INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH
ISSN: 3106-8006 | 3106-7999
Volume 2, Issue 3, 2025

INTELLIGENT WEED DETECTION IN SMART AGRICULTURE USING FUZZY INFERENCE AND IMAGE PROCESSING

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Keywords
Fuzzy logic, Smart Agriculture, Membership Function, MATLAB, Input variable, Output Variable

Article History
Received: 15 July 2025
Accepted: 17September 2025
Published: 30 September 2025

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Abstract
Weed detection through image processing is an emerging and rapidly advancing field with the potential to revolutionize modern agriculture. This technology enables farmers to accurately identify and monitor weed growth, facilitating targeted and efficient weed control practices. This study presents the development of an image acquisition and processing system, integrated with a fuzzy logic–based decision-making platform, to determine the appropriate pesticide dosage and application areas within agricultural fields. MATLAB was employed as the processing environment for analyzing field images and identifying grassy weed regions. The fuzzy inference system utilizes weed coverage and patch values, supported by membership functions, to guide herbicide application rates for specific field zones. By enabling precision targeting, this approach reduces chemical overuse, enhances sustainability, and supports healthier agricultural practices.With growing global food demand and increasing pressure on natural resources, sustainable farming methods are essential. The findings of this work highlight the potential of combining image processing with fuzzy logic as a practical, intelligent solution for advancing smart and sustainable agriculture.

INTRODUCTION

Agricultural weeds are perhaps some of the biggest challenges farmers face when managing their produce, as they act as contenders who vie with plants for such necessities as nutrients, water, and light. The management of weeds is very important since it helps in maintaining healthy crops and increasing on yield. The previous techniques that formed the basis of weed detection and management include visual examination and broad-spectrum use of herbicides, which are extremely tedious, time-consuming, and rampantly pollute the environment. In response to these challenges, smart agriculture has adopted technological improvements where image processing and artificial intelligence dominate [1].

There are a lot of significant subjects in farming science, such as the usage of fertilizers, the management of pests and diseases, the approach to weeds, crop-watering, seed-care, and the nurturing of soil. Such domains are usually subject to change in things such as weather, climate, geographical location, and living organisms like pests and germs. Due to all these factors that are changing, it is difficult to come up with perfect farming plans or apply the old methods effectively. It is here that fuzzy logic comes in handy.

Fuzzy logic does not have anything in common with typical logic. It not only gives unequivocal answers such as yes and no, but also lets there be in-between answers. This comes in handy when one is dealing with farming, as nothing is always black or white.

Take, as an example, the situation where fuzzy logic can be used to determine whether soil can be planted based on moisture, quality, and seed strength. It, too, could participate in the irrigation process by determining the weather and the soil to determine how much water should be provided. In pest and disease control, it considers factors such as the temperature and the humidity to determine just how dangerous the condition would be. It is also useful in terms of fertilizer because it examines what crops and soil will require. During weed control, fuzzy logic can be used to detect the different kinds of weeds and their influence on desired crops to enable the farmer to adopt the most appropriate method of controlling the weeds.

In contemporary agriculture, it is of very high essence to detect the weeds since weeds compete with the crops for the sunlight, water, and nutrients. This has the potential to reduce crop yields. The past methods of detecting weeds either require manual effort or uncritical guidelines, but are time-consuming, costly, and some are never accurate. A more intelligent solution is provided by fuzzy logic. It is more human-like in its way of thinking and treats uncertainty better. Like in the case of saying this is a weed or this is not, it can give results such as this plant is 70 percent likely to be a weed, taking into consideration its height, its leaf shape, color, and where it is growing.

The cameras and sensors in such systems, working on fuzzy logic weed detection, capture the real-time field information. A fuzzy system checks this information with the help of the rules of the form of the writing of experts, which are called if-then. To take an instance, one may make a rule as follows:- Assuming that a plant is short, with wide leaves,-this is likely to be a weed. These rules are applied in the system to determine the probability that a plant may be a weed. This enhances recognition of the weed with a high degree of accuracy, even when the crops and weeds are rather similar.

Once the weeds have been detected, the system will be able to perform some action itself, such as spraying specifically the weeds, or sending a robot to clear them. It saves costs, lowers the amount of chemicals to use, and safeguards the environment by not causing destruction to crops. Fuzzy logic can also be applied to such real-time farming devices as drones and robots, which can scan enormous areas in a short period of time and decide even spot-by-spot. Summarily, fuzzy logic is an intelligent, pliable, and environmentally friendly approach to resolving most issues in agriculture, particularly with regard to the identification and suppression of weeds in a more precise manner.

