International Journal of Scientific Research in Multidisciplinary Studies
Vol.**10**, Issue.**11**, pp.**08-15**, November **2024**
E-ISSN: 2454-9312 P-ISSN: 2454-6143
Available online at: www.isroset.org

Research Article

Fuzzy Logic-Based Precision Foliar Application Amount Determination Using Digital Image Processing of Maize Canopy

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Received: 19/Sept/2024; **Accepted**: 21/Oct/2024; **Published**: 30/Nov/2024

Abstract— In this research an automatic and nondestructive method of precision farming (like foliar application of nutrient / herbicide /pesticide) was developed with the help of maize canopy cover and fuzzy logic. For this study it used data from an experiment conducted at the Department of Agronomy and Agricultural Extension, Field Laboratory, University of Rajshahi. Digital image taken from the field and processed for a precise amount of nutrient / herbicide /pesticide recommendation. The system input variables based on fuzzy rules were canopy cover (%) being defined as three fuzzy sets. The output variable was foliar agrochemical application recommendation. For output variables 3 fuzzy sets were defined. Canopy cover (%) based precise amount of nutrient / herbicide /pesticide application will optimize production cost with the right amount and ensure a sustainable environment. The results of the simulation showed significant reductions in agrochemical usage compared to a uniform blanket application across the field. For areas with sparse canopy cover, agrochemical use was reduced by as much as 75%.

Keywords— image processing, canopy cover, fuzzy logic, foliar spray

1. Introduction

The increasing global demand for agricultural productivity, coupled with concerns about environmental sustainability, has driven the need for innovative solutions in farming [1]. Agrochemicals—whether fertilizers, pesticides, or herbicides—have undeniably contributed to significant increases in global crop production. However, excessive use has resulted in numerous adverse effects, such as soil degradation, water pollution, and harmful consequences for human health and biodiversity. [2]. Traditional methods of agrochemical application are often based on uniform field-wide treatments, ignoring the variability in crop density, soil conditions, and pest infestations across different parts of the field. Such practices not only waste valuable resources but also increase the likelihood of environmental damage. However, a key challenge in precision agriculture is determining the appropriate amount of agrochemicals to apply based on real-time assessments of crop health and growth [3].

To address this, precision agriculture advocates for the site-specific application of agrochemicals, where different parts of the field receive tailored treatments according to the local crop needs [4]. For this purpose, accurate and real-time information about crop status is crucial. Among the various metrics used in precision agriculture, canopy cover—the percentage of the ground covered by the plant canopy—emerges as a critical factor in determining crop health and density [5]. Canopy cover reflects the amount of sunlight intercepted by the crop, which correlates with biomass accumulation and overall plant vigor [6].

High canopy cover usually indicates a dense, healthy crop, while low canopy cover could signal poor growth due to nutrient deficiencies, pest infestations, or environmental stress [7]. Therefore, monitoring canopy cover across the field can provide invaluable insights into crop conditions and help farmers make informed decisions about where to apply agrochemicals [8]. However, accurately measuring canopy cover across large fields can be time-consuming and labor-intensive if done manually. Canopy cover can be measured through various methods, including remote sensing, ground surveys, and digital image analysis, each providing valuable insights into vegetation density and distribution [9],[10],[11].

Recent advancements in remote sensing and digital image processing have provided a more efficient solution [12] Through the use of unmanned aerial vehicles (UAVs) or drones, farmers can capture high-resolution images of their fields. These images can then be processed using specialized software to measure canopy cover and other key parameters. This automated, non-destructive method allows for continuous monitoring of crops, providing a more accurate and timely assessment of crop conditions than traditional methods [13. Despite these technological advancements, one of the challenges that remain is how to translate canopy cover data into actionable recommendations for agrochemical application. This is where fuzzy logic comes into play. Fuzzy logic is an artificial intelligence technique that can handle imprecise and uncertain data, making it ideal for applications in agriculture where environmental conditions are often variable and unpredictable. Unlike traditional binary logic systems that operate on "true" or "false" values, fuzzy logic operates on a spectrum of truth values, allowing for more nuanced decision-making [14]. In automation, fuzzy logic optimizes control systems, robotics, and smart devices by processing various inputs. Its flexibility, simplicity, and capacity to handle imprecise data make it ideal for precision farming applications, including irrigation, fertilization, and pest control [15],[16],[17]. These systems can then recommend the precise amount of agrochemicals required at each location in the field. By integrating fuzzy logic with digital image processing, it is possible to automate the process of agrochemical application, optimizing both economic and environmental outcomes.

