponentially Weighted Moving Average (EWMA) algorithm. (B) Conceptual illustration of linear regression used to interpolate and predict future UAV positions based on recent data points.

2.3 Capsule development and bioagent testing

The capsule design was developed in collaboration with entomologists, building upon existing manual release methods that employed cardboard envelopes with biogel-applied *Trichogramma* eggs.[30] New prototypes were fabricated from biodegradable paper, cardboard, and polymers available on the Kazakhstani market, selected to ensure complete degradation within five years under field conditions.[31] Capsule dimensions were standardized at 39 × 59 × 4 mm, enabling stackability in the dispensing compartment. Structural features included interlocking petals for assembly without adhesives and 0.5–1 mm exit holes to facilitate parasitoid emergence.[32]

Unit economics were assessed by fabricating capsules via laser cutting. One sheet produced up to 80 capsules, with per-unit costs of 31.75–36.25 KZT depending on material (Table 1). A total of 100 capsules were fabricated for testing in the prototype device. Laboratory experiments evaluated parasitoid emergence under different temperatures. Each capsule contained 10 *Sitotroga* eggs infected with *Trichogramma* spp. and experiments were performed in four replicates inside a thermostat.

Emergence was recorded at 3, 5, and 7 days post-incubation (Table 2). Results demonstrated 100% emergence within 6 hours at 30 °C, and within 24 hours at 23–25 °C, validating capsule suitability for biological release.

2.4 Bench and field validation

Bench tests were conducted to assess the reliability of the release mechanism independently of UAV integration. The device was mounted on a stand and programmed for continuous release cycles over one hour, during which jamming events, motor stoppages, and capsule misfeeds were recorded. Design refinements, including chamfered capsule edges and guide rails, significantly reduced failure rates.

Table 1: Unit cost breakdown for capsule fabrication using a typographic laser cutter (prices in KZT).

Cost Component	Value per Sheet (KZT)	Capsules per Sheet	Cost per Capsule (KZT)
Material cost	40-200	80	0.5-5
Laser cutter operation cost	2500	80	31.25
Total cost (Material + Operation)	-	-	31-75-36.25

Table 2: The output of the imago trichogram, “KazRIPPQ named after Zh.Zhiembayev” LLP, 2023.

T, °C	Exit of imago, %		
	6 hours	12 hours	24 hours
23	25	50	100
25	50	75	100
27	75	100	-
30	100	-	-

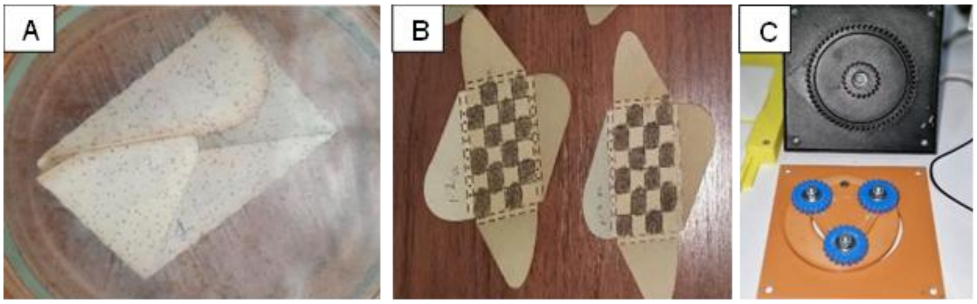

Fig. 4: Examples of capsule and device components used in the UAV-mounted entomophage dispersal system. (A) Cardboard envelopes with entomophage eggs. (B) Biodegradable capsule templates. (C) Prototype gear mechanism for device testing for jamming.

Field trials were performed on a 0.1 ha test plot, where UAVs equipped with the dispersal device released 100 capsules along pre-defined flight paths. GPS accuracy, capsule drift under different wind conditions, and release reliability were evaluated (Figs. 4 – 6). Drift experiments determined that a release altitude of 3 m minimized both rotor-induced turbulence and wind displacement. The device was also tested under real mission conditions with software-based control and GPS-guided release intervals, confirming the system's feasibility for field-scale biological control applications.

3. Results and discussion

The performance of the UAV-mounted capsule dispersal device was systematically validated through a combination of bench trials, field experiments, and biological assays, providing evidence that the system can achieve precision, reliability, and ecological compatibility. The study illustrates that technological refinements in navigation, capsule design, and release mechanisms have the potential to overcome many of the barriers that have historically hindered the large-scale adoption of biological pest control.

The accuracy of the GPS navigation system is illustrated in Fig. 5, which shows the results of prototype testing under real operating conditions. In Fig. 5A, the control algorithm triggered capsule release every five meters, and Fig. 5B visualizes capsule ejection points recorded on the map via the GPS module. These results confirmed that deviations from the intended trajectory did not exceed one meter, demonstrating that low-cost GPS/GLONASS modules, when coupled with filtering algorithms, can achieve accuracy suitable for field-scale pest management. The custom-developed smartphone interface, depicted in Fig. 5C, enabled straightforward remote control of missions, while Fig. 5D validated that capsule release events were correctly aligned with programmed waypoints. This level of precision ensures reliable spatial distribution of entomophages, a prerequisite for effective biological control.

