RESEARCH ARTICLE

SABRAO Journal of Breeding and Genetics
57 (5) 2097-2105, 2025
http://doi.org/10.54910/sabrao2025.57.5.30
http://sabraojournal.org/
pISSN 1029-7073; eISSN 2224-8978

# AUTOMATED UAV-BASED SYSTEM DEVELOPMENT TO ESTABLISH ENCAPSULATED ENTOMOPHAGES FOR PEST CONTROL IN KAZAKHSTAN

**A.M. RYSBEKOVA*, M.A. TAISHIKOV, R.R. FAZYLBEKOV, Z.B. BEKNAZAROVA, M.D. BOLTAYEV, K.A. ALPYSBAYEVA, A.P. NIKONOROV, and U.T. USMANOV**

Kazakh Research Institute of Plant Protection and Quarantine named after Zh. Zhiembayev, Almaty, Kazakhstan
*Corresponding author's email: rysbekova949r@gmail.com
Email addresses of co-authors: maliktaishikov777@gmail.com, fazylbekov@gmail.com, zibash_bek@mail.ru, boltayevmarat81@gmail.com, karlygashazirbekovna@gmail.com, aniko.inbox@gmail.com, usmanovus2001@gmail.com

## SUMMARY

Crop losses due to insect pests pose a significant threat to food security and farming economics. Globally in crop plants, insect pest damage caused up to 38% of yield losses in crops. Excessive reliance on chemical pesticides has led to pest resistance and environmental harm, prompting increased interest in biological control using entomophages (beneficial predatory and parasitic insects). *Trichogramma evanescens* Westwood (1833), an egg parasitoid wasp, is a widely used insect to biologically control the cotton bollworm (*Helicoverpa armigera*) and other lepidopteran pests in Kazakhstan. However, distributing *Trichogramma* efficiently at the field scale remains challenging when done manually. The presented study explored the development and evaluation of a novel unmanned aerial vehicle (UAV)-based system for the automated dispersal of *Trichogramma* in encapsulated form. The developed system integrates a custom-designed capsule delivery device integrated with a commercial drone, enabling precise, controlled release of entomophages over crop fields. The UAV-based system proved eco-friendly, labor-saving, and effective, achieving over 90% emergence rates and high parasitism levels, comparable to manual application.

**Keywords:** UAV, drone, *Trichogramma evanescens*, entomophages, biological control, capsule delivery, precision agriculture, cotton bollworm (*Helicoverpa armigera*)

**Key findings:** A UAV-based system, successfully developed for precise release of biodegradable capsules with *Trichogramma* for biological pest control, achieved over 90% emergence and high parasitism rates. It also matches manual effectiveness while offering eco-friendly and labor-saving management.

Communicating Editor: Prof. Naqib Ullah Khan

Manuscript received: May 19, 2025; Accepted: September 05, 2025.


**Citation:** Rysbekova AM, Taishikov MA, Fazylbekov RR, Beknazarova ZB, Boltayev MD, Alpysbayeva KA, Nikonorov AP, Usmanov UT (2025). Automated UAV-based system development to establish encapsulated entomophages for pest control in Kazakhstan. *SABRAO J. Breed. Genet.* 57(5): 2097-2105. http://doi.org/10.54910/sabrao2025.57.5.30.

## INTRODUCTION

Agricultural pests cause severe crop losses worldwide, undermining agroecosystem productivity and farm income. Insect pests are responsible for nearly 38% of global crop yield losses (Culliney, 2015; Avelino *et al.,* 2015; Cerda *et al.,* 2017). Excessive reliance on chemical pesticides has created ecological imbalances, including resistance and environmental degradation (Mahato and Anupama, 2014). This situation intensified interest in developing strategies for eco-friendly pest management. One of those strategies is the use of entomophages, the natural enemies of pests (parasitoids, predatory insects, and mites). Entomophages suppress pests with minimal ecological impact, preserve biodiversity, and are central to integrated pest management (IPM) and organic farming.

