

Application of Unpowered Automatic Fertigator for Aquaculture and Horticulture

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Abstract: The clean water crisis and the increasing scarcity of agricultural land pose significant challenges to food security. However, household yard areas, when managed productively, have the potential to contribute to family-level food production. The *Powerless Automatic Fertigator* (FONi) is an appropriate technology that has been shown to enhance productivity and facilitate various horticultural cultivation practices. This study integrates aquaculture and horticulture using the FONi system (referred to as *FONi Minahorticulture*) with the following objectives: (1) to develop the system design and evaluate its performance; (2) to assess the production of fish and vegetables; and (3) to analyze land and water productivity. The experiment was conducted over a two-month period in a trial garden using a fish pond connected to 30 downstream planting pots. The water level in each pot was maintained at approximately 10 cm below the soil surface. Plant growth was measured weekly and monitored using CCTV. The results demonstrate that the FONi Minahorti model achieved a fish (grass carp) growth rate of 73% with a survival rate of 100%. Land and water productivity for red spinach were 7.67 g/m² and 8.77 g/L, respectively, while for green spinach they reached 10.08 g/m² and 11.53 g/L, respectively. The crop coefficient (Kc) for both spinach varieties during the growth period ranged from 0.40 to 0.71. These findings indicate that the FONi Minahorti system is a viable approach for enhancing yard productivity by simultaneously producing fish and vegetables to support daily household needs.

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1. Introduction

The water crisis has become a critical challenge facing the agricultural sector today [1]. Insufficient water availability significantly affects plant morphology and physiology, leading to reduced growth and yield [2]. Globally, more than 2 billion people still lack adequate access to clean water. This crisis directly impacts household needs, agricultural production, and other essential sectors [3]. As reported by Yolanda and Rajib [3], the consequences include crop failure, disrupted food availability, poor sanitation, and increased risks of hunger, which may lead to food-related diseases and malnutrition.

One strategy to enhance food self-sufficiency is the utilization of household yards [4]. Yard areas have significant potential to support family-level food production and are commonly used to meet daily food needs [5]. Among horticultural crops, spinach is frequently cultivated due to its short growth cycle (21–30 days after planting) and ease of cultivation under local

farming conditions in Indonesia [6]. In fact, food crops are more widely grown in yards than non-food crops [7].

To address the dynamic challenges in agriculture, irrigation systems continue to evolve. Subsurface irrigation, in particular, is increasingly being adopted in urban agriculture due to its advantages in water-use efficiency, automation capability, and environmentally friendly operation. However, irrigation systems still face several technical challenges, including high evaporation losses, low root water uptake efficiency, excessive percolation, and uneven water distribution, all of which contribute to water inefficiency.

Subsurface irrigation systems utilize capillary soil movement to deliver water directly to the root zone [8]. This approach minimizes water loss due to evaporation and surface runoff, making it highly suitable for water-scarce environments. One such technology developed by the Bogor Agricultural Institute is the FONi system (gravity-driven automatic fertigator).

The fertigation system enables efficient water management through controlled, automated, timely, and precise water application. It is flexible and suitable for small-scale dryland agriculture. The implementation of such systems supports sustainable, environmentally friendly, and cost-effective agricultural practices [9]. Moreover, automation contributes to improvements in productivity, product quality, energy efficiency, and water resource conservation [10].

This study aims to integrate aquaculture and horticulture using the FONi system (FONi Mina-horticulture) with the following objectives: (1) to develop the system design and evaluate its performance; (2) to assess fish and vegetable production; and (3) to determine land and water productivity. The experiment was conducted over a two-month period in a pilot garden using a fishpond connected to 30 downstream planting pots.

2. Methodology

This study was conducted at the Integrated Laboratory, Department of Civil and Environmental Engineering, Faculty of Engineering and Technology, Bogor Agricultural University, located at Jl. Tanjung No. 21, Babakan, Dramaga District, Bogor Regency, West Java (6°33'25" S; 106°43'44" E). The experiment was carried out over a six-month period from July to December 2025.