A weed detection based on the concept of a fuzzy interface involves the use of the image processing method to distinguish weeds from crops accurately. This system encompasses ideas from the fuzzy logic system because the method is effective in dealing with the uncertainties and imprecision that characterize the conditions of farmland[2]. Through field image pre-processing, feature extraction, and using fuzzy classification rules, this approach ensures thorough weed identification in conditions such as overlapping vegetation, fluctuations in lighting, and other crop-weed interactions.

The creation of such a system fits the mission of precision agriculture, to minimize the utilization of resources while lowering costs and preserving the environment[3]. Incorporating real-time imaging and automation, this technology can help improve efficient weed removal and limit the use of herbicides, promoting green agriculture. This paper examines the approaches, benefits, and drawbacks of a fuzzy interface-based weed detection system that indicates its potential toward revolutionizing today's farming technologies.

2-Literature review:

It is a plant that grows where it is not wanted, and since it is not as wanted as the crops, it grows side by side with the crops, and it affects the quality and quantity of crops that farmers take to the market. Traditional methods of weeding involve applying herbicides (weed killing chemicals) on the entire farm or garden[4]. Despite its efficiency, this approach negatively impacts the environment, human health, and indeed squanders resources. Modern technology offers a better solution: smart weed detection systems. These systems employ two main techniques of image processing and fuzzy logic to identify and exclude the weeds in precision[5]. The integration of image processing techniques in smart agriculture has significantly improved weed detection and crop management. Traditional weed control approaches, including hand removal and chemical products, create various challenges because they require excessive human effort while harming the environment and being costly to implement [6]. Various studies have explored the use of machine learning, deep learning, and fuzzy logic-based approaches to improve weed classification accuracy, offering a more adaptable and intelligent solution for real-time agricultural applications[7].

The detection of weeds in agricultural environments through fuzzy interface systems utilizes fuzzy logic principles for uncertainty management to achieve superior results. Fuzzy systems differ from threshold-based approaches because they effectively identify weeds through processing vague or overlapping data sets, which leads to higher accuracy. Several Research studies across multiple investigations reveal how image processing methods, along with fuzzy logic properties, achieve weed discrimination from crops. Image processing techniques such as edge detection, segmentation, and feature extraction are used to distinguish weeds from crops [8]. Through these methods, the classification performance improves as they analyze leaf forms along with colors and textures, and size features to decrease incorrect weed detections while optimizing weed control practices [9]. The detection of weeds depends heavily on image processing methods to carry out feature-based classification also identify objects. The field of weed image processing and classification depends on the three main methods: CNNs, alongside k-means clustering and SVMs [10]. Multiple research works have proved that deep learning systems achieve high recognition accuracy for weeds across diverse datasets. New detection methods using hyperspectral and multispectral imaging have been explored to read weed species based on spectral signatures, which improves detection reliability further. The Deep learning models are also being used in agriculture [8] [9], Health [10] [11], road sign detection [12], and other industries, but due to some limitations, they are restricted in some situations.. Through integration with fuzzy logic and these techniques, the system becomes robust for handling various agricultural settings.

The advancements in herbicide systems fail to overcome three major obstacles consisting including changing lighting environments and obstructed plants, and crop plants appearing similar to each other. Scientists advocate the combination of sensor integration along with Internet of Things (IoT) technology to improve real-time detection of weeds[13]. The expansion of sustainable weed management appears promising because of the integration between fuzzy logic AI and image processing in conjunction with intelligent farming methods. Scientists should direct their research toward developing faster computational methods along with user-friendly interfaces because this will promote more farmer acceptance. Image processing techniques linked with fuzzy logic systems have become a prominent agricultural approach to boost efficient weed detection systems and weed management solutions. Hand removal of weeds as well as herbicide treatments cause substantial labor requirements and environmental risks in conventional weed management systems. The output of automated weed detection systems emerged from uniting computer vision with artificial intelligence capabilities, with contemporary improvements in ML technologies. These automated systems have improved weed differentiation capabilities because of their digital image processing methods that perform color segmentation as well as edge detection and feature extraction[14].

When implementing weed detection systems based on fuzzy logic operators, researchers gain a dependable method to manage analytical uncertainties. Fuzzy logic systems use a different approach than standard binary classification by implementing membership degrees to determine different features in the image[15]. The methodology leads to enhanced classifications of weeds because it handles difficult agricultural settings, which present issues related to lighting conditions and overlapping plants, and blocked views. Research indicates that applying fuzzy logic to image processing techniques increases both the detection reliability and cuts down false identifications while enhancing the optimization of herbicide off-targets.[15].

