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Localized Biopesticide Application Using UAVs for the Control of Migratory Locusts in Kazakhstan

Valerij Azhbenov[1*], Daulet Shamuratov[2], Zhan Niyazbekov[3], Almat Dinassilov[4], Semby Arystangulov[1], Kurmet Baibussenov[5], Nursultan Bashkarayev[6], Aitugan Zhumagaliyev[4]

[1] Scientific and Analytical Group, Kazakh Scientific Research Institute for Plant Protection and Quarantine, 050070 Almaty, Kazakhstan
[2] Faculty of Agrobiology, Horticulture, Plant Protection and Quarantine Department, Kazakh National Agrarian Research University, 050000 Almaty, Kazakhstan
[3] Kazakh Scientific Research Institute for Plant Protection and Quarantine, 050070 Almaty, Kazakhstan
[4] Plant Quarantine Department, Kazakh Scientific Research Institute for Plant Protection and Quarantine, 050070 Almaty, Kazakhstan
[5] Plant Protection and Quarantine Department, Saken Seifullin Kazakh Agrotechnical University, 010000 Astana, Kazakhstan
[6] Pesticide Registration Department, Kazakh Scientific Research Institute for Plant Protection and Quarantine, 050070 Almaty, Kazakhstan

[*] Correspondence: Valerij Azhbenov (azbenovvalerij@gmail.com)

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Abstract: The migratory locust has become a principal threat to agricultural production in Kazakhstan, exacerbating risks posed by drought, fires, and other natural disasters. The widespread and persistent use of chemical pesticides, often referred to as "chemical press" tactics, has been the conventional approach to locust control. However, such methods are associated with escalating costs, environmental contamination, and the development of pesticide resistance. In response, alternative strategies that focus on preventive control and localized treatment have been explored. This approach aims to mitigate the negative ecological impacts of indiscriminate pesticide application by targeting locust populations with biological control agents and low-toxicity plant protection products in identified foci. This study evaluates the use of unmanned aerial vehicles (UAVs) for the precision application of biopesticides in Kazakhstan's locust-affected regions. Orthophotographic maps generated from UAV imagery were employed to detect locust presence based on indirect diagnostic indicators. These maps facilitated the identification of locust aggregations, which were subsequently treated with biologically based pest management solutions. The effectiveness of UAV-based localized treatments was assessed, demonstrating significant control over locust populations in focal areas, with minimal environmental impact. The results suggest that UAV technology, combined with targeted biological treatments, offers a promising alternative to traditional chemical methods, potentially reducing pesticide resistance and ecological harm while maintaining effective pest control. This approach aligns with sustainable agricultural practices and enhances the efficiency of pest management strategies in locust-prone regions.

Keywords: Gregarious locusts; Chemical press; Preventive control; Population management; Local treatments

1. Introduction

In the context of anthropogenic influence and global climate change, a high threat of locust pests has become an urgent issue in food and phytosanitary security in Kazakhstan, Russia, the Caucasus, and Central Asia. The range of locust pests has significantly expanded in Kazakhstan, and there are territories of periodic mass breeding that overlap state borders with neighboring countries of Central Asia and adjacent Russian territories (FAO, 2012; Lachininskii et al., 2002; Monar & Shiris, 2009; Uvarov, 1966; Uvarov, 1977).

In Kazakhstan, a pressing issue within the agro-industrial complex is the periodic mass breeding and subsequent invasions of locust species, particularly the Italian locust (*Calliptamus italicus L.*), the migratory locust (*Locusta migratoria migratoria L.*), and the Moroccan locust (*Dociostaurus maroccanus Thunb.*). These species cause severe damage to crops and natural vegetation, which disrupts local ecosystems and agricultural productivity. The invasions occur in cyclical patterns. Consequently, these locust populations have become a significant threat to food security and economic stability in the region. Due to large-scale migration, high resistance, and extreme harmfulness, gregarious locusts have become the main agricultural production risk (Kambulin et al., 2010; Kurishbaev & Azhbenov, 2013; Toleubayev et al., 2007; Yskak et al., 2012).