2.1. Tools and Materials

The equipment used in this study included a pipe-based irrigation system, an Automatic Weather Station (AWS), a water meter, and a laptop for data processing. The materials consisted of grass carp (*Ctenopharyngodon idella*) fingerlings, green spinach and red spinach seeds, and a planting medium composed of a mixture of rice husk charcoal and organic matter, supplemented with Provbio organic fertilizer. The planting medium was placed in polybags positioned inside rubber buckets with dimensions of 32 cm in upper diameter, 24 cm in lower diameter, and 31 cm in height. In the FONi system, the series of buckets were interconnected using 1/2-inch PVC pipes

2.2. Research Procedures

The study was initiated with a literature review, problem identification, and experimental preparation. Subsequently, field measurements were conducted to determine the available land area and to specify the irrigation system requirements. Secondary data on environmental variables, including rainfall, temperature, humidity, solar radiation, and wind speed, were also collected. The research then proceeded with the installation of the FONi Mina-horticulture system, consisting of one fish pond and 30 planting pots, followed by system performance testing. Finally, data were collected and analyzed to evaluate system effectiveness.

2.2.1 Design of Unpowered Automatic Fertigator (FONi)

Figure 1 illustrates the design of the FONi Mina-horticulture system. The system comprises 30 planting pots arranged in series and interconnecte ½ inch PVC pipes, which are connected to a water level control unit and the main water source. The first tank (drum) functions as a fish pond for grass carp,

while the second tank serves as an intermediate water storage unit prior to distribution to the planting pots containing green and red spinach. An automatic float valve is installed to regulate the water level within the system. In addition, a stop valve and water meters are used to measure the inflow (irrigation) and outflow (drainage) water volumes. Water flows sequentially from the fish pond to the second tank (capacity: 60 L), then to the control tank, where the water level can be adjusted as required. Subsequently, water is distributed to the planting pots. The automatic float mechanism maintains a constant water level to ensure that plant water requirements are consistently met.

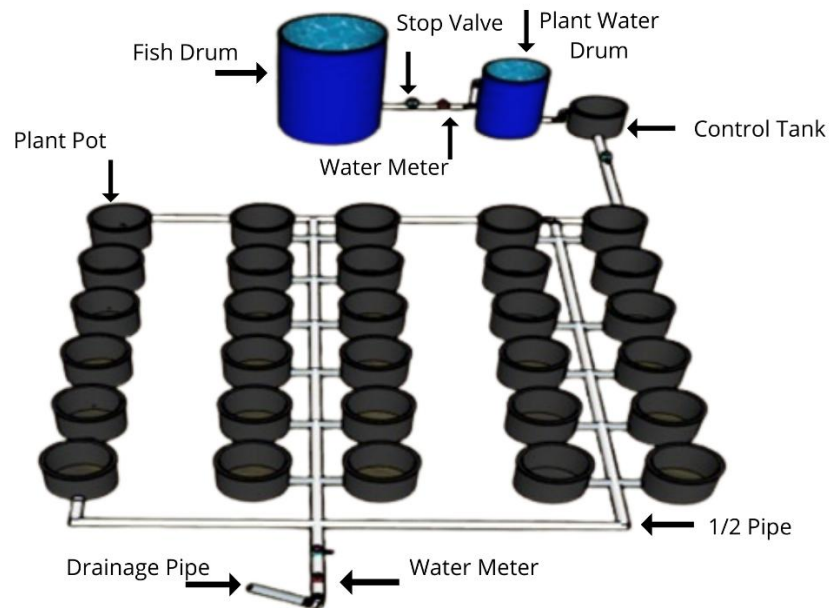


Figure 1. FONi Design for mina-horticulturae

2.2.2 Irrigation System Performance Test

The irrigation system performance test was conducted to evaluate the ability of the system to operate effectively in delivering water according to plant requirements. The evaluation focused on key performance indicators, including water distribution efficiency, irrigation uniformity, and plant response to water application. This assessment aimed to determine whether the system could maintain a stable and efficient water supply within the root zone.

The performance test was carried out by integrating aquaculture (grass carp) and horticultural crops (spinach) over a cultivation period of approximately two months until harvest. Grass carp (*Ctenopharyngodon idella*) were stocked at a density of 10 fish m⁻² with an initial size of approximately 7 cm. Fish were fed once daily using vegetable-based feed, including kale and moringa leaves.