The methodology leads to enhanced classifications of weeds because it handles difficult agricultural

settings, which present issues related to lighting conditions and overlapping plants, and blocked views. Multiple studies show that incorporating fuzzy logic into image processing methods strengthens detection accuracy by decreasing false positive results while improving the use of herbicides.[16].
Despite the progress, challenges such as variability in plant species, environmental
factors, and computational costs remain. Researchers suggest integrating sensor fusion techniques, Internet of Things (IoT) applications, and real-time decision support systems to enhance weed detection efficiency. Future studies should focus on improving the adaptability of fuzzy-based models, increasing computational efficiency, and developing user-friendly interfaces to encourage widespread adoption in precision farming[17].

3-Method:

The following part details our proposed model, which detects weeds using a Fuzzy interface. The proposed weed detection methodology flows as presented in Figure 1.

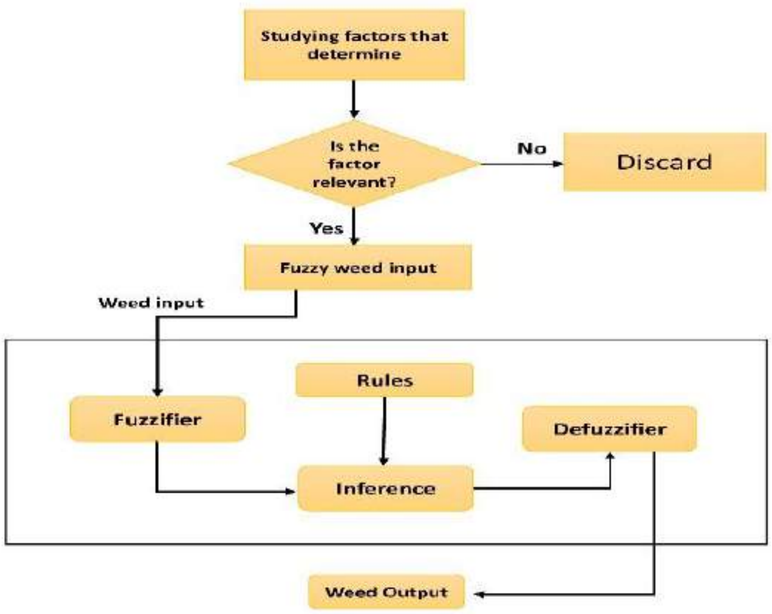
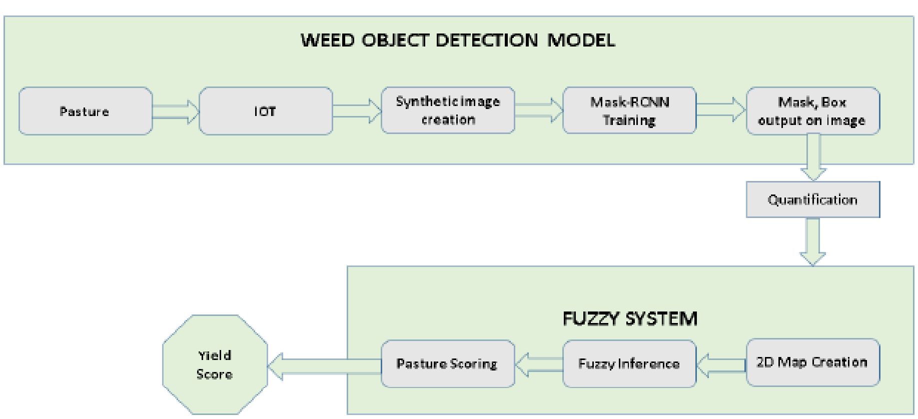


Figure 1: Proposed Fuzzy interface-based weed detection logic diagram

Model Workflow:



The diagram shows the integrated system of smart weed detection and estimating the yield to one

INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH
ISSN: 3106-8006 | 3106-7999
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hectare in the pasture lands based on computer vision and fuzzy logic. The procedure starts with the Real-time collection of images of recent pasture with devices facilitated by the IoT, like drones or field sensors. Such images are augmented through synthetic image generation so as to augment the training set. Their improved images are afterward applied to train a Mask-RCNN model, which is a way of deep learning vis-à-vis object detection and image segmentation. The trained model produces not only variable region boxes or bounding boxes but also masking or segmentation boxes that denote weed-infested regions in the pasture pictures. This output undergoes quantification, whereby the level of the presence of the weeds is quantified in figures.