It is problematic to carry out massive chemical treatments using traditional technology during an outbreak and migration of locusts. The analysis of locust control companies in Kazakhstan during 1997-2003, 2012-2014, and 2016-2017 shows that the traditional technology of "chemical press" in the "fire extinguishing" mode has the following disadvantages:

a) The fire extinguishing mode technology causes high costs;

b) The extermination of natural enemies and natural epizootics leads to the destabilization of the ecological situation;

c) Violation of the chemical treatment regulations and leaving untreated territories are risk factors for forming dangerous swarms;

d) Repeated treatments (cleaning of the territory) increase the pesticide load on ecosystems;

e) When carrying out treatments in the fire extinguishing mode during migration, the initial stages of locust accumulation remain unnoticed (Kambulin et al., 2010; Kurishbaev & Azhbenov, 2013; Toleubayev et al., 2007; Yskak et al., 2012).

It is important to use modern methods and means of phytosanitary monitoring and forecasting in the preventive control and management of locust populations. Various surveys have been conducted for phytosanitary information on gregarious species of locust pests (Kenzhegaliev et al., 2021). Monitoring is carried out through ground-based route observations. To control locust populations effectively, it is crucial to advance forecasting and monitoring methods using technologies like remote sensing, Geographic Information System (GIS), Global Positioning System/Global Navigation Satellite System (GPS/GLONASS), and machine learning. This integrated, data-driven approach supports targeted interventions, helping reduce locust-related agricultural and economic impacts in Kazakhstan and beyond (Azhbenov et al., 2015; Baibussenov et al., 2021; Baibussenov et al., 2022; Ochieng et al., 2023; Shao et al., 2021; Sun et al., 2022).

Thus, it is important to continuously study the patterns of development and reproduction of locust populations by region and change strategic settings toward preventive measures. To reduce the number of locusts and address environmental issues, it is necessary to use biological preparations, biological pesticides, and low-risk insecticides in locust foci through local and barrier treatments.

In this field, great prospects appear as a result of the use of UAVs in local treatments for the introduction of biological preparations for locust foci and in phytosanitary monitoring and control of the number of dangerous pest organisms in hard-to-reach territories (sands, abandoned territories, reservoirs, etc.), which are often the primary foci of mass reproduction and invasion of especially dangerous gregarious locusts.

This study aims to evaluate the effectiveness of UAV-based localized biopesticide application in controlling gregarious locust populations in Kazakhstan. Specifically, it hypothesizes that UAV technology, combined with biological control agents, can significantly reduce locust populations while minimizing environmental impacts compared to traditional chemical methods.

2. Methodology

2.1 Study Area and Conditions

Research on improving methods of controlling the number of gregarious species of locust pests was initiated by the Kazakh Research Institute for Plant Protection and Quarantine (KazNIIZiKR) in 2018-2020 by order of the Ministry of Agriculture of the Republic of Kazakhstan within the framework of the budget program "Increasing the Availability of Knowledge and Scientific Research." Then it continued within the framework of the grant of the Ministry of Science and Higher Education of the Republic of Kazakhstan, which is AP 19678905 "methodology for forecasting invasions, preventive control, and management of populations of particularly dangerous Moroccan locusts based on the use of geographical information and information technology."

Research on the development of methods of examination and local treatments with biological preparations against gregarious locust species in the larval stage using UAVs was carried out in the natural habitats of pests in the Turkestan, Kyzylorda, Zhambyl, and Almaty regions. These areas were selected due to their known periodic mass breeding of gregarious locusts and their overlap with key agricultural zones.

The study areas have a continental climate, with moderately warm winters (thaws up to +10℃, cold spells to -15℃, and down to -40℃ in Kyzylorda). Summers are long and hot, reaching up to +45℃ and +49℃ in southern

Turkestan. Annual precipitation ranges from 100–200 mm, up to 1,600 mm in mountainous regions.