This study presents a methodology for combining digital image processing of maize canopy with fuzzy logic to determine the optimal foliar agrochemical application amounts. Using images captured by UAVs, we quantify the canopy cover in different sections of the field. These data are then fed into a fuzzy logic system, which generates site-specific recommendations for foliar applications based on predefined rules. The goal of this approach is to reduce the over-application of agrochemicals, lower production costs, and minimize the negative environmental impact associated with traditional farming practices.

In the following sections, we describe the materials and methods used in this study, including the image acquisition process and the development of the fuzzy logic system. We also present the results of our experiments and discuss the potential of this technology for broader applications in precision agriculture.

2. Experimental Method/Design

2.1 Study Area and Experimental Setup

The study was conducted at the Agronomy and Agricultural Extension Field Laboratory, University of Rajshahi, located at 24°22’36” N latitude and 88°38’27” E longitude, with an average altitude of 71 feet above sea level. The experimental fields consisted of maize crops grown under standard agronomic practices. The field experiments took place between January 20 and February 20, 2024, which corresponds to a critical growth stage for maize where foliar agrochemical applications are essential for promoting crop health and controlling pests and diseases. These dates were selected based on the typical agrochemical application periods for maize production in the region, ensuring that data were collected d33uring peak foliar application timings.

Three images were taken from randomly selected locations within the field to ensure a comprehensive representation of the canopy variation across the field.

2.2 Image Acquisition

The DJI Mini 2 drone was utilized to capture aerial images of the maize canopy. This drone was selected due to its high-quality image capture capabilities, portability, and ease of use. It is equipped with a 12 MP camera and a 1/2.3-inch CMOS sensor, capable of capturing still images with high resolution. The drone’s 3-axis gimbal stabilization system ensured minimal image shake and blur during flights, allowing for consistent image quality even under varying field conditions.

The drone was flown at a predetermined altitude to ensure a clear and comprehensive view of the maize canopy, and images were taken from multiple angles to capture variability in crop density and health.

Figure 1. Efficient image collection from the experimental field

2.3 Image Processing

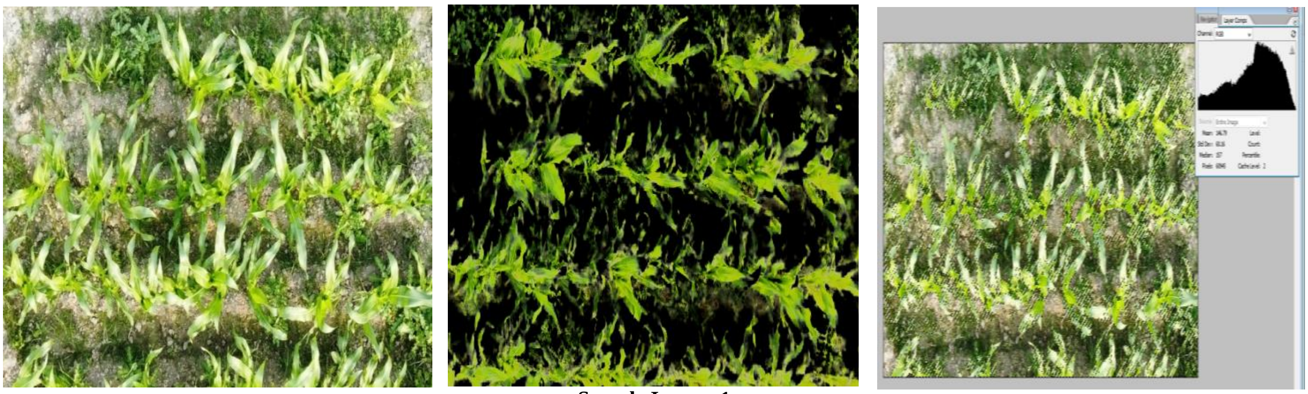
After the images were acquired, they were processed using Adobe Photoshop CS_3 to determine the canopy cover percentage in each image. The following steps were carried out to process the images [10].