The data in quantitative form is then filtered through the fuzzy system, which operates further on it to determine the health of the pasture. To have a visual representation of the distribution of weeds, a 2D spatial map will be formed, and any analysis considering uncertain or varying conditions applied to the data may be performed using fuzzy inference logic. Depending on a set of defined rules, this system is used to determine the effect of weed invasion and gives a score for the pasture. The system gives the final output of yield score, which is the potential overall productivity of the pasture. This smart system contributes to precision farming as it allows addressing the issue of weeds timely manner and making decisions on the level of yield.

3.1 Input variable. The statistical values known as fuzzy input variables serve to detect weeds. Three distinct input variables make up the total variables in this search. The study includes vegetation density, shape complexity, and proximity to crop as input data variables that are shown in the table1 and Figure 3.

Sr.no	input
1	Vegetation density
2	Shape complexity
3	Proximity to crop

3.2 Output variable. In this search, fuzzy interface-based weed detection uses output in the name of weed.

3.3 Membership Functions. The membership functions within this system create curved values ranging from 0 to 1 and simultaneously generate graphical displays with statistical data about input and output variables.

3. I/O Rules. Any fuzzy inference system (FIS) depends heavily on these elements for its proper functioning. The rules determine the performance of all expert systems. Rules are explained in Figure 4.

3.5 Inference Engine. Any expert system needs an inference engine, which functions as its fundamental processing unit. The research utilizes the Mamdani inference engine as its main operational calculation method.

3.6 Defuzzifier. The expert system depends heavily on the functionality of a component known as the defuzzifier. Different types exist that compose a class of defuzzifiers. The graphical representations of the defuzzifier appear in Figures 6(a)–6(d).

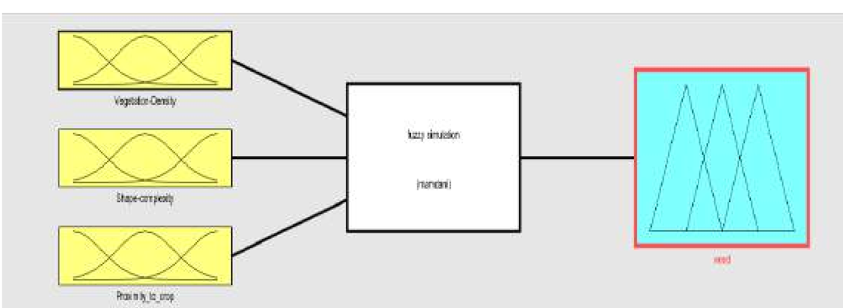


Figure 2: Input variable of weed detection

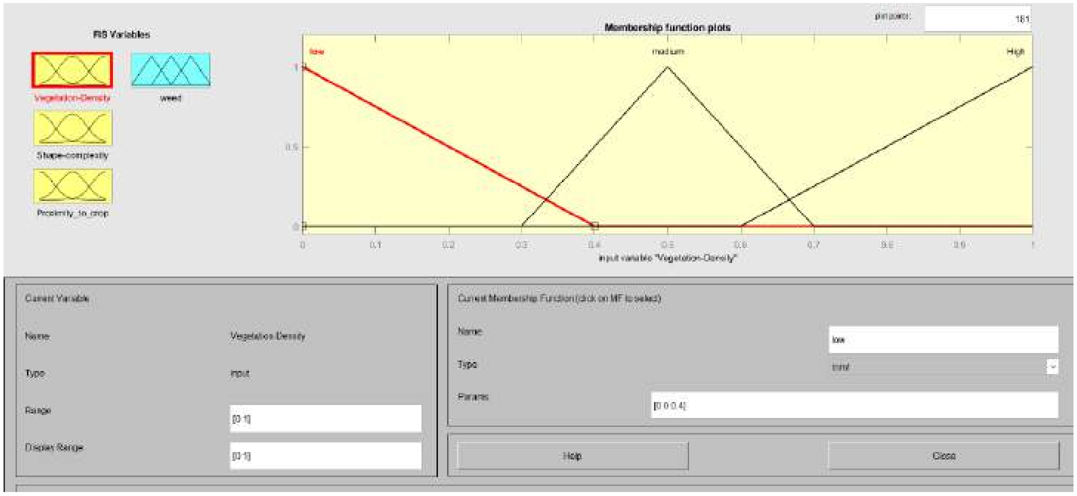
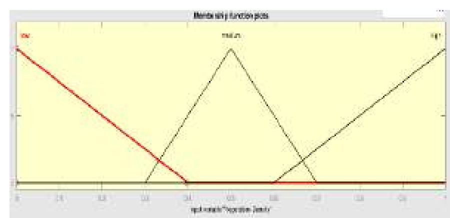
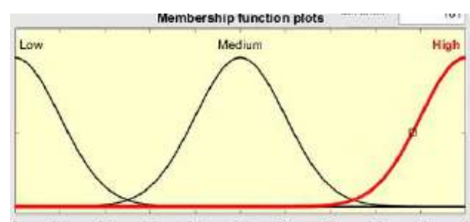
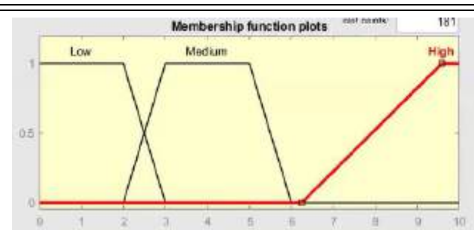
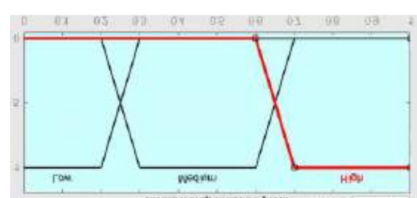


