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A Fuzzy Logic–based Weighting Method for Increasing the Efficiency of Cotton Spraying

Summary

Chemical pest control is essential in cotton cultivation but traditional uniform-dose spraying leads to excessive pesticide use, environmental damage, and economic losses. This study introduces a fuzzy logic-based system that optimizes pesticide spraying by adjusting the dose based on the plant's growth stage and canopy coverage. The system was tested on a 50-hectare cotton field, resulting in a 30-35% reduction in pesticide use compared to traditional methods, while maintaining pest control effectiveness and crop yield. The fuzzy logic system offers a flexible, cost-effective solution, reducing pesticide use without compromising efficiency. Its adaptability to real-time conditions makes it a valuable tool for precision farming, contributing to more sustainable agricultural practices.

Keywords: fuzzy logic; precision spraying; cotton; chemical control; sustainability

JEL-codes: M10; M14; Q56

Introduction

Due to the diversity of pests in cotton (Gossypium hirsutum) cultivation, chemical control is essential; typical sucking pests (jassids, thrips, aphids, mealybugs) and chewing pests (American and spotted bollworm caterpillars) can destroy up to 40–50% of the crop in severe infestations, justifying plant protection interventions (Bhad, 2022). However, traditional, experience-based, uniform dose application often leads to excessive pesticide use, fluctuating efficacy and increased environmental burden (Jiao et al., 2025; Zheng-Xu, 2023). The excessive use of pesticides poses a serious ecological risk: it can contribute to the pollution of living waters and the development of resistant pest and weed populations (Yadav, 2010; Tudi et al., 2021). In fact, cotton is one of the most chemical-intensive crops – accounting for ~24% of global insecticide use and ~11% of total pesticide applications, which is a good indication of the current level of chemical control (Bhad, 2022). In addition, chemicals are expensive, so wastage also causes direct economic losses to producers.

For sustainable agriculture, the goal is to promote precision spraying and integrated pest management (IPM) methods that reduce chemical intervention to the minimum necessary (Deguine et al., 2021). The key to this is proper monitoring – continuous observation of pests and plant health – and adaptive control based on this, which sprays only when and as much as necessary (Jiao et al., 2025).

Precision spraying and process monitoring in cotton production

In precision agriculture, modern sensors, IoT devices and data-driven decision support systems have enabled real-time monitoring and intervention (control) of production processes. In the case of cotton, several major pests can cause damage per season, so monitoring populations is key to effective control (Jiao et al., 2025). Traditionally, farmers spray in advance without knowing the specific level of infestation, which often results in unnecessary applications or intervention being delayed in relation to the appearance of pests (Jiao et al., 2025). In recent years, intelligent monitoring systems have emerged that automatically detect pests with sensors and initiate targeted control: for example, an IoT-based prototype detects the presence of cotton pests with infrared sensors and wireless communication, then uses localized data to direct a UAV to spray the infected patch, minimizing chemical use (Azfar et al., 2023). In weed control, smart spraying systems supported by machine vision separate crops from weeds based on camera images and apply herbicide only to weeds; in a cotton field experiment, targeted spraying hit nearly 90% of weeds while avoiding the vast majority of cotton plants, thereby drastically reducing herbicide use (Lamm et al., 2002). Such precision technologies simultaneously reduce environmental burden and costs, while also improving biological efficacy (Jiao et al., 2025; Zheng-Xu, 2023).

The essence of precision spraying is to apply the pesticide in a differentiated manner in space and time: only there, then and in the amount needed, where, when and as much as is needed. For this, sensor networks and digital technologies provide data, which the on-board controller processes and controls the application based on this. In modern spraying systems, the sensor chain of pump-pipe network-flow meter-pressure sensor-speed sensor is supplemented with electronically controlled valves/nozzles and an embedded control unit. In addition to traditional PID control, intelligent control algorithms – including fuzzy logic – are increasingly appearing for stable and fast tracking of nonlinear, time-varying processes, enabling the

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compensation of nonlinearities in spraying equipment resulting from, for example, the "backlash" of valves (Schutz et al., 2024; Zheng-Xu, 2023).