2.2 Monitoring and Data Collection

UAV-based monitoring utilized standard methods for processing remote sensing data, subsatellite observations, and GIS integration, as outlined by Chandra & Gosh (2008). Surveys focused on assessing habitats of *C. italicus*, *L. migratoria*, and *D. maroccanus* to gather data on development timing, population size, density, and area occupied. Additionally, morphometric analyses were conducted to determine the phase state of each species, following the guidelines provided by Azhbenov et al. (2015), Kurishbaev & Azhbenov (2013), Uvarov (1966), and Uvarov (1977). These recommendations ensured a structured approach to studying locust population dynamics and physical characteristics. The assessment of the biological effectiveness of biologic treatments was carried out according to the study by Veizer & Compston (1974).

To differentiate between gregarious and solitary locusts, the elytra-to-hind femur length ratio (E/F) was used. In solitary *C. italicus*, E/F is ≤1.40 for females and ≤1.42 for males; gregarious specimens exceed 1.60 and 1.625, respectively. For *L. migratoria*, solitary individuals have an E/F ≤2.00, while gregarious types exceed 2.161 (females) and 2.106 (males). In *D. maroccanus*, solitary forms have E/F ≤1.47 (females) and ≤1.45 (males), while gregarious forms exceed 1.69 and 1.70, respectively (Kurishbaev & Azhbenov, 2013; Uvarov, 1966; Uvarov, 1977).

The main concept of the study was to conduct simultaneous surveys using a ground description and a route flyby of ground monitoring points with UAVs, aiming to compare and identify them in the image.

The selection of test polygons was carried out in compliance with the following criteria:

- Similarity of physical and geographical conditions to reduce the influence of the factor of differences in climatic, geological, and soil features of the polygon territories;
- Flat terrain, as it assumes the absence of such differences as illumination, exposure, and differences in water and temperature conditions.

2.3 Research Process

At the time of the photography, the locusts were mostly in the larval phase of ages 2-3. The number of specimens in the swarm, depending on the species and region, varied from 100 to 1,000 specimens/m^2. For aerial photography of the area (test site), the method of constructing a rectilinear parallel route was used. This method considered the maximum width of the UAV camera's field of view at a given altitude and constant flight speed.

Route planning and UAV flight were carried out in various configurations, with the overlap of the adjacent flyby lane from 10 to 40%, and the longitudinal one from 30 to 80%. The findings indicate that for effective aerial photography of flat terrain, a transverse (side-to-side) overlap of 15-20% between images is sufficient. This overlap percentage minimizes gaps in coverage and improves data consistency across the survey area. A longitudinal (front-to-back) overlap of 40-50% is optimal, ensuring that each image captures a significant portion of the previous one. Together, these overlap parameters provide a reliable framework for aerial survey operations, enhancing the quality of data captured and supporting precise geographic assessments.

The photography was carried out in clear, cloudless weather for 2-3 hours after sunrise and two hours before sunset. Aerial photography at other times of the day did not give proper results for several objective reasons.

As a result, several thousand images were obtained. The result of combining all the images was a geometrically corrected and color-corrected orthophotomap.

According to the images, field and visual decoding of aerial photographs were performed, and direct decoding signs of pests (shape, size, tone, structure of the swarm image) and indirect signs of pests (traces of vital activity, changes in the properties of vegetation, etc.) were established.

The QGIS software was utilized to classify the study area into five distinct categories, facilitating the calculation of the Visible Atmospherically Resistant Index (VARI). This index is particularly effective in assessing vegetation health and the extent of damage caused by external factors like locust infestations. The VARI was selected for its ability to assess vegetation health through light reflectance in the red, green, and blue (RGB) spectra, a process that is less sensitive to atmospheric variations compared to other vegetation indices like the Normalized Difference Vegetation Index (NDVI). In contrast, undamaged or minimally affected areas displayed colors ranging from green to blue, indicating robust vegetation health. This visual classification using VARI in QGIS not only streamlined the process of identifying damage patterns across large areas but also enabled targeted monitoring and response, allowing for more efficient resource allocation in mitigating locust damage. An example is shown in Figure 1.

