JURNAL TEKNIK SIPIL DAN LINGKUNGAN| EISSN:2549-1407
https://jurnal.ipb.ac.id/index.php/jsil

Vol. 10 No. 01 April 2025
DOI: 10.29244/jsil.10.1.169-178

Development of an Irrigation System Optimization Model for Rice Cultivation Using Fine Bubble Technology Based on Genetic Algorithms

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Abstract: Irrigation systems play a crucial role in enhancing rice production. However, determining the optimal method for irrigation system optimization using conventional approaches is often challenging. This study aims to identify the optimal irrigation system represented by the water table level using a Genetic Algorithm (GA) model. The GA model was chosen for its advantages in addressing non-linear problems and finding global solutions without being trapped in local optima. The model was developed based on a laboratory-scale rice cultivation experiment involving four water table treatments: 0–7 cm with oxygen enrichment via Fine Bubble Technology (TA1), 4–7 cm (TA2), –5 to 0 cm (TA3), and 2–4 cm (TA4) above the soil surface. The research was conducted from February to June 2024 at Kinjiro Farm, Bogor City. The four treatments produced varying yields, with TA 2 achieving the highest yield of 6.86 tons/ha, followed by TA1 (5.35 tons/ha), TA3 (5.00 tons/ha), and TA4 (4.80 tons/ha). Based on these data, the GA model successfully identified the optimal water table level of 3.5 cm above the soil surface, which could increase production to 7.40 tons/ha. This water level represents a moderate irrigation depth, requiring a medium level of irrigation compared to the four tested treatments perlakuan.

Keywords: Genetic Algorithms; identification; irrigation system; optimization; paddy fields

Submitted: 06 Feb 2025
Revised: 05 Apr 2025
Accepted: 21 Apr 2025

1. Introduction

Rice serves as a primary carbohydrate source for approximately 50% of the global population. In Indonesia, more than 95% of the population consumes rice as a staple food, thus requiring continuous production increases to meet the growing demand driven by population growth [1]. The country's topography, which ranges from 0 to 1000 meters above sea level, enables agricultural activities to be carried out across nearly all regions of Indonesia [2]. In light of this, efforts are needed to maintain the availability of rice in the market while also improving the quality of domestically produced rice [3].

With advancements in technology, the modernization of irrigation systems has become a key focus in enhancing agricultural efficiency and productivity. One such initiative by the Ministry of Agriculture of the Republic of Indonesia is the pompanisasi (pump irrigation) program. This program aims to ensure an adequate water supply for agricultural lands through the use of efficient water pumps integrated into existing irrigation systems. In line with efforts to improve rice paddy productivity and leverage this pump irrigation initiative, the adoption of emerging technologies such as Fine Bubble Technology (FBT) is showing promising potential in the agricultural sector. FBT employs micro- or nano-sized bubbles to enhance physical and chemical processes in water. Its application in rice cultivation has been proven to improve nutrient absorption efficiency, soil conditions, and oxygen solubility in water—an essential factor for plant health [4].

In addition to nutrient management, water availability must also be optimized to support optimal plant growth. Crop water requirement refers to the amount of water needed to compensate for losses due to evapotranspiration [5]. Determining the optimal irrigation system is often challenging due to the complexity and dynamic nature of plant–environment interactions. The Genetic Algorithm (GA) is an alternative optimization model capable of solving complex problems efficiently [6]. GA can handle non-linear problems, find global optima without getting trapped in local minima, and is flexible in dealing with varying parameters. Therefore, this study aims to optimize the irrigation system for rice paddy cultivation using a GA model based on experimental data involving various water level treatments, including the application of Fine Bubble Technology.

2. Methodology

This research was conducted from February to June 2024 at Kinjiro Farm, located at Jl. Hegarmanah IV, Gunung Batu, West Bogor District, Bogor City, Indonesia.

2.1. Materials

The materials used in this study included compost soil, rice seeds, and irrigation water. The equipment consisted of four 125-liter water tanks, PVC pipes and connectors, four water faucets, one fine bubble generator, a dissolved oxygen (DO) meter, a water pump, sheet pipes, and four water meters. Environmental parameter measurement tools included an Automatic Weather Station (AWS), an EM50 data logger, and GS-3 sensors capable of measuring soil moisture, soil temperature, and electrical conductivity (EC).