Spinach cultivation began with seed germination in seedling trays for approximately 20 days. The seedlings were then transplanted into a growing medium consisting of 50% soil and 50% compost. The water level for both red and green spinach was initially maintained at 14.5 cm below the soil surface during the first week after transplanting and adjusted to 10 cm during the subsequent growth stages. Fertilizer was applied periodically throughout the cultivation period. Plant height observations were conducted from 0 days after planting (DAP) until 41 DAP.

2.2.3 Data Analysis

Data analysis was conducted by compiling all primary and secondary data collected at the research site. Environmental data were recorded using an Automatic Weather Station (AWS) installed at the site,

with measurements taken at 30-minute intervals. The observed parameters included solar radiation (R_s), air temperature (T), relative humidity (RH), and rainfall.

Evapotranspiration represents the combined process of evaporation and plant transpiration, which occur simultaneously and are difficult to separate analytically [11]. Reference evapotranspiration (ET_o) outside the greenhouse was estimated using the Hargreaves method [12] as presented in Equation (1):

$$ET_o = 0.0023 (T_{mean} + 17.8) R_s \left(\frac{238.8}{595.5 - 0.55 T_{mean}} \right) \quad (1)$$

where ET_o is the reference evapotranspiration (mm day^{-1}), T_{mean} is the average daily air temperature ($^{\circ}\text{C}$), and R_s is the solar radiation ($\text{MJ m}^{-2} \text{day}^{-1}$).

Land productivity (LP), water productivity (WP), crop evapotranspiration (ET_c), and water use efficiency (WUE) were calculated using Equations (2)–(5), respectively:

$$LP = \frac{W}{A} \quad (2)$$

$$WP = \frac{W}{V} \quad (3)$$

$$ET_c = K_c \cdot ET_o \quad (4)$$

$$WUE = \frac{ET_c}{V} \times 100\% \quad (5)$$

where LP is land productivity (g m^{-2}), W is spinach yield (g), A is land area (m^2), WP is water productivity (g L^{-1}), V is irrigation water volume (L), ET_c is crop evapotranspiration (mm), K_c is the crop coefficient, and WUE is water use efficiency (%).

Fish performance was evaluated based on specific growth rate (SGR) and survival rate (SR), calculated using Equations (6) and (7), respectively:

$$SGR = \frac{W_t - W_0}{t} \times 100\% \quad (5)$$

$$SR = \frac{N_t}{N_0} \times 100\% \quad (6)$$

where SGR is the specific growth rate (%), W_t is the final fish weight (g), W_0 is the initial fish weight (g), t is the culture period (days), SR is the survival rate (%), N_t is the final number of fish, and N_0 is the initial number of fish.

3. Results and Discussion

3.1 Microclimate during the season

Microclimate components, including air temperature, relative humidity, solar radiation, and wind speed, play a significant role in influencing plant physiological processes. These climatic variables are critical factors in estimating plant evapotranspiration. **Figure 2** presents the variation in air temperature and relative humidity over a 41-day observation period. The air temperature at the research site ranged from 21.1°C to 34.3°C , with an average of 25°C , while relative humidity ranged from 68% to 97%. The maximum temperature was recorded at 37 days after planting (DAP), reaching 34.3°C , whereas the minimum temperature of 21.1°C occurred at 36 DAP. In comparison, the average temperature in Bogor is approximately 25.5°C , with a typical daily maximum of 27°C [13]. These observed conditions are generally within the optimal range for spinach growth, which requires temperatures between 20°C and 30°C and relative humidity above 60%. Suitable temperature and humidity conditions are essential for supporting plant physiological functions, particularly nutrient uptake and metabolic processes [14].

Therefore, the microclimatic conditions during the study were considered favorable for spinach cultivation and likely contributed to the observed plant growth performance.