The aerial surveys were carried out in three stages:

- The preparatory stage: It included the calibration of cameras and the geographical reference of characteristic points on the ground.
- The aerial photography stage: It included calculating the elements of aerial photography, designing UAV flight routes, and conducting scheduled aerial photography.

- The desk work stage: It included the processing of aerial photographs and the creation of orthophotomaps.

To develop a biological method for controlling the number of locusts, two options were used as equipment: a) Solo 450 backpack sprayer and b) helicopter-type Gaia 160 AG UAV with spraying equipment. The plots where Solo 450 was used were 0.5 ha, and the plots for UAV treatment were 1 ha.

The range of gregarious species of locust pests was photographed using DJI Phantom 4 PRO and 3DR Solo quadcopters in the visible and IR ranges of the electromagnetic spectrum. The images taken in the IR range by the camera mounted on the UAV were processed in the ENVI 5.1 software.

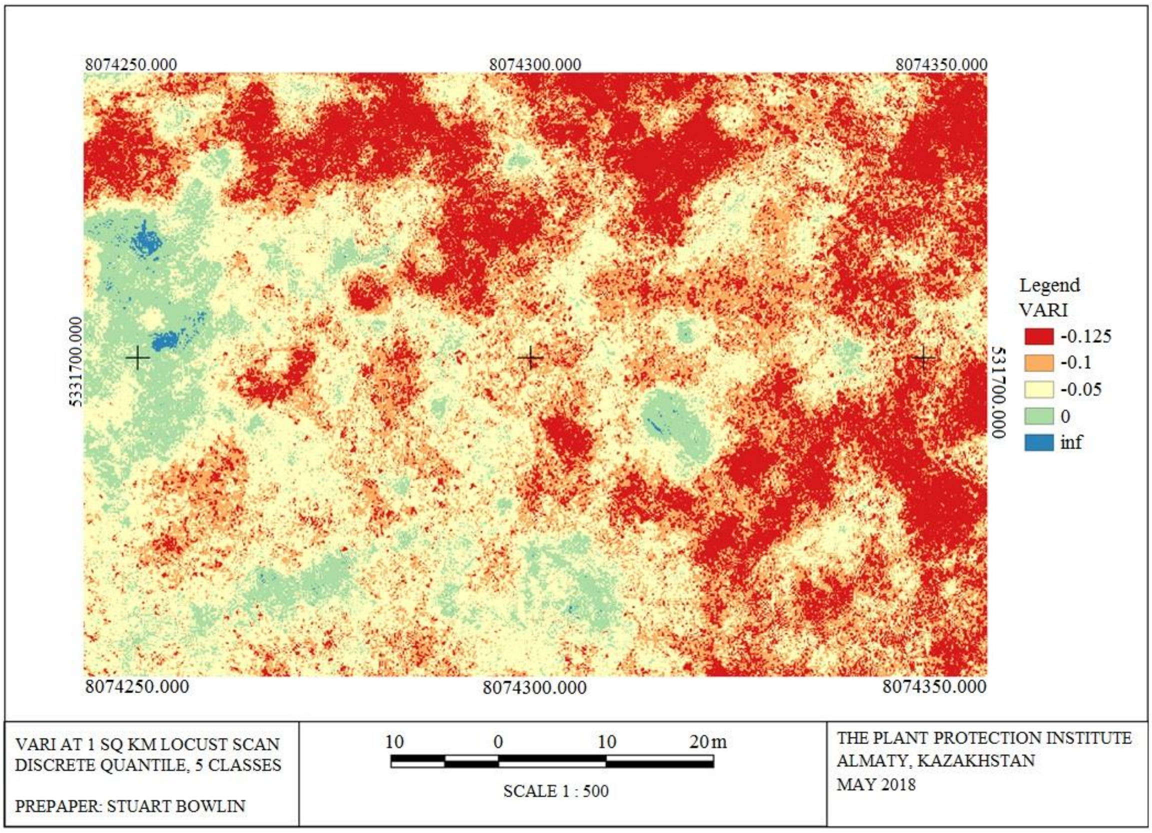

Figure 1. Calculated VARI of the test site divided into five classes

2.4 Data Analysis

The IsoData classification method, an unsupervised algorithm, was chosen for its ability to cluster pixels into distinct categories based on their spectral signatures. This method iteratively refines clusters, ensuring optimal differentiation between healthy vegetation, partially damaged areas, and severely affected zones. The selection of IsoData was driven by its robustness in analyzing complex land cover types, particularly in dynamic environments like those impacted by locust swarms. Its implementation involved preprocessing UAV imagery for atmospheric corrections, applying spectral clustering algorithms, and validating classifications with ground observations and GIS data layers.