Crop the Image: The first step involved cropping the images to isolate areas of interest, specifically the green vegetation (maize plants) and the surrounding soil. This was done using the ‘Crop Tool’ in Photoshop.

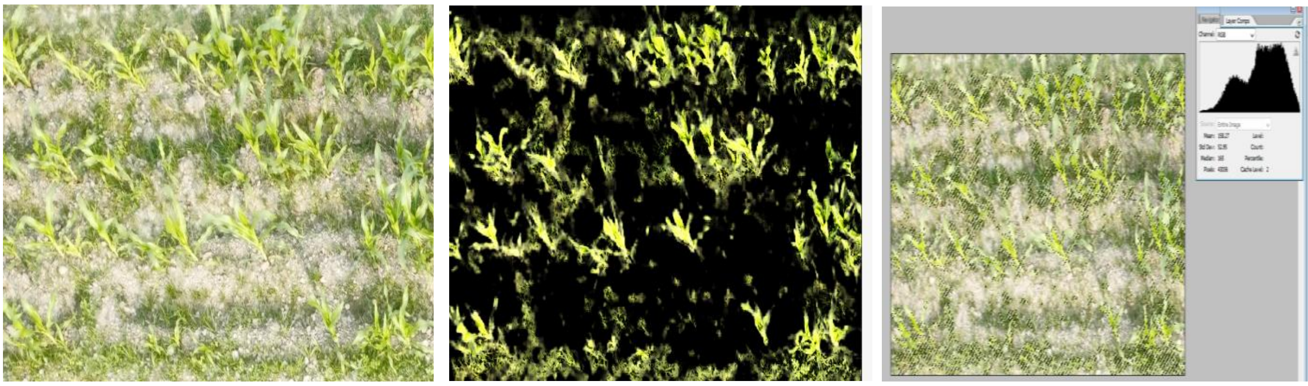
Selection of Vegetation Areas: The green areas in the cropped image, representing the maize canopy, were selected using the ‘Magic Wand Tool’. This tool allowed for easy selection of contiguous green pixels, differentiating the canopy from the background soil.

Measurement of Pixels in the Vegetation Selection: Once the green areas were selected, the histogram function in Photoshop was used to calculate the number of pixels in the selected area. This provided a quantitative measure of the maize canopy coverage in each image.

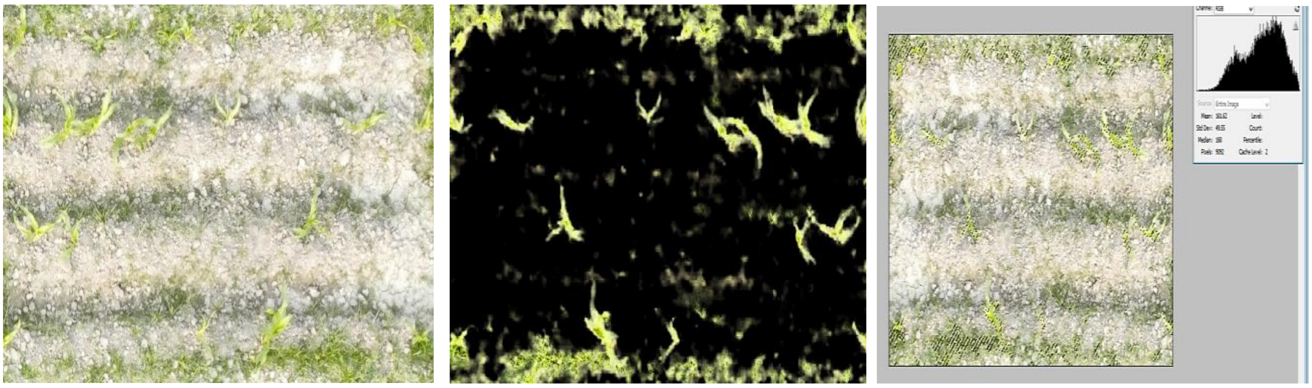
Measurement of Total Pixels in the Image: The same process was used to select the entire image and measure the total pixel count. This provided the basis for calculating the percentage of the image covered by the maize canopy.