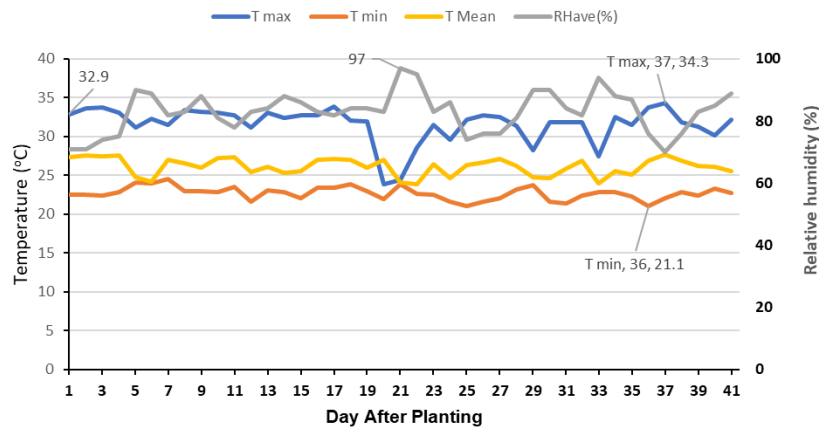


Figure 2. Air temperature and relative humidity fluctuations during cropping season

3.2 Performance of the FONi Irrigation System

Previous study has reported that subsurface irrigation systems, including cone-shaped configurations and bucket-based reservoirs, are capable of maintaining stable water levels and functioning effectively under field conditions [15]. The performance evaluation of the FONi system in this study demonstrated that the system operated reliably without leakage, and water was distributed uniformly from the storage tank through the distribution network to each planting pot. The water level in the pots was consistently maintained at the target depth of 10 cm below the soil surface. Continuous water flow ensured adequate moisture within the root zone, as indicated by the sustained soil wetness inside the pots. These results confirm that the gravity-driven FONi irrigation system was able to function effectively and maintain stable water availability throughout the observation period.

3.3 Irrigation Water Consumption

Irrigation water consumption refers to the total volume of water utilized by plants during the growth period to satisfy evapotranspiration demands and maintain soil moisture conditions. This consumption is influenced by climatic factors, including air temperature, relative humidity, solar radiation, and wind speed, as well as the performance of the irrigation system. Adequate water supply at each growth stage is essential to support plant physiological processes and ensure optimal growth. In this study, irrigation water consumption represents the total volume of water delivered to the planting system over a defined growth period. The pattern of water use in spinach cultivation is presented in **Figure 3**.

Irrigation water application at the early stage of the planting period showed relatively low values. The highest irrigation volume was recorded on day 37 after planting, reaching 0.55 L, after which it gradually decreased toward the end of the 41-day cultivation period. Notably, no irrigation was applied on day 28 due to rainfall, indicating that natural precipitation contributed to meeting plant water requirements. The average daily irrigation water applied to spinach during the 41-day period was 0.25 L, with a total accumulated irrigation volume of 10.49 L. This value is slightly lower than that reported by Safriyadi (2023), who observed an average irrigation requirement of 0.26 L day⁻¹ using a similar system. The relatively low irrigation requirement observed in this study indicates that the FONi system is capable of supplying water efficiently in accordance with plant needs. This finding is consistent with Muharomah et al. [16], who reported that the FONi system can achieve irrigation efficiency approaching 100%.