In areas where locust swarms were detected, the classification results revealed a significant lack of vegetation, indicating either complete destruction or very sparse plant cover. This absence or minimal presence of vegetation suggests severe damage caused by the locusts' feeding activity, underscoring the impact of locust swarms on local ecosystems (Figure 2).

An attempt was made to streamline the image classification process to identify three types of gregarious locusts by using ready-made automated solutions available through the DroneDeploy platform. DroneDeploy, a cloud-based service and application, facilitates the processing of aerial images captured by UAVs, enabling the creation of high-resolution 2D maps and 3D terrain models.

A key tool in this process is the application of plant health algorithms, such as the VARI, which uses the relative intensities of light in the RGB spectra to assess vegetation health. By analyzing the light captured from each pixel on a map, the VARI algorithm assigns a numerical value to indicate plant health. Healthy vegetation reflects a higher proportion of green light than red or blue light, as opposed to damaged or stressed plants, which show altered reflectance patterns due to reduced chlorophyll content. This differentiation helps identify areas impacted by locust activity, where vegetation health declines and thus reflects different light values, enabling efficient and accurate mapping of affected zones.

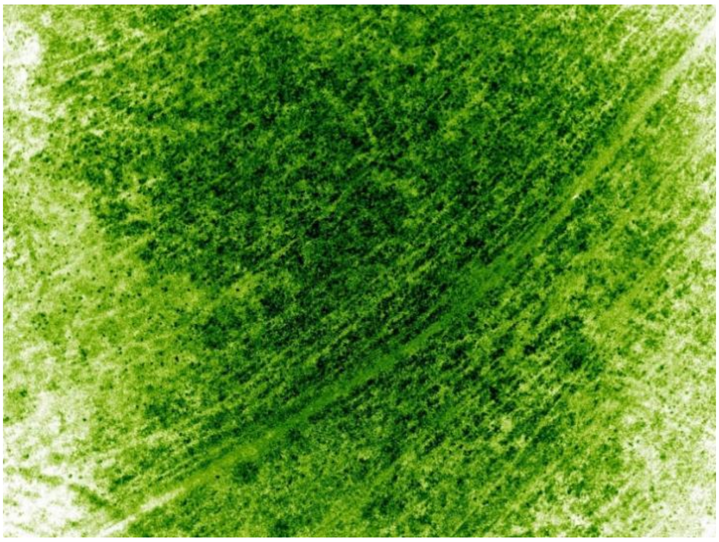

Figure 2. Processed images in the IR range from UAVs divided into classes according to vegetation density

3. Results

3.1 UAV-Based Monitoring

It can be concluded that the use of DroneDeploy showed identical results in identifying locusts in UAV images.
To gather comprehensive information on locust populations, the research included developing digital thematic maps of *D. maroccanus* distribution and abundance, utilizing a GIS created for this project. These maps were based on cloud-free, medium-resolution satellite images taken throughout the growing season, providing a foundation for analyzing soil and vegetation cover. Topographic vector data, including district boundaries, road networks, hydrographic features, settlements, and field survey data (such as locust detection coordinates), were integrated as layers in the GIS.

3.2 Image Classification

By combining processed remote sensing data, GIS layers, and field information, digital maps were generated, detailing the distribution and density of gregarious locust species in the study areas. Over the following two years (2020-2021), further studies were conducted to identify the locust distribution areas and estimate their population sizes across their natural habitats. The studies were conducted with the same methodology using data from the same source. Therefore, comparative analysis and mapping of locust distribution over two years had a basis.