Figure 3: Input variable of Vegetation Density

Table 1: Input and output variables membership functions used in the proposed Weed detection expert system.

Sr. No.	Variable	Membership Function (MF)	Graphical Representation
1	Vegetation Density (V)	$\mu_{V,\text{low}}(x_1),\ \mu_{V,\text{medium}}(x_1),\ \mu_{V,\text{high}}(x_1),\ \mu_{V,\text{none}}(x_1)$	
2	Shape Complexity (S)	$\mu_{S,\text{simple}}(x_2),\ \mu_{S,\text{moderate}}(x_2),\ \mu_{S,\text{complex}}(x_2),\ \mu_{S,\text{none}}(x_2)$	
3	Proximity to Crop (P)	$\mu_{P,\text{close}}(x_3),\ \mu_{P,\text{moderate}}(x_3),\ \mu_{P,\text{far}}(x_3),\ \mu_{P,\text{none}}(x_3)$	
4	Weed (W)	$y^* = \dfrac{\int y\,\mu_{\text{agg}}(y)\,dy}{\int \mu_{\text{agg}}(y)\,dy}$	

INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH
ISSN: 3106-8006 | 3106-7999
Volume 2, Issue 3, 2025

4-Results: For simulation results, MATLAB R2024b tool is used. MATLAB is also used for modelling, simulation, algorithm development, prototyping, and many other fields.