Variable-rate spraying modifies the applied rate in real time based on sensor data and driving conditions. The main architectures of rate control are: (i) pressure-based control, (ii) flow/PWM-based control, and (iii) concentration control (with direct chemical injection) (Jiao et al., 2025). Pressure control is a simple and inexpensive solution, but it also modifies the size distribution of the spray droplets, which affects coverage and drift; the advantage of PWM-based solutions is that the pressure remains nearly constant, while the applied rate can be precisely controlled by changing the opening cycle; concentration control avoids tank residue and allows for quick recipe changes (Jiao et al., 2025; Zheng-Xu, 2023). In practice, the feedforward–feedback combination proves to be effective for predictive tracking and compensation of progress speed and mapped state changes (Schutz et al., 2024; Jiao et al., 2025).

By integrating IoT and wireless sensor networks (WSNs), systems can be built that trigger automatic alerts and targeted interventions – such as phasing or drone spot spraying – as soon as pests are detected (Azfar et al., 2023; Jiao et al., 2025). Unmanned aerial vehicles (UAVs) allow for rapid detection and targeted treatment, but they are limited by payload, operating time and wind sensitivity – therefore, in practice, the complementary use of smart ground sprayers and UAVs is advisable (García-Munguía et al., 2024; Jiao et al., 2025). Several recent studies address drone-based precision spraying: according to a comprehensive review, the use of variable-rate spraying drone systems can significantly reduce the ecological burden of pesticide use (Taseer-Han, 2024). A UAV spraying prototype equipped with a LiDAR-based sensor system achieved similar biological efficacy in a field experiment using ~30% less chemicals than the traditional, constant-input method, demonstrating the promising potential of drone-based targeted application (Liu et al., 2025).

Fuzzy logic in agricultural automation

Unlike classical binary logic, fuzzy logic handles uncertainty and gradation using partial truth values (levels between 0 and 1), making it excellent for controlling noisy, nonlinear, and difficult-to-model agricultural processes. Expert language categories that arise in agriculture (e.g., low/medium/high infestation or sparse/medium/dense foliage cover) can be mathematically quantified with membership functions and then connected in the form of IF–THEN rules; defuzzification following the inference of the rule base provides a specific output command (e.g., in the form of pump power adjustment or valve position) (Lee et al., 2023).

The advantage of fuzzy-based control is that expert knowledge and experience can be incorporated into the system, and it has been proven in many smart farming applications: it is used for irrigation control, nutrient application, greenhouse climate control, and even crop protection decision support (Lee et al., 2023). For example, in an experiment implemented in a cotton plantation, an irrigation control system based on fuzzy rules significantly reduced water waste while maintaining plant health and crop security (Li et al., 2023). Fuzzy algorithms have low computational requirements, so they run reliably on simple hardware and embedded controllers – thanks

to this, they can be considered one of the key technologies for real-time field control (Lee et al., 2023).

Fuzzy logic in cotton spraying

Fuzzy logic is particularly promising for increasing the efficiency of spraying because it can consider heterogeneous information (e.g. pest density, canopy density, weather factors, plant development stage) and transform them into a weighted, finely tuned control signal. It has been pointed out for more than a decade that constant-rate, full-area spraying cannot adapt to spatial and temporal changes in the needs of the target area; in contrast, a variable-rate application system built on sensor data and fuzzy controller enables fast-setting and stable control during spraying (Shi et al., 2007).

Recent developments combine fuzzy logic with other control techniques to optimize the spraying process. For example, fuzzy-based gain scheduling continuously adjusts the parameters of a predictive controller (GPC) to the current operating conditions, which significantly improves the control accuracy and robustness of the nonlinear spraying system compared to conventional control (Schutz et al., 2024). In laboratory and field experiments with an adaptive fuzzy controller supported by machine vision and canopy area estimation, the amount of applied chemical could be reduced by ~60% compared to constant-rate spraying, while the deposition efficiency and biological effect were significantly improved (Luo et al., 2025).

Some studies have shown that advanced fuzzy controllers can also increase the proportion of spray droplets falling within the optimal size range (100–300 µm). For example, a fuzzy controller combined with chaotic optimization increased the proportion of droplets of the appropriate size from ~81% to ~89%, resulting in a noticeable improvement in coverage quality (Song et al., 2020). In practice, fuzzy-PID hybrid solutions maintain fast response and application accuracy of ±5–10% under varying ground speed, canopy cover, and wind conditions – especially when coupled with feedforward correction and sensor fusion (Jiao et al., 2025).