Sample Image: 1



Sample Image: 2



Sample Image: 3

Figure.2 Determination pf canopy cover (%) from sample images (1-3) using Adobe Photoshop CS_3 software

Calculation of Canopy Cover: The percentage of the image covered by the maize canopy was calculated using the following formula:

Canopy Cover (%)= (pixels of shaded area) / (pixels of whole area) x100

Three different images from different parts of the field were processed in this manner to obtain an accurate and representative measure of the canopy cover across the experimental field.

2.4 Fuzzy Logic System Design

To determine the appropriate amount of foliar application based on canopy cover, a fuzzy logic system was developed using the Fuzzy Logic Toolbox in MATLAB R2015a. Fuzzy logic was chosen because of its ability to handle imprecise and uncertain data [18], which is inherent in agricultural environments due to variability in weather, soil conditions, and plant health [19].

The system was designed to take canopy cover percentage as the input variable and provide foliar agrochemical recommendation as the output. Both the input and output variables were divided into three fuzzy sets.

Membership Functions were designed for both the input and output variables using triangular membership functions. These functions allow the system to account for gradual transitions between the categories (e.g., from thin to average canopy cover). The use of triangular functions simplifies the design and computation process while providing sufficient flexibility to capture the variation in crop canopy and agrochemical needs [20].

2.5 Fuzzy Rules and Inference Mechanism

The fuzzy logic system used a set of expert-defined rules to determine the foliar agrochemical application amount based on the canopy cover. These rules were formulated to mimic the decision-making process of an experienced agronomist [21]. The rules are summarized in Table 1.

The system used the minimum method for rule combination, which is a widely used approach in fuzzy logic systems to determine the degree of truth for each rule. The fuzzy inference mechanism processed the input canopy cover data and applied the relevant rules to generate a recommendation for foliar agrochemical application. The resulting output was a crisp value, representing the percentage of agrochemical to apply.

Table 1. Fuzzy rules for site-specific agrochemical application model

Canopy cover (%) (Input)	Foliar agro chemical recommendation (%) (Output)
Fuzzy set	Fuzzy set
Thin, Triangular [0, 25, 50]	Low, Triangular [0, 25, 50]
Average ,Triangular [25, 50, 75]	Medium, Triangular [25, 50, 75]
Thick, Triangular [50, 75, 100]	High, Triangular [50, 75, 100]

2.6 Simulation on a Hypothetical Field

To evaluate the performance of the fuzzy logic system, a simulation was carried out on a hypothetical 1-hectare field. The canopy cover values were randomly assigned to different areas within the field, based on the data obtained from the experimental images. The fuzzy logic system was then applied to each area to generate site-specific foliar agrochemical recommendations [22], [23]. The output of the fuzzy logic system was compared to a standard uniform application of agrochemicals, where the entire field would receive the same amount of agrochemicals regardless of canopy cover variability. The difference between the site-specific application and the uniform application was calculated to determine the potential savings in agrochemical use.

2.7 Agrochemical Reduction Analysis

In addition to simulating the application, a quantitative analysis was performed to determine the percentage reduction in agrochemical usage. By applying the fuzzy logic system, the areas with lower canopy cover received less agrochemical, resulting in a significant reduction in overall agrochemical use. For instance, areas with thin canopy cover received up to 75% less agrochemical compared to uniform applications, while areas with thick canopy cover received a more substantial application to match the crop's needs.