2.2. Experimental Procedures

2.2.1. Irrigation system set up

The experiment was conducted on a laboratory scale using four plots, each measuring 2 m × 2 m. Soil cleaning and preparation were performed before planting to remove debris and weeds that could hinder plant growth. The GA optimization model was developed based on four irrigation system scenarios as follows:

a) **Treatment 1 (TA1):** An irrigation system with a water level of 0–7 cm above the soil surface, enhanced with a fine bubble generator and sub-surface water distribution via sheet pipes. The Fine Bubble Technology (FBT) was applied starting at 28 days after planting (DAP).
b) **Treatment 2 (TA2):** An irrigation system with a water level of 4–7 cm above the soil surface.
c) **Treatment 3 (TA3):** A sub-surface irrigation system with a water level of –5 to 0 cm below the soil surface, using sheet pipes for water delivery.
d) **Treatment 4 (TA4):** A surface irrigation system with a water level of 2–4 cm above the soil surface, serving as the control treatment typically used by local farmers

The irrigation water source was supplied from individual storage tanks for each plot. Water was distributed through pipes according to each irrigation method. For surface irrigation, a container (bucket) was embedded into the soil to measure water levels, while for sub-surface irrigation, sheet pipes were used to regulate water levels. An illustration of the irrigation system setup is shown in **Figure 1**.

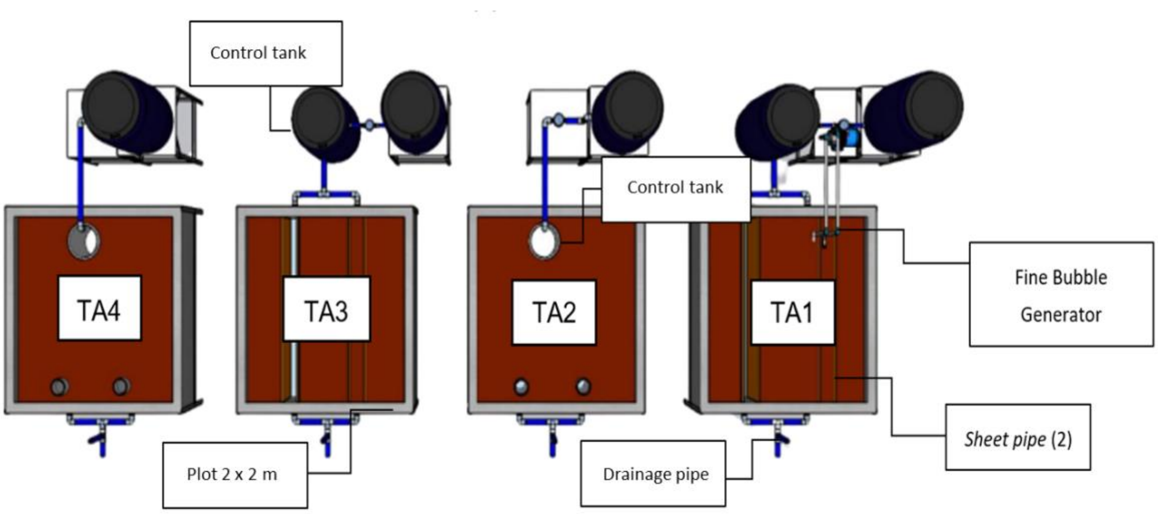

Figure 1. Irrigation system set up in this experiments

2.2.2. Rice cultivation

The rice variety used in this study was IPB 3S. IPB 3S is a high-yield rice variety with a potential harvest of up to 11.2 tons/ha. It has been cultivated in various regions across Java, Sumatra, Sulawesi, and Kalimantan [7]. The initial step in seed preparation involved soaking the seeds in water. Floating seeds were discarded, while viable (sunken) seeds were left to soak for 24 hours. After soaking, the seeds were transferred to a seedling tray containing soil as the growing medium.

Seedlings were grown for 15 days before being transplanted to the main plots. Transplanting was carried out with a spacing of 20 cm × 20 cm, placing one seedling per planting hole. Each seedling was planted with its roots positioned in an L-shape to optimize anchorage and growth. The rice plants were harvested at approximately 112 days of age, or when around 90% of the grains had turned yellow and dried. During the growth period, crop maintenance included fertilization and weed control to ensure optimal plant development. The first fertilization was conducted at 7 days after transplanting, the second at 21 days, and the third at 35 days. Pest control was performed through periodic pesticide spraying. At harvest, rice yield was measured and converted into tons per hectare (ton/ha) for analysis.