The efficiency and economy of cotton spraying can be significantly increased if monitoring and control are integrated and supported by real-time data. A fuzzy logic-based weighting method allows for the combined assessment of environmental and plant condition parameters, and based on this, a balanced determination of the urgency and dose of interventions. Documented field results show chemical savings of 20–60%, as well as better coverage and deposition indicators for targeted, variable-rate applications – especially when canopy geometry and travel parameters are incorporated into the decision model in real time (Luo et al., 2025; Jiao et al., 2025; Zheng-Xu, 2023). Fuzzy-based decision support and control are therefore a key element of precision spraying, which enables the simultaneous achievement of environmental, crop safety and cost-effectiveness goals in cotton production.

Results

The economical and efficient use of pesticides is of paramount importance in modern agriculture. In cotton cultivation, pest and disease control is traditionally achieved by applying uniform spray doses to the entire field. Although this approach is simple, it does not take into account the variability within the crop, for example, the degree of development of the plants and

the canopy coverage (how much of the soil surface is covered by vegetation) that may vary within the field or over time. As a result, traditional spraying with the same dose everywhere is often wasteful, as in areas with sparser vegetation, unnecessary amounts of chemicals reach the soil, while in areas with denser vegetation, some of the spray may be washed off by the leaves. Uniform application ignores spatial and temporal changes in plant cover and growth status, which leads to a waste of valuable resources and increased environmental impact. To address this challenge, precision agriculture advocates site-specific spraying methods, where different parts of the field receive treatment tailored to local needs. However, this requires accurate information on the current state of the vegetation (development, cover, etc.). The density of the plant stand is well characterized by the canopy coverage ratio, i.e. what percentage of the ground surface is covered by the foliage of the plants. This value is closely related to the biomass and the health of the plants. High coverage usually indicates a healthy, abundant plant stand, while low coverage may indicate poor growth (e.g. due to nutrient deficiency, pests or drought). The growth phase is also a key factor. Cotton grows a small leaf area in its initial development phase, later during flowering and fruit (boll) formation, the canopy closes, and then at the end of ripening the foliage loses its mass. The dynamic change of these factors justifies the adjustment of the spray volume and dose to the conditions.

Fuzzy logic is an approach that allows the handling of uncertain or gradually changing information. Fuzzy logic does not work with sharp boundaries, but with "partial truth values", so it can handle descriptive categories such as "sparse vegetation" or "medium development" in mathematical form. This case study presents a fuzzy logic-based weighting system for optimizing the spraying process in a cotton plantation. The system categorizes the input parameters with triangular fuzzy membership functions and generates a weighting factor that gives the recommended spray solution dose modification. Our goal is to demonstrate that by applying this method, the spraying process can be made more efficient and economical, while the effectiveness of plant protection is not reduced. The system also generates a report after each spraying event, giving feedback to the farmer in order to support decision-making (e.g. showing how much chemical was saved for the given treatment compared to the traditional method).

The challenges of traditional spraying in cotton production

Cotton requires multiple sprays during the growing season to control pests (e.g. bollworm larvae) and diseases. Traditionally, spraying is done at full dose, regardless of the plant's stage of development. For example, during a typical cotton spray, approximately 100 liters of spray solution are applied per hectare, regardless of whether the plants are just 20 cm tall seedlings or have already developed a full canopy. In the early stages, the plants rarely cover the soil (even <20% coverage), and most of the spray solution ends up on the ground, which is a waste of money and increases the chemical load in the

environment. Later, when the cotton crop is closed (80-100% coverage), the leaves cover the soil, but the same amount is still applied uniformly, although the full dose may be justified at this time, but less than on previous occasions would have been sufficient. The traditional method is therefore not flexible, does not respond to the developmental stage of the plant or the density of the foliage. As a result, too many chemicals are often used during the season, which increases costs and environmental impact without proportionally increasing the effectiveness of the control. There is a need for flexible spraying strategies that take into account:

– the current growth phase (phenological state) of the plant,
– the canopy coverage rate (degree of plant cover),
– and, if necessary, other factors (e.g. pest pressure, weather conditions).

Based on this information, the dose to be applied could be weighted so that neither overtreatment nor undertreatment occurs. The fuzzy logic system achieves exactly this in practice by integrating expert knowledge in the form of linguistic rules (e.g. "if the vegetation is sparse and the development stage is early, then a low dose is enough") into a formalized decision-making mechanism.

