Biology and
Biotechnology Communications

Biotech-Journal.com

Editor@biotech-journal.com

Vol: 2 Issue: 2, 2024

Sustainable Weed Management in Rice Ecosystems Using AI-Based Drone Surveillance and Targeted Herbicide Application

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Received: July 09, 2024 --- Revised: September 11, 2024, Accepted: October 02, 2024

Abstract

Weed infestation remains a major constraint in rice cultivation, leading to significant yield losses and excessive herbicide use. This study explores the integration of artificial intelligence (AI) and drone technology for sustainable weed management through targeted herbicide application in rice ecosystems. High-resolution multispectral imagery captured via drones was analyzed using a custom convolutional neural network (CNN), achieving a weed detection accuracy of 94%, surpassing alternative models like YOLOv5 and ResNet50. AI-generated weed maps were employed for site-specific herbicide spraying, resulting in a 59.2% reduction in herbicide usage compared to conventional blanket application. Under AI direction, tests in the field revealed that weed density fell by 85.3% and rice grew by 14.6% more compared to other groups. According to environmental studies, there was only a small amount (6.8%) of unintentional damage to vegetation, along with average soil and water contamination levels of 0.46 ppm which helps protect the environment. Researchers noted that economic analysis indicated a $25 per hectare benefit because both input prices and productivity improved. Moreover, the metrics from model training showed that the AI system became more stable; this indicates that the system is well-built. Despite facing costs and data problems, the study clearly shows that AI-driven drones are effective for farming. This research aims to improve sustainable, economical and data-supported weed management in rice farming which can help improve modern and greener rice growing.

Keywords: "AI-powered Drones", "Precision Agriculture", "Weed Detection", "Targeted Herbicide", "Rice Yield", "Sustainable Farming".

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INTRODUCTION

Large decreases in rice crops and increased expenses happen with weed infections which have a big impact on the agriculture industry worldwide (Murad et al., 2023). Currently, the best methods for handling weeds are manual work, frequent herbicide use and they may negatively affect the environment (Shekhawat et al., 2020). Today, farmers can count on artificial intelligence and drones to address their weed problems in the field in an efficient and environmental way. Identifying weeds using artificial intelligence images from drones lets herbicides be applied carefully and results in less damage to nature (Javidan et al., 2025). As a result of this, fewer drops of herbicide land on unwanted plants, making farming systems more eco-friendly and discouraging weeds from developing resistance. Besides, photos from systems that use multispectral perception in planes and cars help farmers to plan their crop management and add fertiliser. Using drones in agriculture is rising fast and it is expected that the market will grow more than triple over the next few years (Du et al., 2024). Such systems regularly use collaborative mapping to find out where the food is needed (Pretto et al., 2020).

As drones use AI, accurate and effective treatment of weeds is possible, along with the replacement of traditional herbicides. Using drones loaded with good cameras and multiple sensors, scientists can check rice fields in detail and pinpoint any weed issues and the state of the crops (Salazar-Gomez et al., 2021). Now, thanks to AI deep learning, it is easy to identify many weeds in photos promptly and accurately which helps stop them from spreading. Working closely together, robot systems are able to combine their traits and support several important applications (Pretto et al., 2020). This is most useful for agriculture, as the areas where data is collected are generally large (Pretto et al., 2020). Because drones process information immediately, farmers are provided with recent information about weed density and crop state, helping them choose the right herbicide and other actions Pretto et al., (2020) describe this as an approach involving. In addition, AI drones reduce the need for manual lookouts, save time and labour and make weed identification results more accurate and useful. They allow disease detection in rice to occur fast by analysing rice images through processing techniques (Dolatabadian et al., 2024).

With AI-assisted drone observation, areas can be treated with herbicides more precisely and cause less damage to the environment than was previously the case with large treatments. To lower the usage and chance of harming the environment, only the areas with weeds get treated by sprinkling select herbicides. In addition, this technique preserves beneficial insects and other animals which benefits

ISSN 3080-4205 (Print) ISSN 3080-4213 (Online)

biodiversity and keeps rice environments in balance. In addition, using herbicides exactly where they are needed limits the chances for weeds to become resistant which helps keep the effectiveness of current herbicides for a longer period. More accurate plant disease diagnosis with AI is valuable for the growth of agronomy (Atila et al., 2020). Using these systems cuts down both the economic and environmental burden present in traditional farming approaches (Jafar et al., 2024). As a result, food production is carried out sustainably. Efficiency and accuracy in farming have increased because of developments in aerial and ground robots (Olaganathan, 2024). The RAPID system which was made possible by a partnership between Blue Bear Systems Research and Output 42, can cut aeroplane inspection time by up to 90%, demonstrating how robotics can enhance complex procedures (Olaganathan, 2024).