In Kazakhstan, *Trichogramma evanescens* (Hymenoptera: *Trichogrammatidae*) is among the most widely used entomophagous biocontrol agents. *Trichogramma evanescens* is an egg parasitoid that proved effective against the cotton bollworm (*Helicoverpa armigera*), a major lepidopteran pest of crops, such as cotton, tomato, and maize (Vdovenko and Chenikalova*,* 2009). The cotton bollworm is highly polyphagous, attacking many crops, including chickpeas, alfalfa, tobacco, legumes, cucurbits, and weeds. Under greenhouse conditions, it severely damages solanaceous vegetables (tomato, eggplant, and pepper) by feeding on their leaves, flowers, and fruits. In the following study, tomato was the choice target crop due to its vulnerability to bollworm infestation and wide cultivation in Southeastern Kazakhstan (Nurmatov, 1983).

Despite the proven efficacy of *Trichogramma* in pest control (Vdovenko and Chenikalova*,* 2009), however, its efficient distribution over larger areas is a key challenge. Traditional manual and carrier-based broadcasting is labor-intensive and imprecise and exposes fragile bioagents to damage, reducing survival and control effectiveness. Encapsulation of biological control agents offers a potential solution to distribution and survival challenges. Packaging entomophages in protective capsules helps safeguard them from mechanical injury and desiccation, while the timing of adult emergence is more manageable (Kang *et al.,* 2024). Similar techniques are already well-established in microbial biocontrol. For example, encapsulation of beneficial bacteria and fungi in alginate or polymer beads has been shown to improve field survival, prolong shelf life, and provide the release of living organisms gradually under stress conditions (Kang *et al.,* 2024). These microbial encapsulation approaches demonstrate how controlled release systems can stabilize fragile bioagents and increase efficacy in variable environments.

However, while microbial encapsulation benefits from simple formulations and mass-production methods, applying similar techniques to entomophages is more complex due to their larger size, mobility, and sensitivity. This makes the development of efficient large-scale delivery mechanisms for insect capsules a critical next step. UAVs (unmanned aerial vehicles) are emerging as a promising platform for precision agriculture, including the distribution of biocontrol agents. Drones offer automated, targeted distribution with reduced labor, uniform coverage, and timely release before pests reach threshold levels (Martel *et al.,* 2021; Cui *et al.,* 2022; Song *et al.,* 2023). Recent studies have also explored multi-UAV coordination strategies for time-sensitive operations, offering valuable insights for future applications in precision agriculture (Kutpanova *et al.,* 2025).

The rapid adoption of agricultural drones demonstrates their transformative role in modern farming, with over 500 million hectares treated worldwide by mid-2024 (Stark Flight, 2025). Several countries have pioneered drone-based *Trichogramma* releases, including Canada and China (Martel *et al*., 2021; Song *et al*., 2023), France (through the Skyinnov 'T-Drop' system), and Italy with specialized 3D-printed drones by Soleon (Soleon, 2024). These initiatives highlight a growing global shift toward automated, drone-assisted biological pest control.

However, in Kazakhstan, UAV-based entomophage release is still to be adopted due to limited research and development, lack of equipment, and insufficient encapsulation techniques. Local producers also lack practical experience, highlighting the need for applied research. The goal of the presented research was to develop and field-test a UAV-compatible hardware–software system for automated, metered release of entomophages in capsule form, improving the precision and efficiency of biological crop protection in Kazakhstan.

## MATERIALS AND METHODS

In 2024, under Project AP19680280 funded by the Ministry of Science and Higher Education, Kazakhstan, the experiments succeeded in using laboratory-reared *Trichogramma evanescens* Westwood as a biological control agent against *Helicoverpa armigera.* The study occurred at the Kazakh Research Institute of Plant Protection and Quarantine, Almaty, Kazakhstan. All experiments proceeded with a minimum of four biological replicates per treatment, unless otherwise specified, with replicate assays carried out under identical laboratory or field conditions. Pest development monitoring used weekly delta pheromone traps across the Almaty Region to align UAV-mediated parasitoid releases with peaks in bollworm oviposition (Fursov *et al*., 2003; Vdovenko and Chenikalova*,* 2009). A GPS-guided multirotor UAV (payload ~5 kg) executed pre-programmed flight paths at altitudes between 2 and 5 m and speeds of 2–4 m/s, managed via a custom Python/Flask interface. The 1.5 kg 3D-printed PLA dispenser, as attached to the aircraft, comprised a hopper and rotary ejection mechanism controlled by a Raspberry Pi 4. It releases biodegradable 39 mm × 59 mm × 4 mm capsules loaded with approximately 80 parasitized eggs and perforated for adult emergence at precise GPS coordinates (Song *et al.,* 2023).