Design of a weighting system based on fuzzy logic

The developed fuzzy system uses two main input variables to weight the spray solution dosage:

1. The growth phase of the cotton plant – which expresses the stage of the vegetation period the plant is in (initial development, vegetative growth, flowering, fruit formation, ripening).
2. Field coverage rate – the current canopy coverage of cotton in percent, i.e. what percentage of the soil surface is covered by the plant's foliage in a given area.

For both input variables, we defined 5 categories, which are described by triangular fuzzy membership functions. This means that, for example, the growth phase is characterized by 5 linguistic variables, such as:

– Very early – e.g. immediately after emergence, seedling stage (beginning of the growing season).
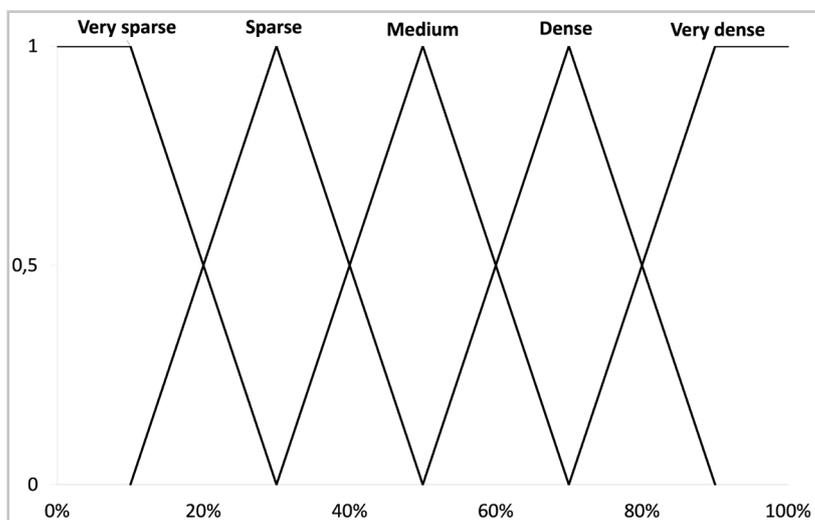

Figure 1. Fuzzy categories of spraying phases
Source: Own editing based on own researh

– Early – a stage of intense vegetative growth, but before flowering.
– Mid-season – the flowering stage of the plant when the canopy is already extensive.
– Late – the period of fruit formation and pod ripening, when the plant's development slows down.
– Very late – the stage before full maturity, leaf closure was maximum, but may be decreasing by this time (half-ripening stock).

Similarly, we divide the current coverage ratio into 5 fuzzy categories, for example:
– Very sparse (minimum coverage, 0-20%),
– Sparse (rare stock, 20-40%),
– Medium (medium density foliage, 40-60%),
– Dense (well-closed canopy, 60-80%),
– Very dense (almost full coverage, 80-100%).

Categories can overlap, and triangular membership functions allow a given measurement (e.g., 50% coverage) to partially belong to two categories. For example, at 50% canopy cover, the fuzzy set "Medium" could have a membership of 0.5 and the fuzzy set "Dense" could have a membership of 0.5 (based on assumed membership functions). This allows the system to handle subtle transitions, rather than just making decisions along sharp boundaries.

The output of the fuzzy system is a weighting factor or recommendation for the spray solution dosage. This is also divided into 5 levels with triangular fuzzy sets, which can be characterized by the following linguistic categories:
– Very low dose – significantly reduced amount (20-30% of the usual dose).
– Low dose – moderately reduced (50% of the usual dose).
– Medium dose – the average, normal amount (70-80% of the full dose, or the standard dose itself).
– High dose – the full recommended amount (100% of the base dose).
– Very high dose – slightly increased amount if necessary (110-120% of the base) if circumstances warrant.

The above categories are illustrated with example ratios only – in a real system, the exact percentage values can be determined based on expert knowledge and experimental data. The point is that the system also categorizes the output variable in a fuzzy way, so the recommended spraying intensity can be flexibly determined using the rules.

Fuzzy rule base and inference method
The rule system is based on IF...THEN fuzzy rules that assign combinations of input categories to output categories. These rules were formulated based on agronomic expertise. Some examples of the rules:
– IF the plant is in a very early stage AND the canopy is very sparse, THEN the recommended dosage is very low.
– IF the plant is in the early stages AND the canopy is sparse, THEN the recommended dosage is low.
– IF the plant is medium-sized (flowering) AND the canopy is medium, THEN the recommended dose is medium.
– IF the plant is in a late stage AND the canopy is dense, THEN the recommended dose is high.
– IF the plant is in a very late stage AND the canopy is very dense, THEN the recommended dosage is very high.