3.3 Locust Distribution Mapping

Gregarious species of locusts have a life cycle starting in August/September. Adult specimens lay eggs in the upper soil horizon, and egg pods overwinter in the soil. In spring, when suitable weather conditions occur, larvae hatch. Within a few months, they grow and pass several ages up to the imago, after which winged adult locusts, after fertilization, lay eggs and die. This cycle has a main feature: the number and place of hatching of locust larvae next year depend on the location and number of egg pods in the previous summer. Therefore, locust distribution and egg-laying sites detected and marked on the 2019 map can be compared with data from 2020 and 2021, and territories with repetition and frequent detection can be deduced. These sites are the most dangerous and require special attention from specialists of the State Department of Phytosanitary Monitoring and Forecasts and Plant Protection Services.
Biological preparations Actarophyte (1.0), Actarophyte (2.0), Zeleny Barier wettable powder (SP), Mycolar B, Mycolar M, and Novacrid of biological origin in various dosages were tested against *D. maroccanus*, *C. italicus*, and *L. migratoria* larvae. Actarophyte (1.0 and 2.0) is a complex of natural avermectins. Avermectin toxins are known to affect the nervous systems of pests, disrupting nerve impulses and causing paralysis and eventual death in pests. Zeleny Barier (wettable powder, SP) is developed based on the fungus Beauveria bassiana. It is used as a

fungicide and pesticide. It releases antifungal metabolites and induces resistance mechanisms in plants. Mycolar/Mikolar B and Mycolar/Mikolar M are based on strains of entomopathogenic fungi of boveria and metarizium. They are used to combat locusts. Novacrid (a drug manufactured by Elephant Vert) leverages entomopathogenic fungi (Metarhizium anisopliae) to infect the insect host (locusts and grasshoppers) through spores that germinate on its exoskeleton.

In the places of the planned treatments, the number of locust pests in the larval stage varied between 10-20 specimens/m^2, mainly of the 2^{nd} and 3^{rd} ages, with an accepted economic injury level above 5 specimens/m^2. Diesel fuel was used as a filler for Mycolar B and Mycolar M when spraying from UAVs, which has never been done before.

3.4 Efficacy of Biopesticide Treatments

According to tests of various strains of biological preparations against gregarious locust species in the larval stage, the most rapid effect against *D. maroccanus* larvae was shown by the preparation Actarophyte (2.0) based on avermectins, which caused up to 100% mortality of larvae on the 10th day (Table 1 and Table 2).

A high effect was obtained when using Novacrid (Elephant Vert). The preparation is very convenient since its consumption per 1 ha is 25-50 g, when used as a working fluid of diesel fuel oil from 2 to 3 L. Zeleny Barier also showed good results. Mycoinsecticides Mycolar B and Mycolar M registered in Kazakhstan did not show high effectiveness (Table 1 and Table 2).

Table 1. Biological effectiveness of the use of various biological preparations against gregarious locust species in the larval stage (Solo 450)

Strain	***D. maroccanus***			
	Mortality %, day			
	7	10	14	17
Novacrid	35±6.45	50.0±5.77	68.0±5.77	92.5±2.5
Mycolar B	15±2.88	40.0±4.08	60.5±2.5	68.0±5.77
Mycolar M	17.5±4.78	47.5±6.26	52.5±4.78	70.0±5.77
Zeleny barier	17.5±2.5	40.0±11.5	60.0±8.16	82.5±2.87
Actarophyte (1.0)	85.0±8.16	97.5±2.5	100	100
Actarophyte (2.0)	93.0±8.10	100	100	100
Control	0.0	0.0	10.0±4.08	10.0±4.08
Least significant difference (LSD)	13.7	21.2	20.1	13.5
C. italicus				
Novacrid	25±2.88	47.5±7.50	65.0±5.00	88.0±5.0
Mycolar B	12.5±2.5	32.5±4.78	42.5±4.78	59.0±2.88
Mycolar M	15.0±2.8	37.5±2.5	52.5±4.78	72.5±7.5
Zeleny barier	17.5±4.78	38.0±4.08	58.5±2.5	85.0±5.0
Actarophyte (1.0)	83.5±6.29	92.5±4.78	95.5±6.29	100
Actarophyte (2.0)	88.2±6.21	95.0±5.01	98.5±6.21	100
Control	0.0	0.0	10.0±4.08	12.5±4.78
LSD	11.2	11.2	15.2	16.3
L. migratoria				
Novacrid	22.5±4.78	35.0±6.45	60.0±8.16	77.8±6.29
Mycolar B	12.5±2.5	30.0±7.07	45.5±2.5	62.5±2.5
Mycolar M	20.0±4.08	40.0±7.07	57.5±2.5	70.0±5.77
Zeleny barier	20.0±3.21	40.0±4.08	52.5±4.78	72.5±4.78
Actarophyte (1.0)	82.5±6.29	87.5±7.5	92.5±6.29	97.5±7.5
Actarophyte (2.0)	85.0±5.21	89.0±8.45	92.5.0±4.73	100
Control	0.0	0.0	5.0±2.88	10.0±4.08
LSD	11.6	17.7	16.0	16.8