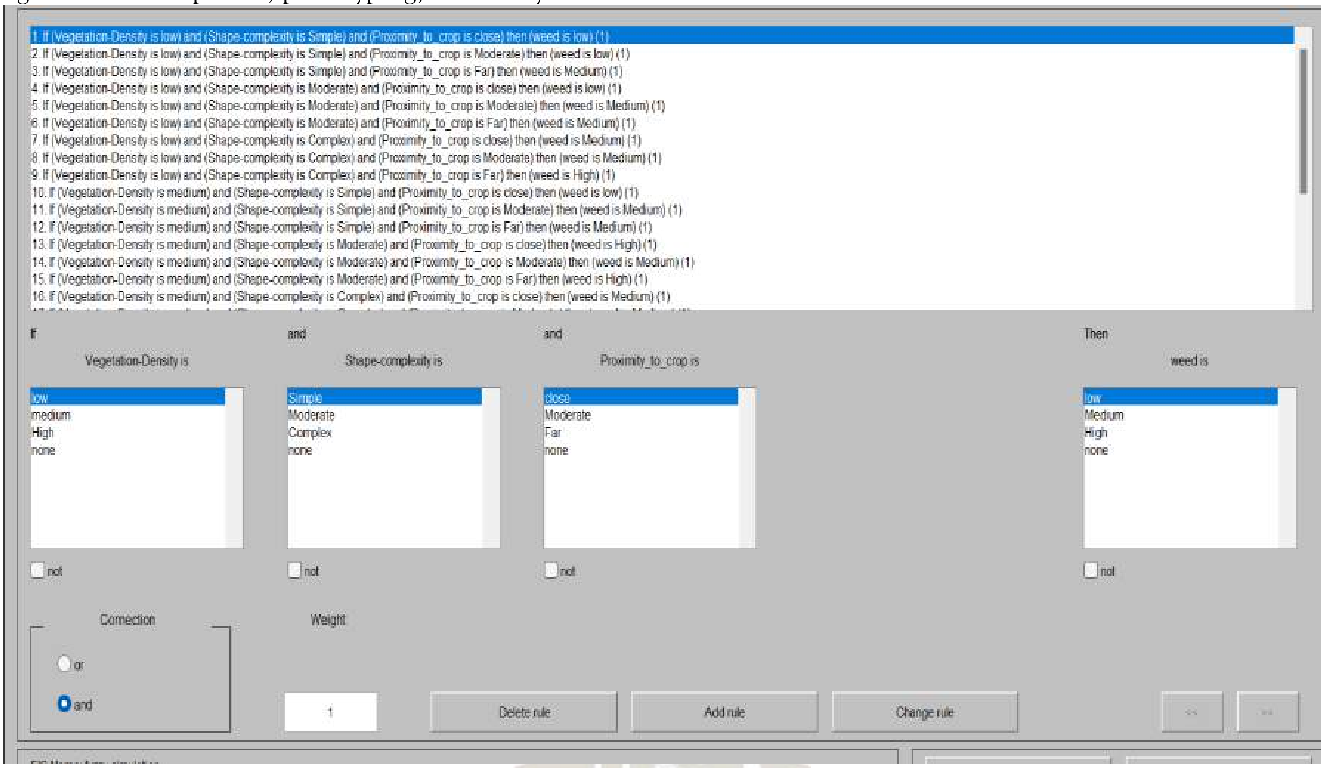


Figure 4: Fuzzy input-output Rules.