The above rules are simplified examples. In a real situation, the rule base may contain additional rules for all relevant combinations, and can even be expanded with extra conditions (e.g. if pest pressure is also taken into account: "IF pest infestation is high AND... THEN..."). The result of each rule is a fuzzy set in the output space. The rules are evaluated in parallel based on the principle of max-min fuzzy inference: we take the degree of fulfillment (membership degrees) of each condition, consider the minimum of these as the "firing strength" of the given rule, and then this "intersects" the output fuzzy set. Finally, the output set recommended by all rules is aggregated (combined), and a defuzzification procedure (e.g. weighted average, centroid method) is used to calculate the crisp output value. This resulting value will be the recommended spray solution quantity multiplier (or percentage) compared to the standard dose.

$$\mu(\omega_i) = max\left(min\left(\frac{\omega_i - a}{b - a}, \frac{c - \omega_i}{c - b}\right), 0\right)$$

Where:
– ω_i: the current value of the indicator under examination,
– a: the lower value of the triangular function (the value from which the membership of the given category begins to increase),
– b: the peak value of the triangular function (the value at which the degree of belonging to the category is maximum, the value is 1),
– c: the upper value of the triangular function (the value above which membership in the category decreases and then ceases).

For example, suppose that in a given situation the phenological phase of the plant is a transition between "early" and "mid-term" (say, with partial membership in both), and the coverage is 50%, which is on the border of the "medium" and "dense" categories. Then several rules come into effect simultaneously, with different strengths. One rule (early + medium -> medium dose) and another (medium + dense -> high dose) are both "active", for example. The resulting fuzzy output set will accordingly be the union of the partial activations of the "medium" and "high" dose sets. After defuzzification, a weighting factor of 0.7 (i.e. 70% of the normal dose) may be suggested. Thus, the system will proportionally reduce the spray dose in this situation.

Practical application on a cotton plantation
We implemented the above fuzzy weighting system on a 50-hectare cotton plantation during the growing season. The area was sprayed with insecticide three times during the season: in the early vegetative stage, at the beginning of flowering, and at the time of boll formation. Each time, the phenological state of the plants and the canopy coverage ratio were recorded, and then the fuzzy system made recommendations for the amount of spray solution based on these. The recommendations were compared with the fixed 100 l/ha spray solution rate according to traditional practice.
– First spray (early stage): In the 4th week after sowing, the cotton was 15-20 cm tall, with few leaves. The coverage rate was estimated at 15% (very sparse). The plant fell into the early phenological category. According to the rules of the fuzzy system, this combination means low plant cover and

early stage, which justifies the application of a low dose. The defuzzified recommendation became a multiplier of 0.3, i.e. the system recommended the application of only 30 l/ha of spray solution. Accordingly, the actual spray solution volume was set to 30 liters/ha. This is only 30% of the traditional 100 l/ha dose, i.e. we achieved significant savings. After the treatment, the pests (aphids) were reduced, we did not experience any signs of insufficient protection, so the lower dose proved to be sufficient in this early stand.

– Second spray (flowering): Approximately 8-9 weeks after sowing, the cotton was at the beginning of flowering. Due to the rapid growth of the plants, the coverage was then around 60% (the border of the medium-dense category). The phenological phase corresponded to the "medium" category. Several relevant rules of the fuzzy system came into play (e.g. "if medium AND medium, then medium dose" and "if medium AND dense, then high dose"). The output recommendation finally became a weighting factor of 0.75, i.e. it recommended the application of 75 l/ha of spray solution. This represented a 25% reduction compared to the standard 100 l/ha. After spraying, the pest infestation (bollworm larval damage) remained low, the fruit setting was adequate, so the reduced dose did not reduce the effectiveness of the control.

– Third spray (crop formation): Towards the end of the growing season, 12-13 weeks after sowing, the cotton was in the boll maturation phase. The canopy was almost completely closed by then, the coverage was approaching 90% (very dense category). At the same time, the plant was phenologically "late", approaching maturity. According to the rules, the combination of dense foliage and late phase justified a high or very high dose. The system gave a multiplier of 0.95, so it recommended the application of 95 l/ha of spray solution. We decided to round this up to 100 l/ha, as the difference is small. At this late stage, pest pressure usually decreases, but good coverage was important due to the entire leaf surface. The control was effective and we did not waste unnecessary excessive amounts of chemical.