2.2.3. Data collection

The data used in the initial data processing stage were obtained through direct field measurements. This primary data included information on water levels across the different irrigation systems, water meter readings, and measurements recorded by the sensors previously described. Data generated from these sensors were accessed using the ECH2O Utility application via a laptop connected to the sensors through the EM50 data logger. In addition to these data, supplementary information related to rice plant growth parameters—such as plant height, number of leaves, and post-harvest weight—was also recorded for analysis.

2.2.4. Data Processing

The data obtained from sensors and daily manual measurements were then processed to determine the crop water requirements. Optimal irrigation management can be achieved by identifying the value of evapotranspiration. The actual crop evapotranspiration (ETa) was calculated using the Solver tool in Microsoft Excel based on the water balance equations, as shown in **Equations (1) - (2)**.

$$\Delta WL = WL_i - WL_{i-1} \quad (1)$$

i : Days after plantin1, 2, 3…..etc.

ΔWL : the difference of water level (cm)

WL_i : Water level on day-i (cm)
WL_{i-1} : Water level one day before (i-1) (cm)

$$\Delta WL = (I + R) - (ETa + Dr) \quad (2)$$

I : Irrigation (mm)
R : Precipitation (mm)
ETa : Actual evapotranspiration (mm)
Dr : Drainage (mm)

In the process of determining ETa, the initial ETa value was based on crop evapotranspiration (ETc). The initial crop coefficient (Kc) values used were obtained from previous studies [8]. ETc was calculated using the following **Equation (3).**

$$ETc = Kc \times ETpH \quad (3)$$

ETc : Crop evapotranspiration (mm/day)
Kc : Crop coefficient
$ETpH$: Reference evapotranspiration by Hagreaves model (mm/day)

Reference evapotranspiration provides an estimate of the rate of water evaporation from a crop under specific climatic conditions, assuming sufficient soil water availability [9]. In this study, reference evapotranspiration (ETpH) was calculated using **Equation (4)** as follow:

$$ETpH = 0.0135(T_{mean} + 17.78)R_s(\frac{238.8}{595.5 - 0.55T_{mean}}) \quad (4)$$

$ETpH$: Reference evapotranspiration by hargreaves model (mm/day)
T_{mean} : average air temperature (^{O}C)
R_s : Solar radiation (MJ/m^2/day)

2.2.5. Developing optimization model by GA

Before developing the optimization model, an identification model was first developed using an Artificial Neural Network (ANN) with a backpropagation algorithm to predict crop production based on each irrigation system. The ANN model consists of three layers: the input layer, hidden layer, and output layer. Each layer is connected by weights. The data on water level height and plant height from the previous day serve as inputs to the input layer, which is then linked to production as the output layer. The ANN modeling scheme is shown in **Figure 2**, and the notation for the functions used is as follows:

$$Y = f(WL, CH_{i-1}) \quad (5)$$

i : Day 1,2,3,….etc.
Y : rice yield (ton/ha)
WL_i : water level on day-i (cm)
CH_{i-1} : Plant height one day before (cm)

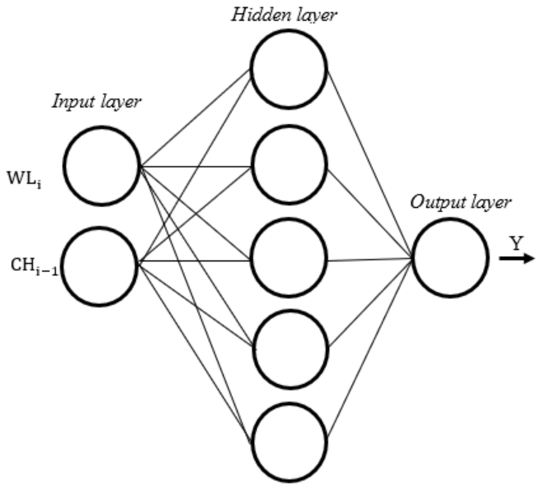

Figure 2. Artificial neural networks model to predict rice yield

The Genetic Algorithm (GA) model was then developed to optimize crop production, specifically rice grain yield (Yi). In this optimization process, the optimal value is derived from potential solutions known as the population. A group of solutions within a population is referred to as a chromosome. The process begins with the random initialization of the population as the initial step in generation. Next, the best population is selected through fitness value selection. Subsequent stages, including crossover, mutation, and sorting, are carried out as final steps to obtain the optimal value, which is represented as a generation through a series of iterations. The fitness value refers to the objective function (F) as **Equations (6) – (8)**.