In the laboratory, the thermal emergence assays exposed capsules to 23 °C, 25 °C, and 30 °C, recording time to first adult eclosion and overall emergence percentages, thereby confirming capsule suitability across typical field temperatures. Wind tunnel trials at 5, 8, and 11 m/s quantified lateral drift of capsules dropped from heights of 2–5 m and refined optimal deployment parameters for minimal off-target displacement (Song *et al.,* 2023).

Field evaluations on open-field tomato plots in the Enbekshikazakh District compared capsule integrity and parasitoid survival after drops onto bare soil, maize canopy, and tomato foliage at varying release heights; meanwhile, manual hand placement served as the control treatment. During the trial period (June–August 2024), average daytime temperatures ranged from 24 °C to 30 °C, and relative humidity ranged from 45% to 60%. Recovered capsules incurred examination for intact *T. evanescens* eggs across four replicates per treatment, with statistical comparison performed using one-way analysis of variance (ANOVA). For efficacy assessment, treated plots (0.1 ha, ~80 000 eggs/ha) sampling for pest egg densities continued immediately before and seven days after UAV releases, with parasitism rates calculated via Abbott's formula to contrast treatment and untreated control outcomes (Liu and Kim*,* 2019).

## RESULTS AND DISCUSSION

### Device and capsule performance

Regarding an automated entomophage delivery system, this research developed a functional UAV-mounted dispensing device and capsule combination. The final prototype of the device integrated onto a drone appears in Figure 1 (an assembled view of the UAV with spreader). The Raspberry Pi 4-based control module interfaces with the drone's navigation system to coordinate capsule releases at specific GPS waypoints. Across a total of 18 UAV test flights, the capsule release system demonstrated high reliability, with no instances of mid-air malfunction or jamming. The remote monitoring interface allowed the operator real-

**Figure 1.** An assembled view of the UAV with spreader.


**Figure 2.** Capsule release mechanism using the unmanned aerial vehicle (UAV)-based system: 1) movement direction of the UAV, 2) spreader device, 3) UAV, and 4) capsules with entomophage eggs.

time mission progress tracking and also confirmed the capsules' release at specific and correct locations.

These results were consistent with previous findings, which also reported that an intelligent UAV system for *Trichogramma* capsule delivery achieved accurate waypoint navigation and high-coverage efficiency (99.33%) with minimal flight deviation and robust capsule release (Martel *et al.,* 2021; Kai *et al.,* 2021). Past findings demonstrated successful deployment of *Trichogramma* using unmanned systems without differences in egg parasitism rates compared with traditional methods, also confirming the UAV reliability in operational settings (Martel *et al.,* 2021).

The PLA capsule design proved essential for success. Focusing on a simple, robust parallelepiped shape that included exit holes, the equipment ensured that nearly all adult wasps could escape after emergence while the capsule itself could withstand handling (Figure 2). The laboratory emergence tests confirmed *Trichogramma* development had no hindrance from encapsulation: at 23 °C, the emergence was slightly slower (~30–36 hours to full emergence), while at 25 °C, it took ~24 hours, and at 30 °C, the emergence was very rapid, with 100% adult emergence in ~6 hours. This indicates that in warm field conditions (around 25 °C–30 °C daytime temperatures), parasitoids deploy from capsules within one day for timely searching for pest eggs. The capsules maintained their integrity in the incubator (with no disintegration), illustrating their suitability for field use.

These results obtained support from Orr *et al.* (1997), who observed capsule placement and microclimate conditions (like temperature) considerably influenced *Trichogramma* emergence rates, particularly under warmer climatic conditions. Additionally, Xing *et al.'s* (2023) findings demonstrated that an optimized UAV capsule delivery system in varied terrains ensured over 97% coverage and capsule stability, validating the field robustness of this approach.