It can be seen that in the early stages the system allowed for a drastic dose reduction without any loss of control. Later, when the foliage thickened, the recommended amount approached the normal amount. Overall, we used about 30-35% less pesticide during the season than we would have applied according to traditional practice. This represented a significant cost saving, while the yield and health of the cotton did not deteriorate compared to the control (traditionally sprayed) plots. It is important to note that the report provided by the fuzzy system recorded the current parameters (phase, coverage), the recommended and applied dose, and the expected savings after

each spraying. For example, after the first treatment, the report highlighted that the coverage was only 15%, so the system recommended a 70% chemical saving, which was achieved. Such feedback helps the farmer understand that the control was effective even with reduced doses. The report also included recommendations for the next period (e.g. "monitor pest traps in the next 2 weeks, during flowering it is expected that the dose will need to be increased for full protection"). The savings and efficiency achieved by using the fuzzy weighting system are also consistent with the experience of other research. For example, in a similar experiment with variable rate spraying based on foliage cover, up to 75% less agrochemicals were used in sparsely vegetated areas compared to a uniform treatment. This indicates that the method can bring significant resource savings not only in theory but also in practice.

CONCLUSIONS

The results of the case study show that the efficiency of chemical use was improved by spraying weighting based on fuzzy logic. By using the system, the amount of spray agent required in cotton was flexibly adjusted to the current plant condition. Where and when the full dose was not needed, the system automatically recommended a smaller one, thus reducing the effort. At the same time, during critical periods (e.g. flowering, with intense pest risk), almost the full amount was applied, so the safety of plant protection was not compromised. It should be emphasized that during the season, the pest infestation and yield of the control plot (which received a dose of 100 l/ha each time) and the plots treated with the fuzzy system were practically the same. This proves that the reduced amount of spray agent did not impair the effectiveness of the protection. However, the reduction in pesticide use brought direct cost savings for the producer (30% savings in proportion to the amount of insecticide used), and the amount of chemicals released into the environment also decreased. The latter contributes to more sustainable farming and environmental protection. The decision-support role of the fuzzy system is also important; the reports available to the company after spraying clearly showed why the dose could be reduced for which treatments, and where it was justified to use almost the full dose. This information increases confidence in the system and helps the farmer in planning subsequent seasons. Furthermore, the fuzzy model can be easily customized for other circumstances or even other crops, only the membership functions and rules need to be modified in light of the new situations.

Of course, like all models, this system works best when provided with reliable input data. The growth phase was determined based on calendar and phenological observations. With

Table 1. Spraying process summary data

Spraying timing	Growth phase (phenology)	Coverage (%)	Conventional dosage (l/ha)	Fuzzy recommendation (l/ha)	Chemical savings
Early vegetative (week 4)	Early (seedling stage)	15% (very rare)	100 l/ha	30 l/ha (~0.3x)	70% less
Start of flowering (week 9)	Middle-aged (flourishing)	60% (medium/thick)	100 l/ha	75 l/ha (~0.75x)	25% less
Crop production (week 13)	Late (maturing)	90% (very dense)	100 l/ha	95 l/ha (~0.95x)	5% less

Source: Own editing based on own research

the development of technology, the field can even be monitored with real-time sensors (cameras, density meters), so the fuzzy system can automatically provide fresh recommendations to control the sprayer.

The presented case study showed that a fuzzy logic weighting system can be successfully applied to optimize the cotton spraying process. Spraying decisions based on the plant growth phase and canopy coverage ratio made the application of chemicals more economical, while the effectiveness of crop protection was not reduced. The 5 categories defined by triangular membership functions allowed the incorporation of expert experience into the system, and the rule base was used to generate fine-tuned, stepwise dosing recommendations instead of traditional yes/no decisions. According to the results, the method not only works in theory, but also provides significant savings and benefits in practice. Reducing chemical use improves cost-effectiveness and reduces pressure on the environment. All this is an important step towards precision farming, where data-driven, intelligent decision support systems help farmers. The spraying weighting system based on fuzzy logic can be further developed by including additional parameters (e.g. weather, soil moisture, pest monitoring data) and can be adapted to plant protection procedures for other crops.