Mechanical reliability was another critical aspect of system performance. Initial bench testing revealed occasional jamming within the magazine, primarily due to capsule misalignment and friction. However, refinements such as chamfered edges and the addition of guide rails improved reliability, with uninterrupted release of 100 capsules achieved under controlled conditions. The field evaluation presented in

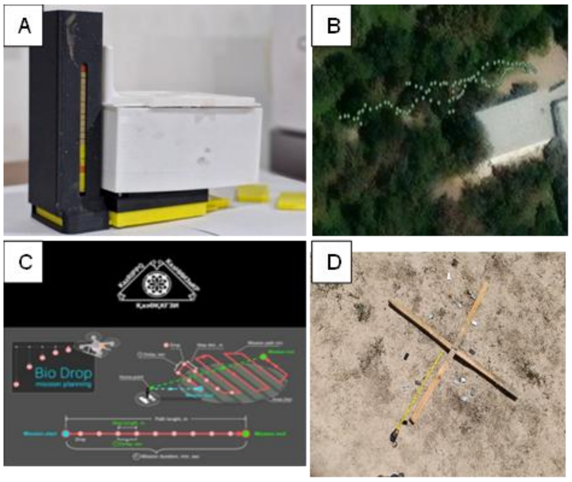

Fig. 5: Field and software testing of the UAV-mounted capsule dispersal device. (A) Prototype testing of the device's control algorithm with GPS tracker signal, triggering capsule release every 5 meters. (B) GPS module testing showing capsule ejection points on the map. (C) Software interface for UAV mission planning and device control. (D) Field validation of capsule release points during UAV operation.

Fig. 6 provides a deeper view of these findings. Fig. 6A shows the landing density of capsules released from a height of three meters, confirming uniform dispersal across the test plot. Fig. 6B displays GPS activation marks, further validating release accuracy, while Fig. 6C highlights a disassembled dispersal mechanism with a jammed capsule. Although capsule jamming was reduced from ~10% in early tests to a single case during 100 field releases, the persistence of occasional failures under dynamic flight maneuvers underscores the need for additional refinement.

The influence of environmental conditions was quantified in Table 3, which presents capsule drift measurements under varying wind speeds and release altitudes. At 2 meters, drift exceeded two meters even under moderate wind (5 m/s), due largely to turbulence from UAV propellers. At 3 meters, drift was reduced to less than half a meter, establishing this altitude as optimal for balancing rotor downwash and environmental wind effects. At higher wind speeds (11 m/s), drift increased at all altitudes, but the effect was minimized at three meters. The importance of selecting the correct release height is further emphasized in Fig. 6A, which depicts the landing density of capsules released at this optimal height. Together, these findings demonstrate that UAV-based biological control systems must be carefully calibrated to both aircraft specifications and local environmental conditions to ensure consistent precision. Field mission performance is exemplified in Fig. 6B, which shows GPS activation marks recorded during UAV operation at a working height of three meters. This visualization confirms that capsule releases followed the intended spatial distribution, even under variable flight paths. However, instability of the dispersal mechanism was observed in longer missions, as illustrated in Fig. 6C, where a disassembled mechanism revealed jamming due to capsule displacement caused by UAV vibration. These results highlight the continued importance of mechanical optimization for reliable performance during dynamic operations.

Table 3: Study of the effect of wind speed on the accuracy of capsule distribution by UAVs, experimental fields of "KazRIPPQ named after Zh. Zhiembayev" LLP, 2024.

Wind Speed, m/s	Capsule Drift by Altitude, m			
	2	3	4	5
5	2.11	0.31	0.52	0.67
8.3	2.32	0.39	0.65	0.83
11	2.21	0.41	0.68	1.3