In experiments on the use of the Solo 450 sprayer and the Gaia 160 AG UAV as a technique in the treatment of gregarious locust species in the larval stage, identical results of the effectiveness for various biological preparations were obtained in all experiments (Table 2).

After the experiment, the dead specimens of locust larvae were taken to the laboratory to determine the cause of death. In a wet chamber, after three days, the dead larvae were covered with mycelial plaque, confirming the death of the larvae from exposure to biological preparations.

The UAV-based approach demonstrated significant strengths, including high precision and accuracy in identifying locust damage zones through advanced classification techniques such as VARI and IsoData, cost-effectiveness by reducing labor-intensive ground surveys, and accessibility to remote areas often overlooked in traditional methods. Moreover, its localized treatment capability reduced environmental contamination and preserved non-target species. However, limitations such as the restricted payload capacity of UAVs, dependency on favorable weather conditions, and high initial costs for equipment and training present challenges for widespread adoption.

Table 2. Biological effectiveness of biological preparations against gregarious locust species in the larval stage (Gaia 160 AG UAV)

Strain	*D. maroccanus*			
	Mortality %, day			
	7	10	14	17
Novacrid	40±4.08	52.5±10.3	65.0±5.00	97.5±2.50
Mycolar B	15±2.88	42.5±6.29	62.5±6.29	70.0±5.77
Mycolar M	22.5±2.5	50.0±4.08	67.5±7.5	82.5±2.5
Zeleny barier	17.5±4.78	42.5±6.29	62.5±2.5	87.5±4.78
Actarophyte (1.0)	90.0±2.0	98.0±2.0	100	100
Actarophyte (2.0)	92.5±1.0	100	100	100
Control	0.0	0.0	15.0±6.45	20.0±7.07
LSD	13.3	16.9	18.6	14.6
	C. italicus			
Novacrid	25±2.88	50.0±4.08	67.5±2.5	89.5±2.50
Mycolar B	15.0±2.88	35.0±6.45	57.5±2.5	65.0±5.0
Mycolar M	22.5±2.5	42.5±6.26	55.0±8.66	68.0±5.00
Zeleny barier	17.5±4.78	42.5±6.29	62.5±2.50	87.5±4.78
Actarophyte (1.0)	82.0±8.16	85.0±5.77	87.5±4.21	95.0±7.07
Actarophyte (2.0)	85.2±8.21	87.2±21.6	92.0±5.77	100
Control	0.0	0.0	10.0±4.08	12.5±4.78
LSD	12.8	16.5	14.2	16.8
	L. migratoria			
Novacrid	25.0±2.88	42.5±6.29	65.0±9.57	80.0±4.08
Mycolar B	15.0±2.88	40.0±4.08	50.0±5.77	60.0±8.16
Mycolar M	20.5±2.5	42.5±6.29	60.0±0.0	67.5±7.5
Zeleny barier	22.5±4.78	37.5±7.50	55.0±8.66	75.0±6.45
Actarophyte (1.0)	81.0±4.65	82.2±6.3	85.0±7.1	95.5±2.5
Actarophyte (2.0)	82.0±8.16	85.0±9.57	87.0±9.6	97.0±4.2
Control	0.0	0.0	12.5±4.78	15.0±6.45
LSD	12.5	19.8	18.2	15.7