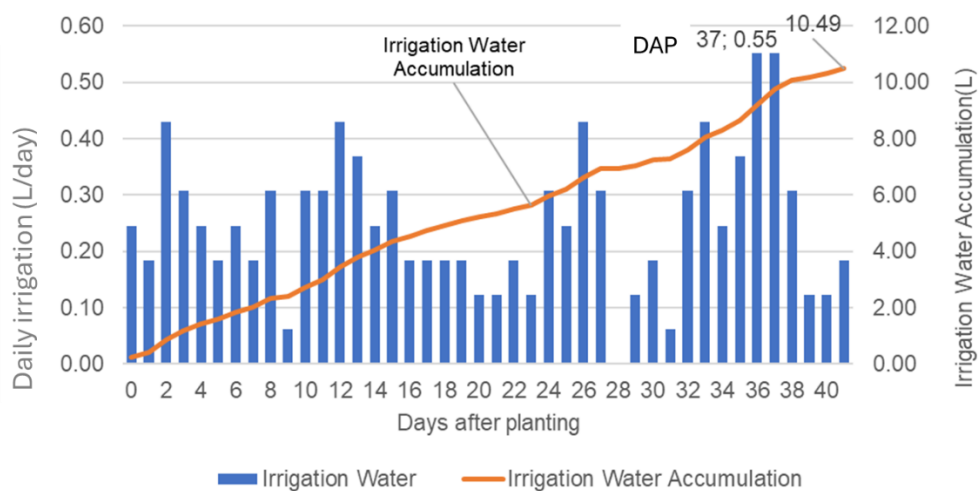


Figure 3. Accumulated irrigation water use during cropping season

3.3 Potential Evapotranspiration (ET_o) and Crop Coefficient (K_c)

Evapotranspiration represents the combined processes of evaporation (water loss from the soil surface or growing medium) and transpiration (water loss through plant stomata) which together describe the total water loss from an agricultural system. The magnitude of evapotranspiration reflects crop water requirements and serves as a fundamental basis for determining irrigation water demand and scheduling. Accurate estimation of evapotranspiration is essential for effective irrigation management, as it ensures that water is supplied in accordance with plant needs [17]. Potential evapotranspiration (ET_o) is primarily influenced by climatic parameters, including solar radiation, air temperature, relative humidity, and wind speed. In irrigation scheduling, these factors are considered alongside soil water availability throughout the crop growth period. The accumulated evapotranspiration during the study period is presented in **Figure 4**.

The potential evapotranspiration (ET_o) in this study was estimated based on a total accumulated value of 70.5 mm over 41 days after planting. Daily ET_o values exhibited considerable variation, ranging from 0.1 to 2.3 mm day⁻¹, with an average of 1.6 mm day⁻¹ during the cultivation period. As shown in Figure 4, the highest ET_o value was recorded at 37 days after planting, reaching 2.3 mm day⁻¹. The elevated evapotranspiration at this stage can be attributed to climatic factors, particularly high air temperature and solar radiation. This is supported by observed data indicating that the air temperature reached 34.3°C on day 37, representing the peak temperature during the study period.

The crop coefficient (K_c), defined as the ratio of actual evapotranspiration (ET_c) to reference evapotranspiration (ET_o), reflects crop water requirements at different growth stages. In this study, the K_c values for spinach across the growth phases—initial, crop development, mid-season, and late-season—were 0.40, 0.65, 0.74, and 0.71, respectively. These values indicate an increasing trend in water demand during the vegetative growth stage, followed by a slight decline toward the late-season phase. Syafriyandi et al. [18] reported lower K_c values for spinach, ranging from 0.12 to 0.32. The higher K_c values observed in this study may be influenced by differences in environmental conditions, cultivation methods, and irrigation system characteristics. In general, K_c values may vary throughout the growing season due to changes in crop development and climatic factors.