**Wind drift and optimal release height**

The important practical question was how high the drone should fly when dropping capsules to maximize coverage while minimizing drift and turbulence effects. The summary of the observed horizontal drift of capsules under different wind speeds and drop heights appears in Table 1. The drift distances were the largest when releasing capsules from the lowest height (2 m)—somewhat counterintuitively, dropping from only 2 m resulted in capsules landing over two meters away in windy conditions. An explanation was the strong turbulent air current generated by the drone's propellers when it was very close to the ground: the prop wash caused the capsules to be blown off-target at the moment of release. However, at higher release altitudes, the influence of the drone's own turbulence diminished, and the major factor became the natural wind. The results revealed that the 3-m height provided the most stable release of capsules with accuracy. At 3 m, drift was minimal (only ~0.3–0.4 m under light-to-moderate breeze) because the capsule quickly cleared the propeller downdraft and then fell near-vertically, and the wind with low altitude imparted limited lateral movement. At the 4-m and especially 5-m height, the drift increased under higher wind (reaching up to ~1.3 m at a 5-m height with ~11 m/s wind) and simply more time spent falling through a windy layer.

In the potential system, the results detailed that an optimal drop height was around 3 m above the crop canopy under typical wind conditions (up to ~5–8 m/s). Similarly, at this height, both drone-induced turbulence and wind drift were minimal, ensuring capsules land very close to their intended targets. Non-recommendation of lower altitude (<2 m) is due to the drone's rotor wash significantly perturbing the capsules, while much higher altitudes (>5 m) expose the capsules to wind drift over a longer fall time. In practice, researchers suggest restricting operations to wind speeds of no more than ~5–8 m/s for reliable accuracy and flying at ~3 m height for capsule release.

The study findings were greatly analogous to the computational modeling, which recognized that a 3-meter capsule release height was optimal for minimizing turbulence and ensuring accurate deposition in UAV spray systems due to balanced airflow and least ground effect (Zheng *et al.,* 2018). Similarly, Wang *et al.'s* (2023) findings demonstrated that excessive spray drift enhanced at the height above 3 m, particularly under crosswinds above 3 m/s, also recommending a mid-range release strategy to minimize off-target drift.

**Table 1.** Effect of wind speed and drop height on capsule dispersal accuracy (drift distance from target point). Field trials in 2024 at the KazRIPPQ Experimental Farm.

| Wind speed (m/s) | Drift at 2 m height (m) | Drift at 3 m (m) | Drift at 4 m (m) | Drift at 5 m (m) |
|---|---|---|---|---|
| ~5.0 (light breeze) | 2.11 | 0.31 | 0.52 | 0.67 |
| ~8.3 (moderate breeze) | 2.32 | 0.39 | 0.65 | 0.83 |
| ~11.0 (near strong wind) | 2.21 | 0.41 | 0.68 | 1.30 |

**Table 2.** *Trichogramma* eggs viability (mean number of undamaged eggs per capsule) after release by different methods and heights in 2024 at the Almaty Region, Kazakhstan.

| Release method | Height | Intact *Trichogramma* eggs (per capsule) – mean ± SD |
|---|---|---|
| UAV drop – bare ground | 2 m | 74.5 ± 2.1 |
| | 3 m | 73.3 ± 1.8 |
| | 4 m | 70.5 ± 2.0 |
| | 5 m | 66.0 ± 2.5 |
| UAV drop – on corn canopy | 2 m | 76.5 ± 1.5 |
| | 3 m | 75.3 ± 1.7 |
| | 4 m | 72.3 ± 2.2 |
| | 5 m | 68.8 ± 2.4 |
| UAV drop – on tomato canopy | 2 m | 76.0 ± 1.6 |
| | 3 m | 75.0 ± 1.4 |
| | 4 m | 73.7 ± 1.9 |
| | 5 m | 67.0 ± 2.6 |

In these experiments, observations also revealed that vegetation ground cover (like a crop canopy) helps arrest the capsule's movement upon impact, preventing bounce. Thus, the capsule releasing over crop foliage is preferable compared with bare ground in keeping capsules to drop at the specific point. Lawson and Uk (1979) reported that dense foliage significantly reduced airborne drift and improved the deposition uniformity by limiting droplet movement post-impact. Their findings also revealed that the vegetation canopy limits turbulence at the ground level and enhances capture efficiency for droplets, including biological agents.