4. Discussion

The results of this study, which is of significant importance to the field of pest management, confirm the efficacy of UAV-based localized application of biopesticides for migratory locust control in Kazakhstan. This study is consistent with recent research, highlighting the ecological importance of targeted, localized treatments. The results agree with the study by Gundreddy et al. (2024), which concluded that drones provide precision, cost efficiency, and environmental benefits, making them ideal for the release of natural enemies, biopesticide application, mating disruption, etc. The results also correspond with the study by Verma et al. (2022), which proved that a Hexacopter UAV sprayer is more effective in terms of quality of spray and effective control of aphid population than a knapsack sprayer.

This study employed remote sensing data, GIS layers, and field information to understand the distribution and density of gregarious locust species. The findings provide data that fills the research gap presented by Klein et al. (2023), who claimed that there needed to be more available information and actual practical usage of geospatial and remote sensing data to support locust management in Kazakhstan. This study also agrees with the findings of Azeem et al. (2023), which highlighted the importance of remote sensing and the latest monitoring technologies as novel, cost-effective, and eco-friendly strategies for combating locust outbreaks in Kazakhstan.

This study found that specific biological agents, such as Actarophyte (2.0), exhibited high locust mortality rates when applied via UAVs. This finding agrees with the work of Yan et al. (2021), which recorded an increased efficiency during the application of biopesticides using UAVs. The results also agree with the study by Ochieng et al. (2023), which concluded that for most biopesticides such as 'Novacrid,' a distance of 10 m was optimal for plant protection and pest mortality; this conclusion creates a gap in the relationship between distance and specific biological preparations. For further research, it is recommended that distance can be considered a determining factor in biopesticide applications using UAVs.

Additionally, this study highlights the ecological advantages of biopesticides, and this agrees with the work of Daraban et al. (2023), which highlighted that biopesticides, in comparison to their chemical counterparts, offer specificity to target pests, efficiency, selectivity to beneficial insects, and non-persistent characteristics in the environment. However, studies like the research by Huang et al. (2022) show that most farmers prefer to combine biopesticides with chemical pesticides for consumption and profitability cases. The findings suggest that UAV applications alone are sufficient in managing locust populations in the early developmental stage. More research should be conducted to make UAV systems and biological preparations cost-effective and easily accessible.

In conclusion, the integration of UAV technology with biopesticide treatments offers a viable, sustainable approach to managing locust populations, with significant ecological and economic benefits. The findings, which correlate with those of Christoffersen et al. (2024) and Hendrichs et al. (2021), indicate that UAVs can effectively complement existing locust management strategies. It is recommended that future research can focus on refining these methods to enhance locust control efficiency and explore the potential for combining UAV treatments with advanced remote-sensing and machine learning technologies for predictive pest management.

5. Conclusions

Research on the development of survey methods using UAVs shows that as a result of combining processed remote sensing data, GIS layers, and ground information, thematic digital maps of the distribution and abundance of locusts can be obtained. Maps of the repeatability of locust detection were developed, presenting locust invasion risks. Research on methods of biological preparation treatments against gregarious locust species using UAVs shows that their use is a safe and effective method of phytosanitary locust control.

Great prospects appear as a result of using UAVs in local treatments with biological preparations for locust foci and in phytosanitary monitoring and control of the number of gregarious locusts in hard-to-reach areas (sands, abandoned territories, reservoirs, etc.), which are often the primary foci of mass reproduction and invasion of dangerous pests.

The findings highlight significant contributions, including the development of thematic locust distribution maps, validation of UAV-based monitoring techniques, and confirmation of biopesticides' ecological benefits over chemical alternatives. These results provide practical implications for scaling UAV-based locust control strategies, emphasizing the need for policy support, technological innovation, and collaboration to address operational challenges.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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