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A STUDY ON AQUAPONIC CULTIVATION OF VANNAMEI SHRIMP (*Litopenaeus vannamei*) AND WATER SPINACH (*Ipomoea aquatica* Forsk) UNDER LOW SALINITY

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ABSTRACT

Cultivation waste poses a severe threat to reducing environmental quality. However, the problem of low salinity cultivation waste can be overcome by converting it into plants. This research was conducted to assess the impact of salinity on the growth performance of Vannamei shrimp (*Litopenaeus vannamei*) and water spinach (*Ipomoea aquatic* Forsk) in a low-salinity aquaponic system. Floating raft system for planting water spinach. Furthermore, the role of water spinach in using N and P nutrients from the culture media of vannamei shrimp was analyzed. The experiment was carried out for 35 days, with two treatments and three repetitions, namely 5 and 10 ppt. Salinity affected the growth performance of shrimp and water spinach. Shrimp reared at 10 ppt exhibited higher growth rate, harvest size, and shrimp yield, along with lower feed conversion ratio (FCR) and water use compared to those reared at 5 ppt. Meanwhile, the performance of water spinach at 5 ppt salinity resulted in higher survival, plant height gain, root length gain, number of leaves, and yield of water spinach compared to 10 ppt salinity. The growth performance of water spinach decreased with increasing salinity, and the efficiency in reducing N and P from the 5 ppt culture media was 1.3 times higher than that of 10 ppt. Water spinach showed better results in the 5 ppt salinity media than 10 ppt, while vannamei shrimp grew at 5 ppt. Therefore, 5 ppt salinity was recommended as a suitable condition for integrated cultivation of vannamei shrimp and water spinach in low-salinity aquaponics. Both species were compatible and complemented each other's role in developing low-salinity aquaponics.

KEYWORDS: Aquaponics; aquaculture wastewater; salinity; shrimp vannamei; water spinach

INTRODUCTION

Vannamei shrimp (*Litopenaeus vannamei*) are euryhaline and can live normally in low salinity levels up to seawater (Jaffer *et al.*, 2020; Mariscal-Lagarda *et al.*., 2012; Miranda *et al.*, 2008; Samocha *et al.*, 1998; Saoud *et al.*, 2003) to be cultivated in both marine and freshwater environments. Additionally, the shrimp are relatively adaptive to water quality and can be raised in various types of cultivation containers, ranging from small to large scale (Makmur *et al.*, 2021).

Intensive cultivating vannamei shrimp involves using the feed to meet their nutritional needs. A portion of the provided feed remains unconsumed by the shrimp, leading to its disposal and dissolution in the water medium. The consumed feed is partially assimilated into shrimp flesh, while the remaining portion is expelled through metabolism in the form of feces and urine containing significant amounts of Nitrogen (N) and Phosphorus (P) (Syah *et al.*, 2014). In super-intensive vannamei shrimp culture, approximately 24.32% of the feed is not consumed and is wasted through excretion, amounting to 15.88% (Paena *et al.*, 2020). The N and P waste loads in vannamei shrimp culture, with a stocking density of 500 individuals/m^2, originating from the feed, reach 50.12 gTN/kg of shrimp and 15.73 gTP/kg of shrimp produced, and the total waste load is affected by the stocking density (Syah *et al.*, 2014). The accumulation of leftover feed and shrimp metabolite waste

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can lead to a decline in water quality and can adversely affect the well-being of the shrimp (Alarcón-Silvas *et al*., 2021; Wongkiew *et al*., 2017). To prevent the deterioration of water quality, periodic exchange is commonly performed. The fundamental concept of environmentally friendly and sustainable cultivation is not fulfilled when the waste load is directly discharged into the aquatic environment, triggering the degradation of the aquatic environment (Muqsith *et al*., 2019; Syah *et al*., 2014).