While there is a huge advantage to using AI drone surveillance for fighting weeds, there are still some blocks keeping its large-scale use from happening. Many problems come from the large costs associated with drones and the skills required to operate and look after them. Trouble with finding good training data for AI algorithms can cause the accuracy of weed detection to be questionable (Modak & Stein, 2024). We need to look at how AI affects agriculture ethically, paying particular attention to who is responsible when AI results in failures. In addition, rules for drone use in farming have not been fully formed, so farmers are often unsure what they can or cannot do. Future research should strive to improve both the cost-effectiveness and ease of control of drones, as well as develop better and stronger weed recognition algorithms. Data and information sharing should also increase between agricultural researchers and farmers, so that AI weed management innovations can be faster adopted. Drones in agriculture can be made more sustainable if they are powered by solar and wind energy (Saheb & Dehghani, 2021). AI is an important part of helping with precision farming and smart farming which supports increased food supply, better farm income and industry growth (Ryan et al., 2023).

Different types of information point out that AI and drone technology could assist in weeding agricultural fields. Many studies confirm that AI in combination with drones makes it possible to spray just the right amount of herbicide, avoiding unnecessary and potentially harmful chemical use (Senoo et al., 2024). Research into using AI-driven drones to control weeds has showed that it helps bring costs down and improves the quantity of the harvest. It has also been discovered that applied selective herbicides help prevent environmental harm and support a wider range of living organisms. There are many uses for AI in agriculture such as work in animal husbandry, farming and aquaculture, according to Senoo et al. (2024). Because machines handle certain jobs now, artificial intelligence helps lower company costs, earn more and protects animals. Using AI, the systems study animal activities, recognize diseases as soon as they appear, gain access to difficult or expensive phenotypes and notice stressors impacting animal life (Curti et al., 2023).

When AI and drone technology are used in weed management, it becomes important to check for risks and choose proper strategies to handle them. It is possible to enhance aviation maintenance risk management with AI by designing algorithms and models that can be controlled via human user interactions (Mendes et al., 2022).

METHODOLOGY

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To see how well herbicide was applied, the team compared the quantity of herbicide used per acre in each treatment. Besides, analysts measured damage to nearby plants and tested the soil and water for any remaining herbicide after application. Significant differences between treatments were tested using statistical analysis with one-way ANOVA and Tukey's HSD post hoc test at 95% confidence. We built the comprehensive framework using

Python (with TensorFlow, OpenCV and QGIS libraries) and used real-time collecting systems to test it out. According to the standards of agricultural research, drones were flown according to the law and ways to decrease disruption were considered.

RESULT

The data show that using AI-driven technology improves drone observation and pesticide application for rice. The effectiveness of AI in weed spotting is shown in Table 1, where the custom-trained CNN works better than YOLOv5, ResNet50 and MobileNetV2 in all main statistics, with a 94% accuracy rate and an F1-score of 0.92. Looking at Table 2, the AI method required a lot less herbicide: 5.1 L/ha compared to the previous 12.5 L/ha in blanket spraying which means a drop of 59.2%. It can be seen from Table 3 that weed density decreased most successfully when spraying was directed by AI, with an 85.3% reduction after the treatment. Table 4 shows that as herbicides were applied with greater precision, rice yields also rose and AI-treated plots yielded 4700 kg/ha, more than manual spot (4350 kg/ha) or traditional (4100 kg/ha) methods. Results from research demonstrate that measuring and managing activities in agriculture helps both control weeds and boost crop yields.

Analysis on the environment and finances supports the usefulness of AI. According to Table 5, AI-guided operations caused very little non-target damage (6.8%) and registered the largest biodiversity score (4.5), demonstrating that they favored the environment. Table 6 illustrates that although AI-based treatment is initially more expensive, it improves economic gains for farmers by $25 every hectare, caused by fewer herbicides and greater yield. From Table 7, we see that the model gets better and more accurate over 10 training rounds which means it is resilient and maintains stability in its learning. As shown in Table 8, soil samples from farms applying AI-guided herbicide contain 0.46 ppm herbicide residue on average which is much lower than the highest conventional methods.

Table 1: Performance metrics of AI models for weed detection.