References

AZFAR, S. – NADEEM, A. – AHSAN, K. – MEHMOOD, A. – SIDDIQUI, MS, SAEED, M. & ASHRAF, M. (2023): An IoT-Based System for Efficient Detection of Cotton Pest. *Applied Sciences, 13*(5), 2921.

BHAD PR. (2022): Biopesticides use on cotton and their harmful effects on human health & environment. *International Journal of Clinical Microbiology and Biochemical Technology*, 5(1), 005-008.

DEGUINE, J.-P. – AUBERTOT, J.-N. – FLOR, RJ. – LESCOURRET, F. – WYCKHUYS, KAG, & RATNADASS, A. (2021): Integrated pest management: good intentions, hard realities. The review. *Agronomy for Sustainable Development, 41(3)*, 38.

GARCÍA-MUNGUÍA, AM – FICARRA, G. – DE LA HOZ, JT, & ACEVEDO-URREA, WA (2024): A Review of Agricultural Crop Spraying Drones: Operation Processes, Key Technologies and Current Challenges. *Drones, 8*(11), 687.

JIAO, Y. – ZHANG, S. – JIN, Y. – CUI, L. – CHANG, C. – DING, S. – SUN, Z. & XUE, X. (2025): Research Progress on Intelligent Variable-Rate Spray Technology for Precision Agriculture. *Agronomy, 15*(6), 1431.

LAMM, RD – SLAUGHTER, DC & GILES, DK (2002): Precision weed control system for cotton. *Transactions of the ASAE, 45*(1), pp. 231–238.

LEE, TY – REZA, MN – CHUNG, SO– KIM, DU– LEE, SY & CHOI, DH (2023): Application of fuzzy logics for smart agriculture: A review. *Precision Agriculture Science and Technology, 5*(1), pp. 1–14.

LI, B. – SHAHZAD, M. – KHAN, H. – BASHIR, MM – ULLAH, A. & SIDDIQUE, M. (2023): Sustainable Smart Agriculture Farming for Cotton Crop: A Fuzzy Logic Rule Based Methodology. *Sustainability, 15*(18), 13874.

LIU, X. – LIU, Y. – CHEN, X. – WAN, Y. – GAO, D. & CAO, P. (2025): LiDAR-Assisted UAV Variable-Rate Spraying System. *Agriculture, 15*(16), 1782.

LUO, Y. – HE, X. – SHI, H. – YANG, SX – SONG, L. & LI, P. (2025): Design and Development of a Precision Spraying Control System for Orchards Based on Machine Vision Detection. *Sensors, 25*(12), 3799.

SCHUTZ, DR – MERCALDI, HV – GAMBOA PEÑALOZA, EA– SILVA, LJR– OLIVEIRA, VA & CRUVINEL, PE (2024): Advanced embedded generalized predictive controller based on fuzzy gain scheduling for agricultural sprayers with dead zone nonlinearities. *Journal of Process Control, 135*, 103164.

SHI, Y. – ZHANG, C. – LIANG, A. & YUAN, H. (2007): Fuzzy control of the spraying medicine control system. In *Computer and Computing Technologies in Agriculture, Volume II (CCTA 2007)* (pp. 1087–1094). Springer, Boston, MA.

SONG, L. – HUANG, J. – LIANG, X. – YANG, SX – HU, W. & TANG, D. (2020): An Intelligent Multi-Sensor Variable Spray System with Chaotic Optimization and Adaptive Fuzzy Control. *Sensors, 20*(10), 2954.

TASEER, A. & HAN, X. (2024): Advances in variable rate spraying for precise spray requirements in precision agriculture using unmanned aerial spraying systems: A review. *Computers and Electronics in Agriculture, 219*, 108841.

TUDI, M. – DANIEL RUAN, H. – WANG, L. – LYU, J. – SADLER, R. – CONNELL, D. – CHU, C. & PHUNG, D. T. (2021): Agriculture development, pesticide application and its impact on the environment. *International Journal of Environmental Research and Public Health, 18*(3), 1112.

YADAV, SK (2010): Pesticide applications – threat to ecosystems. *Journal of Human Ecology, 32*(1), pp. 37–45.

ZHENG, J. & XU, Y. (2023): A review: Development of plant protection methods and advances in pesticide application technology in agro-forestry production. *Agriculture, 13*(11), 2165.