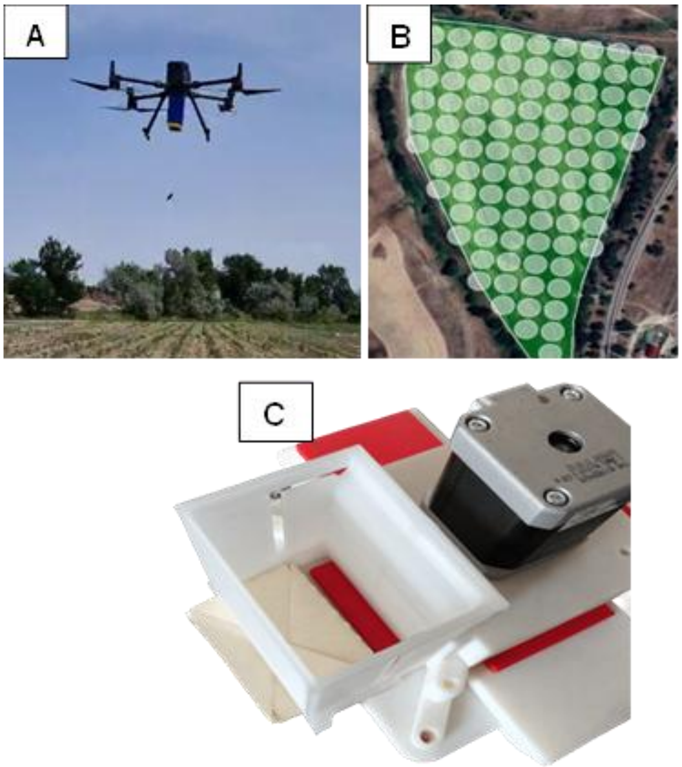

Fig. 6: Field and mechanical evaluation of the UAV-mounted capsule dispersal device. (A) Landing density of bioagent capsules dispersed from a UAV at a release height of 3 meters. (B) GPS sensor activation marks recorded during UAV operation. (C) Disassembled dispersal mechanism showing capsule jamming during testing.

Beyond engineering performance, the biological integrity of the capsules was validated under controlled laboratory conditions. Table 2 summarizes the emergence of Trichogramma spp. imagos from capsules incubated at different temperatures. At 30 °C, 100% emergence occurred within six hours, while at 25 °C complete emergence required 24 hours. These results indicate that the capsule design successfully preserves the viability of parasitoids while allowing timely emergence after release. Field deployment at approximately 25 °C is recommended, as this temperature balances rapid emergence with environmental realism. The biological performance, illustrated in Figure 4A–B, shows both the design of the biodegradable capsules and their suitability for carrying and protecting bioagents.

The economic feasibility of the system was evaluated in Table 1, which reports the breakdown of capsule fabrication costs using a laser-cutting process. With material and operation costs yielding a per-unit price of 31.75–36.25 tenge, the capsules are competitively priced compared to conventional pest control inputs, particularly given their ecological benefits. The biodegradable nature of the capsules ensures that no long-term residues remain in the soil, further strengthening their value as an environmentally responsible alternative.

Collectively, these results establish that the UAV-mounted capsule dispersal device achieves a rare combination of mechanical precision, biological compatibility, and economic feasibility. While occasional jamming during flight indicates that further refinement is needed, the system compares favorably with international prototypes, many of which remain constrained by high costs, operational complexity, or limited adaptability. By demonstrating a regionally tailored, low-cost, and biologically effective solution, this work advances UAV-enabled biocontrol from an experimental concept toward practical agricultural application. The integration of figures and tables throughout this study not only validates the device's performance but also provides a transparent foundation for future scale-up and optimization in real farming systems.

4. Conclusion

This study demonstrates the successful design, prototyping, and validation of a UAV-mounted device for the automated release of entomophages encapsulated in biodegradable carriers. The system directly addresses the limitations of manual deployment by combining engineering precision with ecological compatibility, thereby advancing sustainable pest management strategies for Kazakhstan's agricultural sector and beyond. Laboratory assays confirmed that *Trichogramma* spp. maintained full biological viability following encapsulation, with 100% adult emergence achieved within six hours at 30 °C and within 24 hours at 25 °C. Field experiments verified that the device achieved a release accuracy exceeding 90%, with GPS/GLONASS-guided navigation limiting positional error to within one meter. Optimal performance was observed when capsules were dispersed from a height of three meters, where wind-induced drift and UAV rotor turbulence were minimized. The capsule design itself provides additional advantages: units are lightweight, stackable, and biodegradable, with a production cost of only 31.75–36.25 tenge per unit, ensuring both affordability and environmental safety. Mechanical refinements significantly reduced jamming during operation, with uninterrupted release achieved in bench trials and only isolated failures observed under dynamic field conditions. The integration of algorithmic noise reduction, linear regression for trajectory prediction, and user-friendly mobile control software further enhances the robustness and accessibility of the system. Together, these results confirm that UAV-based entomophage deployment can provide a scalable, cost-effective, and environmentally sustainable alternative to synthetic pesticide applications, particularly in hard-to-reach or flood-prone areas where conventional methods are impractical. The technology fills a critical gap between conceptual UAV applications and practical, field-ready solutions for biologized agriculture. Future work will focus on large-scale field validation to assess capsule survival and parasitoid emergence under real agricultural stressors such as variable temperatures, wind, and mechanical impact during drop events. Long-term trials will also benchmark pest suppression efficacy against cotton bollworm (*Helicoverpa armigera*) by directly comparing UAV-deployed *Trichogramma* with untreated control plots. These efforts will provide the necessary evidence base for scaling this technology to commercial farming systems. In conclusion, the UAV-integrated dispersal system presented here represents a significant technological step toward sustainable crop protection, combining engineering innovation, biological efficacy, and economic feasibility in a manner that can accelerate the transition to pesticide-free agriculture.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

CRediT Statement

Zibash Beknazarova: Supervision, Funding acquisition. **Malik Taishikov:** Methodology, Writing - Original draft, field trials. **Rinat Fazylbekov:** Methodology, Writing - Original draft, field trials. **Marat Boltayev:** Methodology, Field trials. **Alua Rysbekova:** Writing - Review and editing, Data curation, Data visualization, Writing - Review and editing.

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