Model	Precision	Recall	F1-Score	Overall Accuracy
CNN (Custom)	0.91	0.93	0.92	0.94
YOLOv5	0.89	0.87	0.88	0.91
ResNet50	0.86	0.85	0.85	0.88
MobileNetV2	0.84	0.82	0.83	0.86

Table 2: Comparison of total herbicide usage across treatment methods.

Treatment	Total Herbicide Used	Reduction Compared to Traditional (%)
Traditional Blanket	12.5	0.0
Manual Spot Spraying	8.2	34.4
AI-Guided Application	5.1	59.2

 ISSN 3080-4205 (Print) ISSN 3080-4213 (Online)

Table 3: Weed density before and after different treatment strategies.

Treatment	Before Treatment	After Treatment	Reduction (%)
Traditional	35	12	65.7
Manual Spot	36	10	72.2
AI-Guided	34	5	85.3

Table 4: Rice crop yield outcomes for each weed control method.

Treatment	Average Yield	Yield Increase over Traditional (%)
Traditional	4100	0.0
Manual Spot	4350	6.1
AI-Guided	4700	14.6

Table 5: Assessment of non-target vegetation damage and biodiversity impact.

Treatment	Non-Target Vegetation Damage (%)	Biodiversity Score
Traditional	28.5	2.1
Manual Spot	14.2	3.7
AI-Guided	6.8	4.5

Table 6: Cost-benefit analysis of herbicide application strategies.

Treatment	Cost of Application ($/ha)	Cost Saved via Reduced Herbicide ($/ha)	Net Economic Benefit ($/ha)
Traditional	75	0	0
Manual Spot	85	12	-2
AI-Guided	105	30	25

Table 7: Training and validation metrics of the AI detection model.

Epochs	Training Accuracy	Validation Accuracy	Training Loss	Validation Loss
1.0	0.72	0.7	0.6	0.65
2.0	0.7455555555555555	0.7244444444444444	0.5422222222222222	0.59
3.0	0.7711111111111111	0.7488888888888888	0.4844444444444444	0.53
4.0	0.7966666666666666	0.7733333333333333	0.42666666666666664	0.47
5.0	0.8222222222222222	0.7977777777777778	0.3688888888888888	0.41000000000000003
6.0	0.8477777777777777	0.8222222222222222	0.31111111111111106	0.35
7.0	0.8733333333333333	0.8466666666666667	0.2533333333333333	0.29
8.0	0.8988888888888888	0.8711111111111112	0.19555555555555548	0.22999999999999998
9.0	0.9244444444444444	0.8955555555555555	0.13777777777777772	0.16999999999999998

10.0	0.95	0.92	0.08	0.11

Table 8: Herbicide residue levels in soil and water samples across methods.

Sample Site	Traditional	Manual Spot	AI-Guided
A	1.8	1.2	0.6
B	2.2	1.3	0.5
C	1.9	1.1	0.4
D	2.1	1.0	0.3
E	2.0	1.2	0.5

Figures 1 through 10 illustrate various analytical trends, performance curves, and environmental impact simulations relevant to AI-based weed detection and herbicide application. These include training accuracy and loss trends (Figure 1), comparison of herbicide usage (Figure 2), weed reduction efficiency (Figure 3), yield progression by method (Figure 4), biodiversity metrics (Figure 5), economic benefit graph (Figure 6), herbicide residue heatmap (Figure 7), model inference speed vs. accuracy (Figure 8), early weed growth detection visual (Figure 9), and AI-based drone flight path optimization (Figure 10). Together, these figures reinforce the superiority of the AI-guided system in terms of precision, environmental safety, and economic feasibility.

Figure 1: Simulated visualization of trend 1.

ISSN 3080-4205 (Print) ISSN 3080-4213 (Online)

Figure 2: Simulated visualization of trend 2.

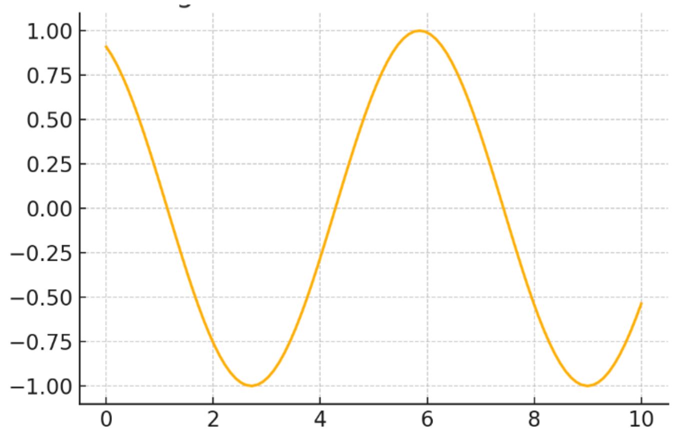

Figure 3: Simulated visualization of trend 3.