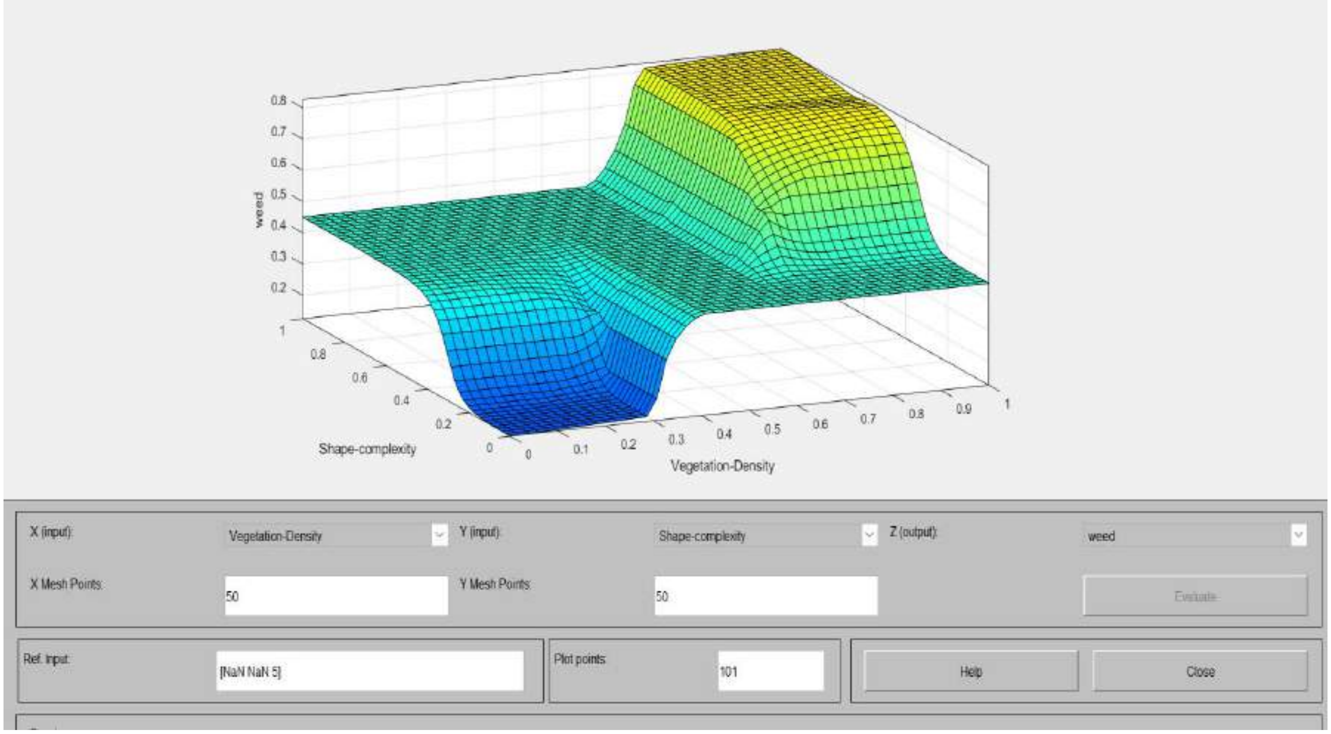


Figure 5: Weed surface of shape complexity and vegetation density

ISSN: 3106-8006 | 3106-7999
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In this research, the proposed fuzzy interface-based weed detection detects weed in smart agriculture. In Figure 7, if vegetation density is 0.814 and shape complexity is 0.729, proximity to crop is 8.31, and output weed is 0.812.

Figure 6a

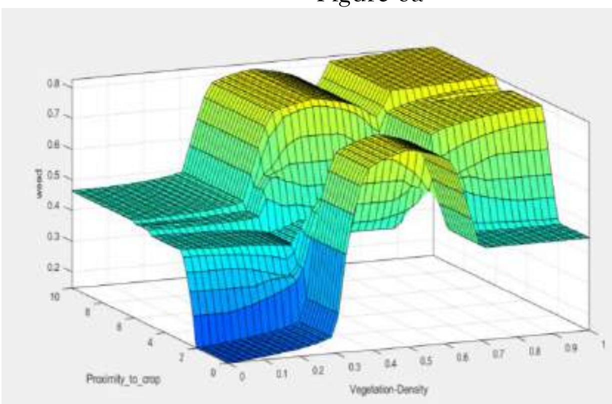
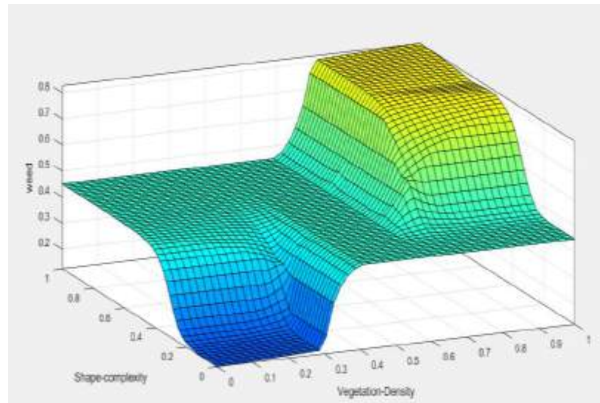
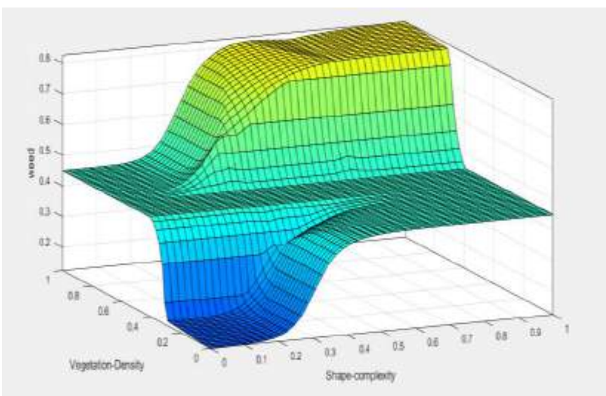


Figure 6b





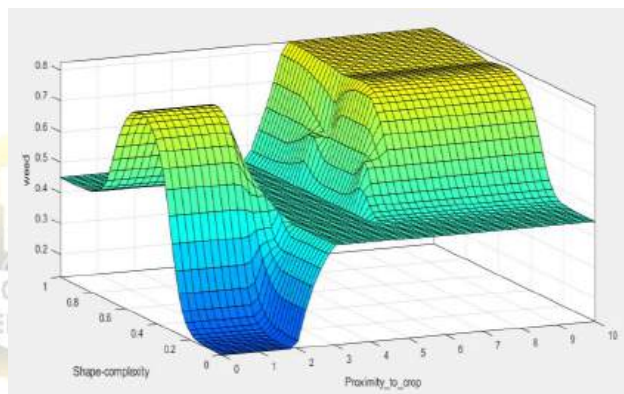


Figure 6c

Figure 6d

Figure 6: (a) Rule surface of proximity to crop and vegetation density, (b) shape complexity and vegetation density, (c) vegetation density and shape complexity, (d) shape complexity and proximity to crop.