**Entomophage survival in different release scenarios**

For the survival of *Trichogramma* eggs after release, the key indicator was the UAV-based delivery success. *Trichogramma* eggs are delicate, and excessive impact during release could also reduce the eggs' viability. Comparing the intact egg counts per capsule after various release methods and heights helped assess mechanical stress effects (Table 2). Each capsule initially held ~80 *Trichogramma evanescens* eggs.

After recovery, careful opening of capsules ensued under a stereomicroscope (×40 magnification), recording the number of intact, unbroken eggs per capsule. Consider eggs as 'intact' if the chorion remained undamaged and no signs of crushing or leakage were visible. Counts proceeded immediately after collection to avoid confounding effects of embryonic development.

Manual hand placement of the capsules served as the control, resulting in ~78.3 intact eggs per capsule—essentially baseline viability with minimal physical stress. However, the UAV drops from 1–2 m over crops maintained nearly equivalent viability, with 75–77 intact eggs, with a negligible 2%–5% reduction. Dropping from 2 m onto bare soil slightly lowered this to ~74.5 eggs, suggesting minor trauma from harder landings. These losses likely stemmed from eggs being dislodged and could be lightly crushed upon impact.

As the capsule drop height increased, the intact egg count declined—more markedly over bare ground. At 5 m, average survival dropped to ~66 eggs on bare soil (18% reduction), while over corn and tomato foliage, the egg count remained higher (~68–69 eggs), reflecting the cushioning effect of vegetation cover. At 4 m, the intact egg count was ~70.5 on bare ground and ~73–74 on various crops.

The data analysis authenticated that both capsule drop height and landing surface significantly ($p < 0.05$) influenced the egg survival; however, the differences between the corn and tomato crops' canopy were nonsignificant. Crucially, at heights up to 3 m, none of the UAV capsule release methods showed significant differences from the control, indicating minimal mechanical damage when operating within this range.

These results align with UAV deployment studies showing the highest accuracy and low biological impact when optimizing delivery systems. For example, UAVs with a capsule-dispensing mechanism have shown over 97% coverage and reliable biological efficacy, even in challenging field conditions (Xing *et al*., 2023), and well-designed release platforms have demonstrated smooth dispersion and minimal degradation of the eggs' viability (Song *et al*., 2023). The UAV-based *Trichogramma* release results in the highest egg survival rates with ≤3 m height over crop canopy. The vegetative cover cushions the impact, preserving ~90%–95% of the eggs. Thus, for optimal integrity of the biological agent, the release of capsules should be at ≤3 m altitude and preferably over plant foliage.

**Field efficacy in pest control**

By evaluating the biological efficacy of the *Trichogramma* wasps against the target pest (cotton bollworm on tomato), the optimal deployment parameters (≈3 m height, moderate conditions) confirmed that the UAV system safely delivers *Trichogramma*. In the treated plots where the drone dispersed *Trichogramma evanescens* capsules, the substantial parasitism of bollworm eggs was evident. After the releases (which were timed during the pest's egg-laying period in early July), pest egg count in the treated plots dropped markedly compared with the control. On average, about 72.4% of cotton bollworm eggs gained parasitism in the UAV-treated plots, whereas pest populations in control plots continued to develop unchecked. This ~72% efficacy was at par with typical results from conventional *Trichogramma* application methods in our region (Fursov *et al.,* 2023), indicating that the drone-based delivery did not reduce the effectiveness of *Trichogramma* in controlling the pests.

Noteworthy, achieving this level of control requires both effective distribution and proper timing based on pest monitoring. In 2024, cooler weather delayed the first bollworm generation, resulting in the second generation flight coinciding with tomato flowering and fruiting. The UAV releases of *Trichogramma evanescens* capsules commenced on 5 and 12 July 2024, scheduled to coincide with peak oviposition of the second generation, as determined by field monitoring. Using the pheromone trap data, the precise scheduled release of the *Trichogramma* wasps targeted the pest's second-generation eggs. This underscores that regular monitoring of pest phenology is crucial to maximize the impact of biocontrol agents.