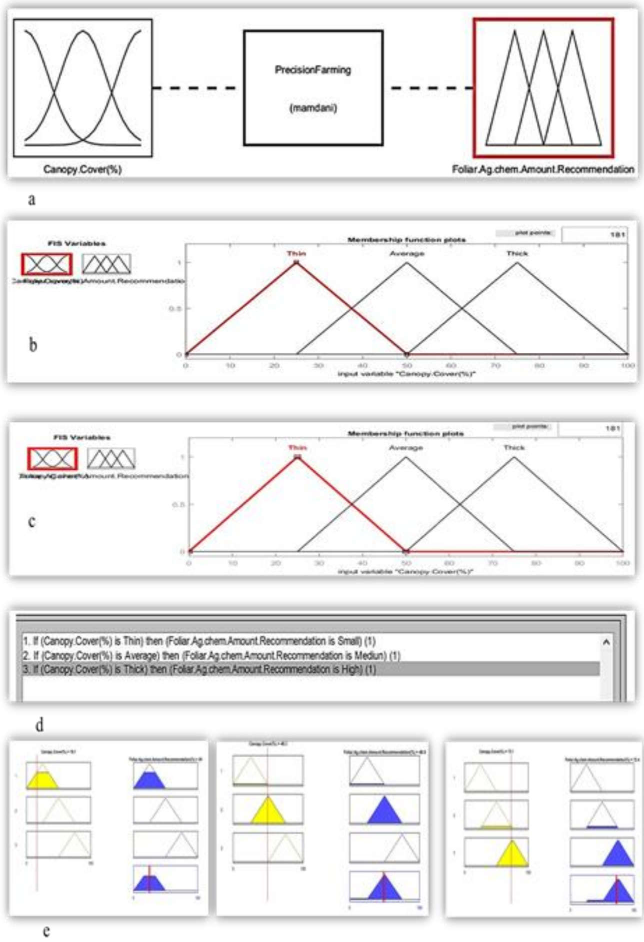


Figure 3. Fuzzy logic based agrochemicals determination model, (a) Fuzzy logic inference, (b) Triangular membership function for input (canopy cover %), (c) Triangular membership function for output (Agrochemicals recommendation), (d) Fuzzy rules for agrochemicals determination and (e) Crisp value for input and output at different points

3. Results and Discussion

3.1 Canopy Cover Distribution

The digital image processing and analysis of the maize canopy produced quantitative data on the canopy cover percentage for various regions of the experimental field. As shown in Table 2, canopy cover ranged from 11.44% to 64.24%, indicating substantial variability in the maize crop density across the field. This variability is typical in agricultural settings, where factors such as soil composition, water availability, and plant health lead to non-uniform growth patterns[24], [25]. By analyzing these images and determining the percentage of canopy cover, it became clear that a uniform application of agrochemicals would have resulted in unnecessary over-application in areas with sparse canopy coverage (low-density areas) and under-application in areas with dense canopy coverage. This highlights the necessity for a site-specific approach to foliar agrochemical application, tailored to the actual conditions on the ground [26].

Table 2: Hypothetical reduction in agrochemical use (%): Variable-rate application based on canopy cover (%) compared to blanket application using fuzzy decision system

Plot	Canopy cover (%)	Agrochemical recommendation (%)	Agro chemical amount in real situation	Hypothetical amount (ha^{-1})	Reduction (%)
			Zinc (micro nutrient); 10- 15kg/ha	6.39	
1	64.24	63.9	Chlorpyrifos 20% EC (maize borer and armyworm); 1.5 to 2 L/ha	0.9585	36.1
			Mancozeb 75% WP (leaf blight and rust) ; 2 to 2.5 kg/ ha	1.278	
			Zinc (micro nutrient); 10- 15kg/ha	2.5	
2	11.44	25	Chlorpyrifos 20% EC (maize borer and armyworm); 1.5 to 2 L/ha	0.375	75
			Mancozeb 75% WP (leaf blight and rust) ; 2 to 2.5 kg/ ha	0.5	
			Zinc (micro nutrient); 10- 15kg/ha	4.45	
3	45.52	44.5	Chlorpyrifos 20% EC (maize borer and armyworm); 1.5 to 2 L/ha	0.6675	55.5
			Mancozeb 75% WP (leaf blight and rust) ; 2 to 2.5 kg/ ha	0.89	
			Zinc (micro nutrient); 10- 15kg/ha	5.55	
4	54.5	55.5	Chlorpyrifos 20% EC (maize borer and armyworm); 1.5 to 2 L/ha	0.8325	44.5
			Mancozeb 75% WP (leaf blight and rust) ; 2 to 2.5 kg/ ha	1.11	
			Zinc (micro nutrient); 10- 15kg/ha	3.98	
5	40.38	39.8	Chlorpyrifos 20% EC (maize borer and armyworm); 1.5 to 2 L/ha	0.597	60.2
			Mancozeb 75% WP (leaf blight and rust) ; 2 to 2.5 kg/ ha	0.796	
			Zinc (micro nutrient); 10- 15kg/ha	6.96	
6	58.89	69.6	Chlorpyrifos 20% EC (maize borer and armyworm); 1.5 to 2 L/ha	1.044	30.4
			Mancozeb 75% WP (leaf blight and rust) ; 2 to 2.5 kg/ ha	1.392	
			Zinc (micro nutrient); 10- 15kg/ha	3	
7	28.96	30	Chlorpyrifos 20% EC (maize borer and armyworm); 1.5 to 2 L/ha	0.45	70
			Mancozeb 75% WP (leaf blight and rust) ; 2 to 2.5 kg/ ha	0.6	
			Zinc (micro nutrient); 10- 15kg/ha	2.5	
8	19.06	25	Chlorpyrifos 20% EC (maize borer and armyworm); 1.5 to 2 L/ha	0.375	75
			Mancozeb 75% WP (leaf blight and rust) ; 2 to 2.5 kg/ ha	0.5	
			Zinc (micro nutrient); 10- 15kg/ha	2.5	
9	17.26	25	Chlorpyrifos 20% EC (maize borer and armyworm); 1.5 to 2 L/ha	0.375	75
			Mancozeb 75% WP (leaf blight and rust) ; 2 to 2.5 kg/ ha	0.5	