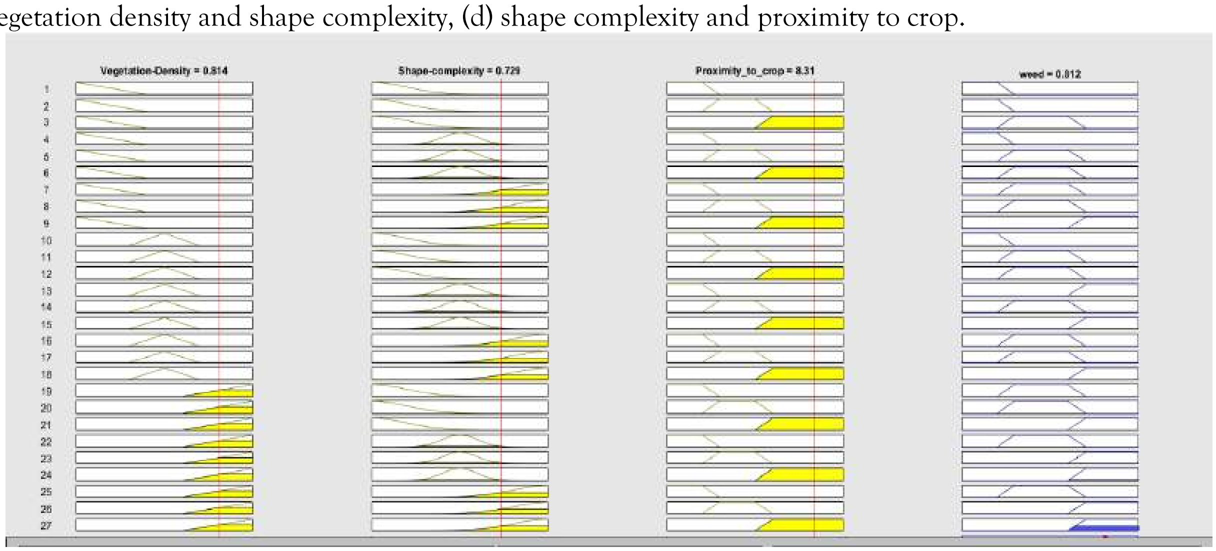


Figure 7: Rule results

INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH
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Baseline Model Comparison

Criteria	Traditional Methods	Machine Learning Models	Fuzzy Logic (Baseline)
Decision Making	Rule-based, rigid	Data-driven, needs training	Human-like, flexible
Need for Large Data	No	Yes	Low to medium
Handling Uncertainty	Poor	Moderate	Excellent
Explainability (XAI)	High	Often low (black box)	Very High
Real-time Capability	Low	Depends on model	High
Adaptability to Conditions	Low	Moderate	High
Accuracy (in complex fields)	Medium	High	Moderate to High (depends on rules)
Implementation Complexity	Low	High (model training needed)	Moderate
Suitability for Small Farms	Yes	Sometimes costly	Yes

5 -Conclusion and Future Work:

The main objective of our research involves creating an interface that detects weeds in smart agricultural systems. Fuzzy logic offers a new, practical, and smart method to detect weeds in contemporary farming. Whereas, in a traditional rule-based or binary system, the aspect of uncertainty and imprecision cannot be dealt with, fuzzy logic offers the ability to make decisions on a scale of truth (as humans do). This particularly makes it effective when it is in the real field condition, since the environmental conditions are continuously varying and the visual difference between crops and weeds is not always a clear cut.

Fuzzy logic systems can also identify and detect weeds very effectively with the help of expert-established rules and the real-time information provided by sensors or cameras in terms of plant shape, size, color, and position. After the weeds have been identified, such systems may take specific activities such as the precise application of herbicides or robotic destruction, which can limit the use of chemicals and reduce crop damage.

On the whole, fuzzy logic can improve the accuracy, efficiency, and sustainability of weed control. It is especially useful in cases involving small sizes, few resources, or in cases where the decisions need to be translated in a comprehensible way. Fuzzy logic analysis will become an indispensable weapon in the battle against weeds because of the intelligent and safe farming trend that is currently underway. The developed system operates with simplicity in smart field operations. In the future, the efficiency of the proposed system could be higher through additional application of computational intelligence techniques such as neural networks and neuro-fuzzy systems.

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