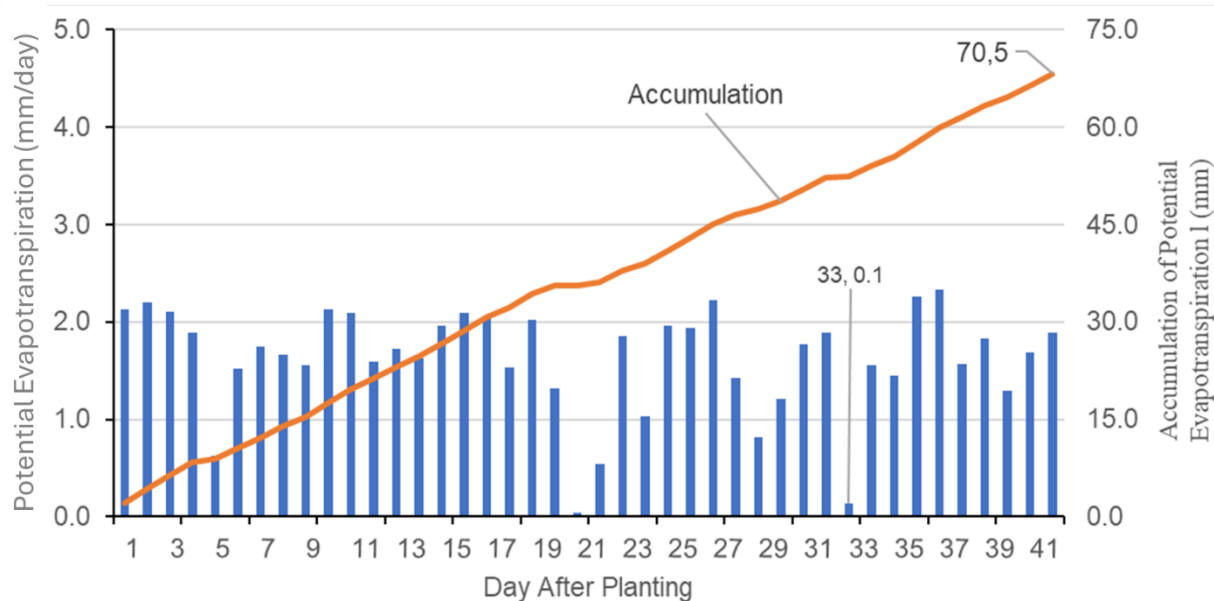


Figure 4. Potential evapotranspiration and its accumulation during cropping period

3.4 Plant and Fish Growth

Plant growth is a biological process characterized by increases in size, volume, and biomass, resulting from integrated physiological activities such as photosynthesis, respiration, and nutrient uptake. This process is influenced by both internal factors (e.g., genetics and plant hormones) and external factors, including water availability, light intensity, temperature, and nutrient content in the growing medium. The FONi system, as a gravity-driven irrigation technology based on the principle of communicating vessels, enables the automatic distribution of water and nutrients in accordance with plant demand. Spinach growth under the FONi system demonstrated a positive response throughout the observation period. This was indicated by consistent increases in plant height, leaf number, and fresh biomass across all growth stages (**Figure 5**). At the seventh week after planting, the average plant height reached 35.5 cm for green spinach and 31.0 cm for red spinach. The maximum plant height observed was 43.0 cm for green spinach and 41.5 cm for red spinach, while the minimum values were 23.0 cm and 18.5 cm, respectively. Overall, both spinach types exhibited continuous weekly growth, indicating favorable growing conditions under the FONi system. The average number of leaves ranged from 12 leaves per plant for green spinach to 11 leaves per plant for red spinach. The maximum leaf number observed at week seven was 16 leaves for green spinach and 15 leaves for red spinach, while the minimum ranged from 11 leaves (green spinach) to 8 leaves (red spinach).

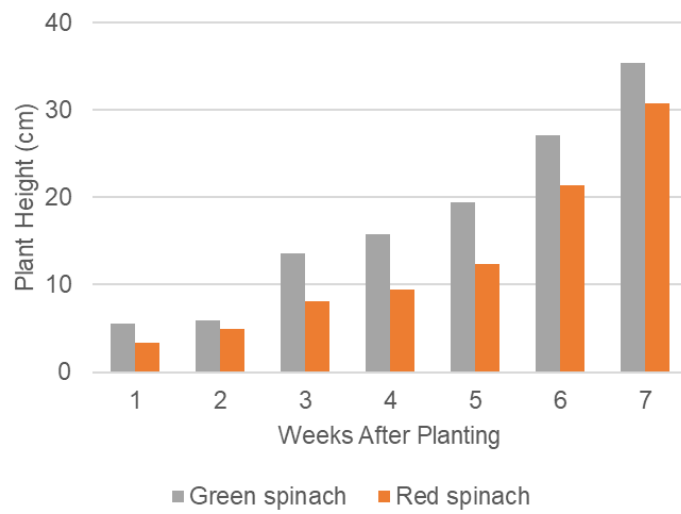


Figure 5. Plant height of spinach during cropping season.