$$F = Y_i \tag{6}$$

With constraint:

$$\mathrm{WL}_{\min} \leq WL \leq \mathrm{WL}_{\max} \tag{7}$$

$$CH_{i-1}{}_{\min} \leq CH_{i-1} \leq CH_{i-1}{}_{\max} \tag{8}$$

Where;

F : Objective function

Y_i : Rice yied (ton/ha)

3. Results and Discussion

3.1. Environmental condition during planting season

During the growing season, rainfall was highly dynamic on a daily basis. The precipitation data for 104 days after planting (DAP) are presented in Table 1 on weekly basis.

Table 1. Weekly precipitation data during planting season

WAP	Precipitation data (mm)		
	Minimum	Maximum	Average
1	0	31.80	8.34
2	2.8	31.60	10.71
3	0	3.80	0.63
4	0	50.80	19.80
5	0	14.21	4.77
6	0	12.69	2.28
7	0	13.13	4.49
8	0	22.85	10.52
9	0	22.09	8.01
10	0	1.27	0.22
11	0	137.16	19.59
12	0	0.00	0.00
13	0	55.62	13.46
14	0	28.44	8.27
15	0	87.00	28.33

The average rainfall during the growing season was 9.11 mm/day, with a maximum daily rainfall of 137.16 mm on the 11th MST. For rice plants, the minimum water requirement is 200-300 mm per month [10]. High rainfall accompanied by strong winds can dissolve fertilizers, thus reducing the nitrogen content in the soil. The average daily air temperature during the growing period was 27.32°C, with a maximum average temperature of 33.55°C and a minimum average temperature of 23.95°C. The optimal relative humidity (RH) for rice growth is between 80-85%, while during the flowering stage, it is between 70-80%. During the growing period, the relative humidity ranged from 75-90%. According to previous studies, the optimal temperature for rice growth in tropical regions is around 20-30°C [11]. Based on these conditions, the average daily temperature and relative humidity during the growing period still met the standards that allow for optimal growth of rice.

Solar radiation is an important parameter in the metabolism of chlorophyll-containing plants, and therefore, rice production is greatly influenced by the availability of sunlight. In addition to increasing the rate of photosynthesis, higher solar radiation generally accelerates the flowering and fruiting processes; conversely, a decrease in solar radiation intensity will extend the plant growth period [12]. During the growing period, the solar radiation values ranged from 1.39 to 15.86 MJ/m²/day, with an average daily solar radiation of 9.55 MJ/m²/day.

3.2. Performance of irrigation treatments

Irrigation measurements used for crop growth in each treatment (TA) were carried out from the time of rice transplanting until 103 days after transplanting (DAP). Based on the research conducted, it was found that subsurface irrigation was more water-efficient compared to surface irrigation. The total irrigation applied during 103 DAP for TA1 through TA4 was 84.6 mm, 189.9 mm, 35.5 mm, and 113.4 mm, respectively. Throughout the growth period, there were frequent fluctuations in irrigation needs, which were influenced by weather factors, particularly solar radiation and rainfall. When rainfall was high, the water level height increased. This excess water was either absorbed by the plants, evaporated due to solar radiation, or drained away through the drainage system.

Irrigation should be adjusted according to the actual evapotranspiration values to ensure that the plants receive an adequate water supply to meet their needs. However, as shown in **Figure 3**, it can be observed that the irrigation values were lower compared to the actual evapotranspiration values. This was due to the high rainfall, which caused water to accumulate on the land, thereby reducing the need for irrigation. The plants met their water requirements from the rainwater that was collected on the field.