Vegetable plants can utilize nitrogen and Phosphorus in shrimp aquaculture effluent. Research on vannamei shrimp (*Litopenaeus vannamei*) aquaponics system with tomato (*Lycopersicon esculentum*) and lettuce (*Lactuca sativa*) has shown a decrease in total N and P concentrations (Fierro-Sañudo *et al*., 2018). Other research, such as the aquaponics system of whiteleg shrimp (*L. vannamei*) and tomato (*Lycopersicon esculentum Mill*) with low salinity groundwater (Mariscal-Lagarda *et al*., 2012). The use of low-salinity shrimp farm effluent for melon irrigation (Miranda *et al*., 2008), and the integration of African catfish with water spinach (*Ipomoea aquatica*) and mustard green (*Brassica juncea*) (Enduta *et al*., 2011). The combination of whiteleg shrimp *L. vannamei* rearing with Batis maritima, *Sarcocornia neei*, and *Sporobolus virginicus* (Schardong *et al*., 2020) provides information that agricultural plants can use nutrients derived from shrimp aquaculture wastewater.

The fundamental principle of aquaponics is to use the nutrient-rich water from shrimp cultivation to be reused by plants (Pattillo *et al*., 2022; Radkhah *et al*., 2021; Radkhah *et al*., 2022; Sunardi *et al*., 2013; Verma *et al*., 2023). Plants' utilization of nutrients is expected to reduce the accumulation and the risk of ammonia exceeding levels that may harm the shrimp. However, plants that can tolerate salinity levels are still limited. Some plants that are tolerant to low salinity levels include chilli, tomato, and cemangi (Armenta-Bojórquez *et al*., 2021; Fierro-Sanudo *et al*., 2015; Fierro-Sañudo *et al*., 2018), and water spinach (Rochmania, 2021; Sihotang, 2021; Yousif *et al*., 2010). Broccoli can also grow with vannamei shrimp (Ni *et al*., 2020), while water spinach plants and vannamei shrimp can live at a salinity of 5-7 ppt (Amriani, 2018), between shrimp and water spinach plants a salinity of 4 ppt, the recirculation system produces a survival rate of 93%, and is able to reduce 12.6 gN and 1.39 gP at a density of 360 fish/m^3. A floating raft system with a density of 100 fish/m^2 produces 100% shrimp survival (Liu *et al*., 2022). However, information on the performance of water spinach (*Ipomoea aquatic*) between super-intensive shrimp densities under different salinity conditions on TN and TP from vannamei shrimp cultivation waste using the floating raft system is not yet available. Therefore, research on low-salinity shrimp aquaponics is necessary to understand the performance of water spinach and the effectiveness of N and P absorption in the culture water.

Water spinach is a plant highly favoured by the community due to its delicious taste and versatility in various dishes, increasing the demand (Adrian, 2012; Febriyono *et al*., 2017; Lubis, 2011). Additionally, the plant can thrive and adapt in different environments, overgrowing in water (Hasan *et al*., 2018) and soil media (Juhaeti & Hidayati, 2014). The aims of this research were (a) to evaluate the impact of two levels of salinity on the performance of vannamei shrimp and water spinach in an aquaponic system and (b) to understand the role of water spinach in using N and P nutrients from the cultivation shrimp culture. The aquaponics system is expected to be one of the ways to convert the cultivation waste load into vegetable biomass, leading to more efficient and economical management and being quickly adopted by the community. Aquaponics will become a widely accepted method for sustainable food production (Hu *et al*., 2012; Paudel *et al*., 2019). This study aims to evaluate the appropriate salinity level for the aquaponic system between vannamei shrimp and water spinach.

MATERIALS AND METHODS

Production system/Experimental design

The research was conducted at the Wet Laboratory of the Brackishwater Aquaculture Research Center and Fisheries Extension, Maros Regency, South Sulawesi Province, Indonesia. The container used was a glass aquarium measuring 50 x 40 x 30 cm, equipped with aeration sourced from a blower, and the shrimp aquarium was placed on a table inside a transparent-roofed greenhouse with natural sunlight illumination. Furthermore, the light intensity was measured using an AS803 Lux Meter with a 0-200,000 Lux range. The sunlight intensity inside the greenhouse during the research ranged from 45,159 ± 40,856 Lux (morning at 07:00) to 200,429 ± 175,918 Lux (noon at 12:00) with an illumination duration of approximately 6-8 hours.