In summary, the UAV-based capsule deployment system succeeded in delivering *Trichogramma* wasps to the field in a manner that preserved their viability and resulted in significant pest suppression. The observed pest control efficacy (~70% egg parasitism) demonstrates that this approach proved to be a viable alternative to manual releases, with the added advantages of automation and precision. Moreover, UAV deployment offers potential cost-effectiveness: drone releases reduce labor demands, enable coverage of larger areas in a shorter time, and minimize material losses compared with hand broadcasting. Although a full economic analysis was beyond the scope of this study, these operational efficiencies suggest that UAV methods could be more cost-competitive than traditional manual releases, especially at larger scales.

## CONCLUSIONS

The BioDrop system ensured accurate and uniform release of *Trichogramma* wasp capsules, achieving high parasitoid survival and parasitism rates, comparable to manual methods. Field trials confirmed ~72% parasitism against *H. armigera* with minimal drift and effective aerial coverage. Its automated delivery, wind-resistant design, and biodegradability offer labor and environmental advantages. The system is readily scalable, as it can be integrated with widely available commercial UAV platforms and adapted for use across different crops and landscapes. Its patent protection and compatibility with existing agricultural drone infrastructure highlight strong potential for commercial adoption, supporting broader biocontrol implementation by both small- and large-scale producers. This study demonstrates the effectiveness of UAV-based entomophage delivery, yet several areas warrant further research. These include the development of multi-agent release systems targeting diverse pest complexes and multi-UAV coordination frameworks using AI-driven path planning to improve scalability and efficiency. Innovations in capsule materials for enhanced biodegradability and controlled release, as well as the integration of sensor-based monitoring for real-time, adaptive pest control, also require further exploration.

## ACKNOWLEDGMENTS

Acknowledgments go to the Ministry of Science and Higher Education of the Republic of Kazakhstan for funding this research according to contract No. 271/23-25 for the project "AP19680280 The hardware-software complex for application of beneficial entomophages (bioagents) to the field using UAV for ecology-conscious plant protection from pests."

## REFERENCES

Avelino J, Cristancho M, Georgiou S, Imbach P, Aguilar L, Bornemann G, Laderach P, Anzueto F, Hruska AJ, Morales C (2015). The coffee rust crises in Colombia and Central America (2008–2013): Impacts, plausible causes, and proposed solutions. *Food Security* 7: 303–321. https://doi.org/10.1007/s12571-015-0446-9.

Cerda R, Avelino J, Gary C, Tixier P, Lechevallier E, Allinne C (2017). Primary and secondary yield losses caused by pests and diseases: Assessment and modeling in coffee. *PLoS One* 12(1): e0169133. https://doi.org/10.1371/journal.pone.0169133.

Cui K, Gong J, Ji S, Zhang Y, Mostafa K (2022). Performance test and parameter optimization of *Trichogramma* delivery system. *Micromachines* 13(11): 1996. https://doi.org/10.3390/mi13111996.

Culliney T (2015). Crop Losses to Arthropods. *Integrated Pest Management.* Springer, Dordrecht. pp. 201–205. https://doi.org/10.1007/978-94-007-7796-5_8.

Fursov V, Bolu H, Suna A (2023) Methodology of collecting, rearing and preserving parasitic entomophagous insects (Hymenoptera) for biodiversity research. *Munis Entomol. Zool. J*. 18 (1): 268–314. https://www.munisentzool.org/Issue/publish/methodology-of-collecting-rearing-and-preserving-parasitic-entomophagous-insects-hymenoptera-for-biodiversity-research_13911.

Kai Y, Chen S, Wang G, Fu J, Lan Y (2021). Biological control technology and application based on agricultural unmanned aerial vehicle (UAV) intelligent delivery of insect natural enemies (*Trichogramma*) carrier. *Pest Manag. Sci.* 77: 3259–3272. https://doi.org/10.1002/ps.6371.