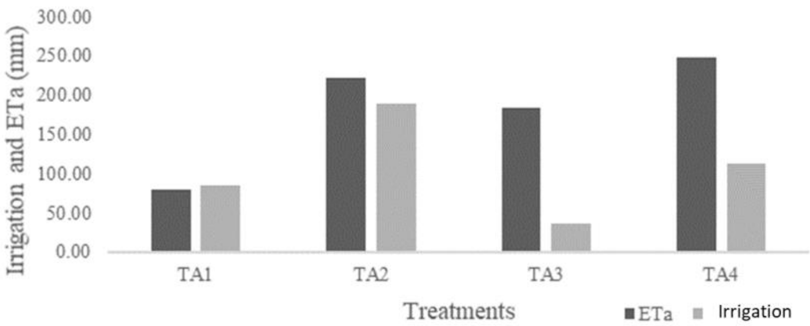

Figure 3. Irrigaton and ETa during the planting season

Table 2 shows the crop production from the four irrigation systems. The rice variety IPB 3S has a high yield potential, ranging from 7 to 11.2 tons per hectare under optimal conditions [13]. Unfortunately, this potential was not fully realized in this experiment. The number of rice grains per hill is one of the indicators used to evaluate the productivity of rice plants. Based on the observations, the number of grains per hill varied among the different irrigation treatments. TA2 produced the highest number of grains per hill, followed by TA1, TA3, and TA4. This result aligns with the total grain yield per hectare, where TA2 also showed the highest productivity. A higher number of grains per hill generally reflects better nutrient uptake and more favourable growing conditions. In addition, Based on the rice yield, TA2 produced the highest yield, with 6.86 tons/ha, followed by TA1 with 5.35 tons/ha, TA3 with 5 tons/ha, and TA4 with 4.80 tons/ha. Based on these results, TA2, with a water level height of 4-7 cm, produced the highest yield.

Table 2. Rice production during planting season

Treatments	Weight per hill (g)	Weight of panicles (g)	Number of grains per hill	Number of Filled Grains per Hill	Weight of 1000 Grain	Rice yield (ton/ha)
TA1	2660	610	22,798	17,561	30.8	5.35
TA2	2920	645	32,914	29,130	32.0	6.86
TA3	1225	500	17,463	14,201	30.7	5.00
TA4	1645	595	20,154	17,078	32.8	4.80

3.3. Performance of FBT

Fine Bubble Technology (FBT) is a technology that produces bubbles with a larger surface area compared to ordinary air bubbles. This larger surface area can help enhance plant absorption, thereby promoting more optimal plant growth [14]. The use of FBT in agriculture has previously been studied in the cultivation of melons, myoga ginger, tomatoes, and spinach.

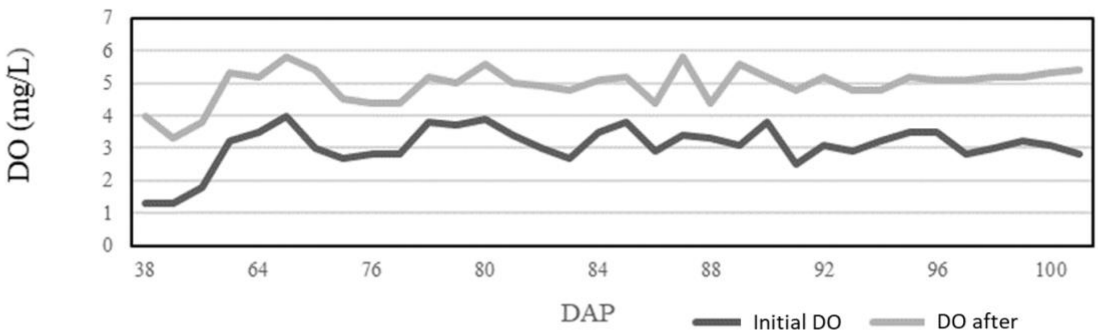

Figure 4. Increasing of DO after FBT application

Based on **Figure 4**, the maximum dissolved oxygen (DO) level reached 6.6 mg/L, showing an increase of 43.48% from the initial DO level after aeration with Fine Bubble Technology (FBT) for one hour. This demonstrates that FBT can significantly increase the DO level in rice paddy fields. Unfortunately, the rice production achieved did not surpass that of the system without FBT in TA2. This indicates that the installation of the fine bubble device in this study was not optimal. Several factors may have reduced the effectiveness of the fine bubble technology in promoting rice growth in this study, including the delayed installation of the fine bubble system. The installation was done at the end of the active vegetative phase, when water absorption had already begun to decrease. There was also a lack of DO measurement points, making it unclear whether the increase in DO was evenly distributed across the plot. Additionally, high rainfall could have affected the dissolved oxygen levels.