3.2 Fuzzy Logic System Performance

The fuzzy logic system was tested on the canopy cover data derived from the experimental images. Using the fuzzy rules defined for site-specific foliar application, the system generated agrochemical recommendations based on the measured canopy cover percentages. As shown in Table 1, the system categorized canopy cover into three sets: Thin (0-25%), Average (25-50%), and Thick (50-100%). Correspondingly, the agrochemical recommendations were categorized as Low, Medium, and High based on the fuzzy rule base.

3.3 Simulation Results for Hypothetical Field

A simulation of the fuzzy logic-based foliar application system was conducted on a hypothetical 1-hectare field to assess potential reductions in agrochemical usage. The canopy cover values for various field sections were assigned randomly, reflecting distributions observed in the experimental field. The system then calculated the optimal agrochemical amount for each section.

1) The simulation results demonstrated substantial reductions in agrochemical usage compared to a uniform application across the field. In areas with sparse canopy cover, agrochemical usage was reduced by up to 75%. Key findings included:
2) For a plot with 64.24% canopy cover, agrochemical usage was reduced by 36.1% compared to a standard uniform application (Table 2).
3) For a plot with 11.44% canopy cover, agrochemical usage saw a maximum reduction of 75% (Table 2).
4) For sections with moderate canopy cover (45.52%), the reduction was 55.5%, indicating that even plots with relatively dense crop coverage can benefit from customized agrochemical applications (Table 2).

These findings are summarized in Table 2, detailing canopy cover percentages for each plot, the recommended agrochemical amounts based on the fuzzy logic system, and the calculated reductions compared to uniform applications.

3.4 Reduction in Agrochemical Use

The fuzzy logic system's ability to adapt agrochemical application rates to canopy cover conditions yielded substantial reductions in chemical use across the field [27]. Table 2 outlines the reductions observed for different canopy cover percentages, with savings ranging from 30.4% to 75%. These results indicate that using a fuzzy logic-based approach can significantly reduce the environmental and economic costs of maize production by minimizing unnecessary agrochemical application.

The greatest savings were observed in areas with low canopy cover, where the system correctly identified that less agrochemical was required. In contrast, areas with dense canopy cover received higher amounts of agrochemicals, ensuring that crop health and productivity were maintained without excessive application.

3.5 Economic and Environmental Benefits

The reduction in agrochemical usage directly translates to economic savings for farmers. Reducing agrochemical costs by 30-75% in certain areas can have a significant impact on overall production expenses, especially for large-scale maize cultivation. Additionally, by applying agrochemicals only where necessary, farmers can avoid the adverse environmental impacts associated with over-application, such as soil degradation, water contamination, and harm to non-target species [28].

The fuzzy logic system also enhances the sustainability of farming practices by ensuring that agrochemicals are used efficiently and judiciously [29]. By reducing the total amount of chemicals applied, this system helps to minimize the ecological footprint of maize farming, supporting long-term agricultural sustainability.

3.6 Precision in Foliar Application

One of the key advantages of using digital image processing in combination with fuzzy logic is the ability to apply foliar agrochemicals with a high degree of precision [30]. This study demonstrated that the fuzzy logic system could accurately determine the foliar application amount based on real-time canopy cover measurements, providing recommendations that are fine-tuned to the specific needs of different parts of the field.