The required water volume was calculated based on the total dimensions of the shrimp aquarium and the reserve water volume for supplementation. Meanwhile, the reserve water was used to maintain the level inside the shrimp aquarium due to water spinach consumption and evaporation rate. The water level reduction in the shrimp aquarium reached 0.9 ± 0.004 cm (Treatment A) and 1.0 ± 0.00 cm per day (Treatment B). The water source was obtained from the sea with a salinity of 30 ppt, which was then diluted using well water/groundwater to achieve water salinity levels of 5 ppt and 10 ppt. The reserve water was filtered using a polyester fibre bag filter (32 cm x 86 cm, 20 microns) and added to each shrimp aquarium in 50 litres.

A completely randomized experimental design was used to evaluate the effect of water salinity on the growth of vannamei shrimp and water spinach. There were two water salinity levels, namely 5 ppt (treatment A) and 10 ppt (treatment B), each with three replications. This study did not use a salinity control of 0 ppt or seawater of 33 ppt, considering that the two commodities have a narrow overlap in salinity range. Water spinach grows well in the salinity range of <10 ppt, while vannamei shrimp, to grow generally at 0 ppt salinity, require a large enough mineral input and harms water spinach life; thus, in this study, the treatment tried is salinity 5 and 10 ppt.

Acclimatization, stocking, and shrimp feeding

Pathogen-free vannamei shrimp seeds (PL10) were obtained from a hatchery with a rearing media salinity of 30 ppt. The shrimp seeds were put into an acclimatization tank with a volume of 3,000 litres and a salinity of 30 ppt at a stocking density of 2 PL/L. Subsequently, salinity reduction was performed by continuously flowing freshwater with an estimated decrease of 1.5 - 2 ppt per day until reaching media salinities of 5 and 10 ppt. The process took place over 14 days, and during the acclimatization period, the shrimp were fed pellets (CP= 40.32%) twice a day at 08:00 in the morning and 16:00 in the afternoon using the blind method. After the acclimatization process was completed, the PL was maintained under the final salinity conditions for 6 days for observation and to improve their growth (habituation period). The purpose of acclimatization was to prepare the shrimp seeds according to the salinity treatment in the rearing media to avoid stress at the beginning of the cultivation process.

The stocking density of vannamei shrimp seed is 1 individual per 2 litres, resulting in 25 per aquarium. During the research, the shrimp were fed pellets with the following nutritional composition: crude protein=34.25%, crude fat=7.31%, crude fiber=7.36%, and ash=9.69%. The feeding was conducted three times a day (08:00; 12:00; 16:00) at a dosage of 6-4% of their body weight.

Planting and harvesting of water spinach

Five water spinach seeds (*Ipomoea aquatic* Forsk) were sown on a moist sponge medium and incubated in styrofoam boxes for 7 days to become water spinach seedlings for each net pot. The seedlings sprouted with leaf openings were selected and transferred to net pots, which were rubber cups with holes at the bottom and sides. Furthermore, the planting density of water spinach in each net pot was 5 plants, and the net pots were placed on the water surface in each aquarium using a floating system with styrofoam measuring 46 x 36 cm. The distance between net pots was 10 cm, with 25 water spinach plants per aquarium. The harvest was conducted on the day of culture (DOC) 35 for the shrimp or 28 days after planting.