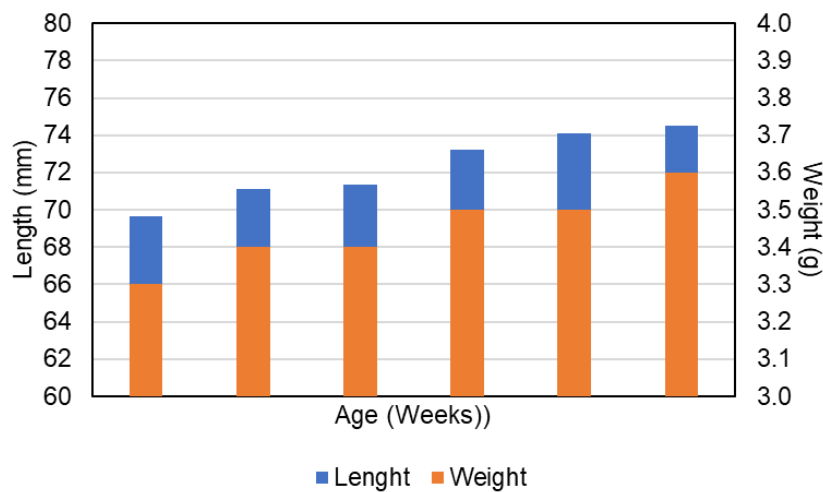


Figure 6. Fish growth during cropping season.

The growth performance of grass carp is presented in **Figure 6**. The results indicate a consistent increase in both fish length and weight under the FONi system. This is reflected in a specific growth rate (SGR) of 73% and a survival rate (SR) of 100%, indicating favorable culture conditions throughout the experimental period. The average fish length increased from 69.7 mm in the first week to 74.5 mm in the sixth week. The maximum length recorded was 78.0 mm in the first week and 79.9 mm in the sixth week. Similarly, the average fish weight increased from 3.3 g in the first week to 3.6 g in the sixth week, with a maximum recorded weight of 4.0 g. These results suggest that the integration of aquaculture within the FONi system was able to support optimal fish growth, likely due to stable water availability and suitable environmental conditions within the system.

3.5 Land Productivity, Water Productivity, and Water Use Efficiency

Land productivity and water productivity are key indicators for evaluating the efficiency of agricultural systems, particularly in optimizing crop yield under limited resource conditions. These indicators reflect how effectively land area and water input are converted into agricultural output. Improvements in both metrics can be achieved through efficient irrigation practices, proper nutrient management, and the application of technologies such as automated fertigation systems, including the FONi system, which

delivers water and nutrients in a controlled manner according to plant requirements. Land productivity (LP) represents the capacity of a given land area to produce agricultural output. In this study, LP values differed between crop types, with red spinach yielding 7.67 g m^{-2} and green spinach 10.08 g m^{-2} . These values are comparable to those reported by Syafriyandi et al [18], who obtained a land productivity of approximately 0.2 kg m^{-2} for spinach cultivation. Variations in land productivity may be attributed to differences in cultivation practices, environmental conditions, and irrigation system performance.

Water productivity (WP), defined as the ratio of crop yield to total water use, is a critical parameter for assessing water-use efficiency in agriculture. In this study, WP values were 8.77 g L^{-1} for red spinach and 11.53 g L^{-1} for green spinach. The higher WP observed in green spinach indicates a more efficient conversion of water into biomass. This finding highlights the potential of the FONi system to enhance water productivity, particularly under conditions of limited water availability. Irrigation efficiency is closely related to the balance between water input and water effectively utilized by plants. Actual crop evapotranspiration (ETc) represents the total water loss through soil evaporation and plant transpiration during the growth period. In this study, ETc values were found to be nearly equivalent to the volume of irrigation water supplied to the planting pots, indicating minimal water loss and efficient system performance. This characteristic is typical of subsurface irrigation systems, which supply water in accordance with plant evapotranspiration demand. The water use efficiency (WUE) achieved in this study was 86%, indicating a high level of efficiency in water utilization. This value is substantially higher than that reported by Julianto et al. [19], who observed a WUE of 54% using the FONi system. The higher efficiency observed in this study may be attributed to improved system configuration, environmental conditions, or more stable water delivery through the gravity-driven mechanism.

4. Conclusion

Based on the results of this study, it can be concluded that the designed FONi mina-horticulture system demonstrated reliable performance, as indicated by the absence of leakage and its ability to automatically maintain water levels by compensating for evapotranspiration losses. The system effectively supported the integrated cultivation of fish and vegetables, as reflected in satisfactory plant growth and a high fish survival rate throughout the cultivation period. Furthermore, the FONi system shows strong potential for broader application in integrated aquaculture–horticulture systems, as evidenced by favorable land and water productivity values, reaching 10.08 g m^{-2} and 11.53 g L^{-1} for green spinach, and 7.67 g m^{-2} and 8.77 g L^{-1} for red spinach.

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