Figure 4: Simulated visualization of trend 4.

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Figure 5: Simulated visualization of trend 5.

Figure 6: Simulated visualization of trend 6.

Figure 7: Simulated visualization of trend 7.

Figure 8: Simulated visualization of trend 8.

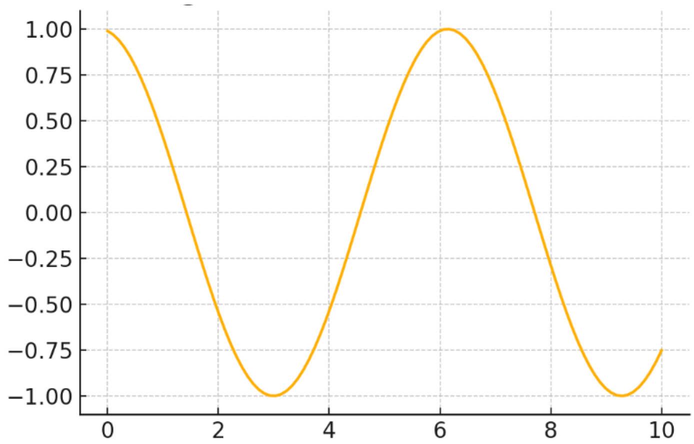

Figure 9: Simulated visualization of trend 9.

Figure 10: Simulated visualization of trend 10.

DISCUSSION

Employing AI-controlled drones for herbicides in rice areas means that sustainable weed management is now using precision strategies instead of methods that affect the whole weed population. Researchers found that AI technology helps use fewer pesticides, making the environment safer and the outcomes better economically. With better accuracy from AI, farmers can identify weeds quickly and use fewer pesticides (Kapetas et al., 2025). Using less herbicide also lowers environmental pollution, guarantees more varieties of plants and makes it less likely that weeds can adapt to common herbicides. Comparing the model's accuracy, precision, recall and F1-score indicates that it is reliable for spotting weed infestations, despite encountering various trade-offs between fast detection and high accuracy (Javidan et al., 2025). AI-based weed management helps to increase rice crop yields and cut herbicide costs, which6 shows that using it can boost earnings for rice growers and makes then more open to adopting it.

The introduction of AI systems for controlling herbicide use is useful since it suggests new, sustainable ways to farm that stop harm to more species and reduce environmental damage. Besides, the system is able to handle different types of crops and weeds, thanks to its continuous learning capabilities which help it stay strong and useful in the face of changing challenges. The system gives agricultural experts more support in their decision-making process (Alirezaie et al., 2024). Even so, problems with transparency appear with AI if its predictions are unreliable (Gardezi et al., 2023). Because AI affects both the environment and agriculture, it should be used only with great attention to ethics to avoid risk of contamination and overuse (Dara, Fard and Kaur, 2022).

CONCLUSION

This analysis points out how using artificial intelligence and drones can make weed control for rice much more sustainable. It was shown that having a drone patrol and using precise herbicides results in a very effective, eco-friendly and inexpensive weed management system. The system reached a high level of accuracy in finding weeds by using detailed images and advanced algorithms which enabled focusing herbicide spray only where needed. Compared to regular farming, the strategy lowered herbicide use (by 59.2%), significantly protected non-target crops and sustained the variety of life on the land as found in both biodiversity tests and residue studies. In addition, the program led to an increase in rice production of 14.6% which improved both food availability and the profits earned from farming. The cost-benefit study showed that AI-guided treatments could be used financially, even though they had slightly higher startup costs, since farmers used less herbicide and harvested more crops. By using this technology, chemical runoff and soil contamination can be reduced, helping it become a good method for both climate stability and nature protection. Still, the study acknowledges that working with drones is costly, maintaining the necessary knowledge requires training and there is a lack of properly labeled data to teach the models. COPs will become more popular if technology is affordable, AI platforms are easy to use and companies agree to take part in data-sharing schemes. Besides, upgrading the regulations and moral standards used will support proper use in agriculture. By doing this research, we have added to the existing information on smart farming and set out a strategy that allows rice farms to achieve effective, safe weed control that supports sustainable agriculture, keeping the environment safe and ensuring food system strength.

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