Sampling and chemical analysis

Water quality measurements for shrimp cultivation include temperature, salinity, pH, and dissolved oxygen (measured with a YSI Professional Pro DO meter), which were conducted every day in the morning (07:00-08:00) and afternoon (16:00-17:00). In-situ measurements were carried out weekly and included parameters such as Total Ammonia Nitrogen (TAN) (phosphate blue indophenol method), nitrite (sulfanilamide method), nitrate (cadmium reduction and ascorbic acid methods), and were measured using a spectrophotometer. Alkalinity was analyzed using titration, while Total Suspended Solid (TSS) was measured using a portable TSS meter from HACH. Total Organic Matter (TOM) was analyzed using titration, while Total Dissolved Solids (TDS) and Electrical Conductivity (EC) were measured using a TDS&EC meter (Hold). Shrimp weight and water spinach samplings (plant height, plant weight, leaf count) were conducted weekly and at the beginning and end of the research, respectively. Plant samples were also dried in an oven for 72 hours at 105°C to determine dry weight. Plant fresh and dry weights were used to calculate the water content in the plants. The dried plant samples were powdered, sieved through a 10-mesh sieve, and placed into plastic vials for nutrient analysis. Proximate analysis of the shrimp and water spinach carcasses was the basis for estimating nutrient retention and the N and P waste load originating from the feed.

Shrimp and water spinach growth, survival, and yield

Shrimp growth was individually weighed once a week for all individuals in the aquarium using an electronic scale with a precision of 0.01 g. The weight data were used to calculate weekly weight gain (WG) and specific growth rate (SGR). Survival, biomass production, and Food Conversion Ratio (FCR) were calculated at the end of the research. The water spinach was measured from the roots to the apex at harvest time, and the biomass was weighed. The number of leaves on the water spinach plants was also counted.

Survival rate (%) = (Final number of shrimp or plant/ Initial number of shrimp or plant) x 100 (El *et al*., 2024)

WG (%) = (Final biomass (g) - Initial biomass (g))/ Initial biomass x 100 (El *et al*., 2024)

SGR (%/week) = [Ln(Final biomass (g)) - Ln(Initial biomass (g))]/week x100 (El *et al*., 2024)

FCR = Total feed intake (g)/(Final biomass (g) - Initial biomass (g) (El *et al*., 2024)

Estimation of the feed waste load

The estimation of N and P waste was calculated based on shrimp production data, total feed during the research, N and P content in the feed, and N and P content in shrimp carcasses (Barg, 1993) as follows:

The equation for loading P is:

kg P = (A × Cdp) – (B x Dfp)

The equation for loading N is:

kg N = (A x Cdn) – (B x Cfn)

Where:

A = Wet weight of dry pellets used (normal moisture content in dry pellets is 8-10%)

B = Wet weight of shrimp produced

Cd = The P (Cdp) and N (Cdn) content of the dry pellets is expressed as % wet weight

Cf = The content of P (Cfp) and N (Cfn) of shrimp carcass, expressed as % fresh weight

Estimation of the role of water spinach efficiency (WSE) on TN and TP

The role of water spinach on N and P is calculated based on (Syah *et al*., 2017) as follows:

WSE- N% = (N water spinach / N feed wasted on cultivation media) × 100

WSE- P% = (P water spinach / P feed wasted into the cultivation media) × 100

Data analyses

The data obtained was first tested using the Shapiro-Wilk test to determine when the result followed a normal distribution (Radkhah *et al*., 2023; Shapiro & Wilk, 1965). Subsequently, the data were analyzed using the t-student test to examine the differences in the measured variable values between the two tested salinity levels. The Shapiro-Wilk and t-student tests were conducted at a 95% confidence level using the SPSS software version 26.

RESULTS AND DISCUSSION

Water Quality

The water quality parameters in the cultivation media were within an acceptable range for the survival of vannamei shrimp and water spinach. Most water quality parameters exhibited relatively similar conditions in salinity treatments of 5 ppt and 10 ppt (Table 1). Electrical Conductivity (EC) and Total Dissolved Solids (TDS) played a crucial role in influencing the physiological processes of water spinach (*Ipomoea aquatica*) in the aquaponic system. These two parameters reflected the fertility and water quality in the aquaponic system, which affected the growth, development, and health of water spinach plants. The concentrations of EC and TDS differed significantly between the two salinity conditions. Salinity levels had a significant effect ($p<0.05$) on the values of EC and TDS, as shown in Table 1. The changes in EC and TDS values remained relatively stable from the beginning to the end of the cultivation period, as shown in Figure 1.