3.4. ANN model to predict rice yield

The Artificial Neural Network (ANN) algorithm used a learning rate (alpha) of 0.9 and was iterated 5000 times. The learning rate determines the speed of training until the system reaches an optimal state [15]. Based on **Figure 5**, it is evident that the comparison between the field measurement results and the ANN model measurements has a coefficient of determination value of $R^2 > 0.9$, or more precisely 0.9979. The closer the R^2 value is to 1, the stronger the relationship between the linked parameters is identified. Based on this, it can be concluded that the previous values of water table height and plant height can influence the resulting crop production, thus allowing the optimization process to proceed.

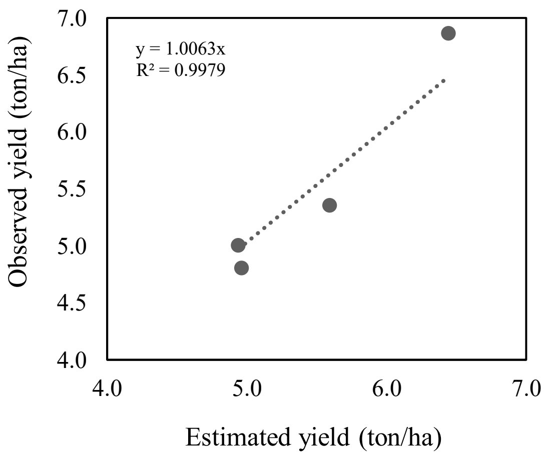

Figure 5. Validation of the ANN model

3.5 Optimization by the GA model

Optimization is the process of selecting a solution from several alternative solutions, subject to certain constraints. Genetic Algorithm (GA) performs a search by mimicking the process of natural biological evolution to determine high-quality chromosomes or individuals within a population. The selection process of individuals is evaluated based on the fitness function [16]. The optimal value is obtained by finding the highest fitness value achievable. The optimization results of the GA model over 100 generations are shown in **Figure 6**. The fitness value reaches a convergent value at generation 5. From generation 5 to generation 100, the fitness value stabilized at 7.404. Based on the identification and optimization performed, the optimal water table height for rice growth is 3.52 cm, resulting in a harvest yield of 7.40 tons/ha, which corresponds to an increase in rice production in TA 1 through TA 4 by 28.9%, 9.8%, 32.4%, and 35.0%, respectively.

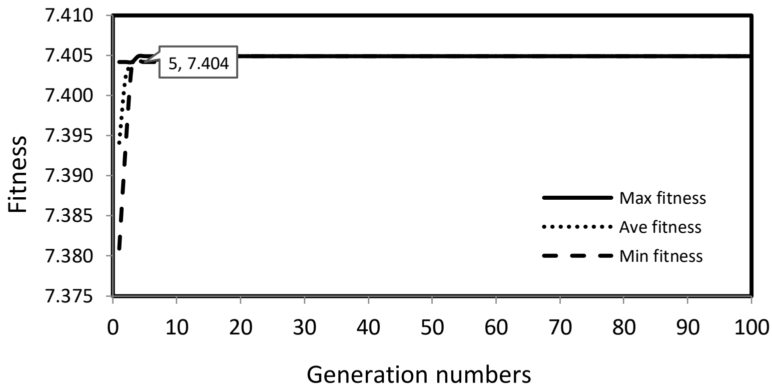

Figure 6. Fitness of GA model in each generation

4. Conclusion

Based on observations made during 103 DAP, the subsurface irrigation system required less total irrigation compared to the surface irrigation system. The total irrigation required for TA1 through TA4 were 84.6 mm, 189.9 mm, 35.5 mm, and 113.4 mm, respectively. However, the surface irrigation system resulted in better harvest yields compared to the subsurface irrigation system. The rice yield obtained at 104 DAP for TA1 through TA4 were 5.35 tons/ha, 6.86 tons/ha, 5 tons/ha, and 4.80 tons/ha, respectively. TA2 provided the highest yield. Based on observations, Fine Bubble Technology (FBT) was able to increase the dissolved oxygen (DO) content in the land of TA1 by up to 43.48%. However, this technology did not show a significant impact on rice production. The Genetic Algorithm (GA) optimization process resulted in an optimal rice yield of 7.40 tons/ha with an optimal water table height of 3.5 cm above the soil surface. This optimization led to an increase in rice production in TA 1 through TA 4 by 28.9%, 9.8%, 32.4%, and 35.0%, respectively.

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