By tailoring the amount of agrochemicals applied to the actual crop conditions, the system not only improves the efficiency of resource use but also contributes to better crop health. Over-application of agrochemicals can lead to phytotoxicity, where excessive chemicals damage the crop, while under-application may leave the crop vulnerable to pests and diseases. The fuzzy logic-based system helps to avoid both of these issues, ensuring that the right amount of chemicals is applied in the right places [31].

3.7 Challenges and Future Directions

Although the results of this study are promising, future research must address several challenges, including the spatial resolution of canopy cover measurements. One such challenge is the spatial resolution of the canopy cover measurements. While the images captured by the DJI Mini 2 drone provided high-quality data, higher-resolution images could further improve the accuracy of the canopy cover analysis and, by extension, the agrochemical recommendations. Integrating satellite imagery or higher-resolution UAVs could offer enhanced data collection, particularly for larger fields.

Additionally, the fuzzy logic system could be expanded to incorporate other variables that influence agrochemical application, such as soil moisture, pest pressure, and weather conditions [32]. By combining these additional data points, the system could offer even more precise recommendations, leading to further reductions in agrochemical use and better crop outcomes.

Another avenue for future research is the automation of real-time foliar application systems. Equipping tractors or drones with real-time image processing capabilities could allow for on-the-fly adjustments to agrochemical application rates, without the need for manual intervention. This would further streamline the process and make it easier for farmers to implement precision agriculture practices.

3.8 Comparison with Traditional Methods

Finally, the fuzzy logic-based approach was compared to traditional methods of foliar application, where agrochemicals are applied uniformly across the field [33]. As expected, traditional methods led to over-application in areas with low canopy cover and under-application in areas with high canopy cover, resulting in both economic inefficiencies and potential environmental harm. The fuzzy logic system, by contrast, offered a more adaptive and efficient solution, reducing costs and minimizing environmental impact while ensuring crop health.

4. Conclusion and Future Scope

This study successfully demonstrated the potential of integrating digital image processing and fuzzy logic for precision foliar application in maize farming. By using high-resolution images of maize canopy cover captured via UAVs and analyzing them through a fuzzy logic system, we were able to develop an efficient, site-specific agrochemical application method. The results clearly show that the fuzzy logic-based approach significantly reduces agrochemical usage compared to traditional uniform application methods, with reductions ranging from 30.4% to 75% depending on canopy cover variability. This reduction translates to substantial economic savings for farmers, minimizing costs while ensuring adequate crop protection and nutrition. Additionally, the targeted application of agrochemicals reduces environmental impact, helping to prevent soil and water contamination and promoting sustainable farming practices.

The system's ability to tailor foliar applications to varying crop conditions across a field highlights the importance of precision agriculture in optimizing resource use. Moreover, the fuzzy logic system can be easily adapted to incorporate other input variables such as soil moisture, pest presence, and weather data, offering even greater precision in future applications. However, further research is recommended to explore real-time automation of this system using advanced UAVs or tractor-mounted cameras, which could allow for on-the-go adjustments to agrochemical application rates. Incorporating higher-resolution imagery and other environmental data points could also enhance system accuracy and effectiveness.

In conclusion, the results of this study underline the value of fuzzy logic in agricultural decision-making and provide a foundation for developing more efficient, sustainable, and cost-effective farming techniques. Future developments should focus on real-time implementation, further expansion of input variables, and field-based validation across diverse crop types and geographical regions. By continuing to refine and enhance this system, precision farming can become more accessible and beneficial for farmers worldwide, contributing to both economic viability and environmental sustainability.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper. There are no financial, personal, or other relationships with people or organizations that could influence, or be perceived to influence, the work presented in this manuscript.

Funding Source

This work was supported by the National Science and Technology (NST) Fellowship, Ministry of Science and Technology, Bangladesh.

Authors' Contributions

Author-1 conducted the literature review, wrote the first draft of the manuscript, and conceived the study. Author-2 was involved in the development of the protocol and image processing. Author-3 is the corresponding author, contributed to protocol development, and revised the final draft of the manuscript. All authors reviewed, edited, and approved the final version of the manuscript.

Acknowledgement

The Authors is grateful for the continuing her PhD at Farming System Engineering Laboratory, department of Agronomy and Agricultural Extension, University of Rajshahi for the scientific contribution made available. This work was supported by National Science and Technology (Nst) Fellowship, Ministry of Science and Technology, Bangladesh

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