Kang H, Fan T, Shi Y, Xie X, Li L, Xiang S, Xie J, Li B, Chai A (2024). Encapsulation of *Bacillus velezensis* and its biocontrol efficiency against *Plasmodiophora brassicae* in Chinese cabbage. *Scient. Hortic*. 337: 113473. https://www.sciencedirect.com/science/article/abs/pii/S0304423824006307.

Kutpanova Z, Kadhim R, Zheng X, Zhakiyev N (2025). Multi-UAV path planning for multiple emergency payloads delivery in natural disaster scenarios. *J. Electr. Sci. Technol*. 23(2): 100303. https://doi.org/10.1016/j.jnlest.2025.100303.

Lawson T, Uk S (1979). The influence of wind turbulence, crop characteristics and flying height on the dispersal of aerial sprays. *Atmos. Environ*. 13: 711–715. https://doi.org/10.1016/0004-6981(79)90200-2.

Liu L, Kim AA (2019). Application of drones in China's agriculture. *Vladivostok State University of Economics and Service Vladivostok, Russia* 4: 115–128 (in Russian). https://cyberleninka.ru/article/n/primenenie-dronov-v-selskom-hozyaystve-kitaya.

Mahato A, Anupama K (2014). Climate change and its impact on agriculture. *Int. J. Scien. Res. Pub.* 4(4): 1–6. https://www.ijsrp.org/research-paper-0414.php?rp=P282518.

Martel V, Johns R, Jochems-Tanguay L, Jean F, Maltais A, Trudeau S, St-Onge M, Cormier, D, Smith S, Boisclair J (2021). The use of UAS to release the egg parasitoid *Trichogramma* spp. (Hymenoptera: *Trichogrammatidae*) against an agricultural and a forest pest in Canada. *J. Eco. Entomol*. 114(1): 291–299. https://academic.oup.com/jee/article/114/5/1867/6130764.

Nurmatov TN (1983). Agronomist's Handbook on Plant Protection. Kainar, Alma-Ata. 183 (in Russian). https://bulbio.enu.kz/index.php/main/article/download/371/55/648.

Orr D, Landis D, Mutch D, Manley G, Stuby SA, King RL (1997). Ground cover influence on microclimate and *Trichogramma* (Hymenoptera: *Trichogrammatidae*) augmentation in seed corn production. *Environ. Entomol*. 26: 433–438. https://doi.org/10.1093/EE/26.2.433.

Soleon (2024). Innovative drones for higher yields. *Italy.* https://www.soleon.it

Song C, Wang Q, Wang G, Liu L, Zhang T, Han J, Lan Y (2023). Study on the design and experiment of *Trichogramma* ball delivery system based on agricultural drone. *Drones.* 7(10): 632. https://www.mdpi.com/2504-446X/7/10/632.

Stark Flight (2025). Stark Flight's Annual Agriculture Report Shows Global Agricultural Drone Industry Booming. https://www.globenewswire.com/news-release/2025/05/29/3090503/0/en/StarkFlight-s-Annual-Agriculture-Report-Shows-Global-Agricultural-Drone-Industry-Booming.html.

Vdovenko TV, Chenikalova EV (2009). Biological control of cotton bollworm and corn stalk borer. *Zashita I Karantin Rasteniy* (*Plant Protection and Quarantine*) 6: 42 (in Russian). https://ia.spcras.ru/index.php/vizr/issue/view/301/215.

Wang J, Lv X, Wang B, Lan X, Yan Y, Chen S, Lan Y (2023). Numerical simulation and analysis of droplet drift motion under different wind speed environments of single-rotor plant protection UAVs. *Drones* 7(2): 128 https://doi.org/10.3390/drones7020128.

Xing H, Li M, Qin Y, Fan G, Zhao Y, Lv J, Li J (2023). Design of a *Trichogramma* balls UAV delivery system and quality analysis of delivery operation. *Front. Plant Sci*. 14: 1247169. https://doi.org/10.3389/fpls.2023.1247169.

Zheng Y, Yang S, Liu X, Wang J, Norton T, Chen J, Tan Y (2018). The computational fluid dynamic modeling of downwash flow field for a six-rotor UAV. *Front. Agric. Sci. Eng*. 5: 159–167. https://doi.org/10.15302/J-FASE-2018216.