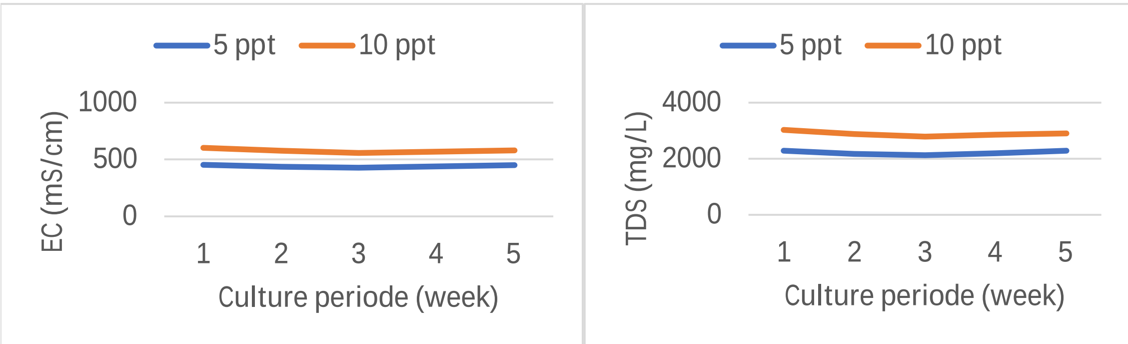
The EC and TDS are two essential parameters for measuring water fertility in the aquaponic system. The higher the salt in the water, the higher the EC value (Wibowo *et al*., 2017). Meanwhile, water salinity affects the values of EC and TDS (Lennard & Leonard, 2006). High salinity increases the EC and TDS values in the water, which is evident from the higher values in the 10 ppt salinity treatment compared to 5 ppt. EC measures the ability of the water to conduct an electrical current, influenced by the concentration of salts and minerals in the water. The correct EC value is crucial for controlling water quality and providing nutrients for spinach plants. Similarly, TDS indicates the density of salts and minerals in the water, and its optimal value is essential to support the growth and health of the plants. EC values that are too high can be a limiting factor for spinach growth (Suseno & Widyawati, 2020). In hydroponic and aquaponic systems, the EC value reaches 1104 mS/cm (Zhu *et al*., 2022). In rice plants, the interaction between pH, N and EC has a real impact on rice decline (Zhu *et al*., 2022); likewise, in this study, the EC value has a real influence on the growth of water spinach.

The optimal values of EC and TDS may vary depending on the system conditions and other factors. However, the optimal EC value for water spinach ranges from 1.0 to 2.0 mS/cm (millisiemens per centimetre). The optimal electrical conductivity for pakchoi (*Brassica campestris* L. ssp. Chinensis) in

Table 1. Treatment water quality was 5 and 10 ppt during the study

Variable	Salinity (ppt)	
	5	10
Temperature (^{O}C)	26.43±1.01	26.41±1.08
Salinity (ppt)	5.28±0.27	10.35±0.24
pH	8.57±0.28	8.52±0.28
Dissolved Oxygen (mg/L)	5.72±0.18	5.43±0.17
Total Ammonia Nitrogen (mg/L)	0.2314±0.1136	0.1923±0.0624
Nitrite (mg/L)	0.0330±0.0576	0.0593±0.1139
Nitrate (mg/L)	0.5494±0.4630	0.3787±0.5096
Phosphate (mg/L)	0.2505±0.1461	0.1902±0.0685
Total Organic Matter (mg/L)	63.45±3.11	62.72±5.22
Alkalinity (mg/L)	237.10±50.73	258.67±41.36
Total Dissolved Solid (mg/L)	221.55±7.14^{a}	289.23±8.75^{b}
Electrical Conductivity (mS/cm)	441.96±11.10^{a}	577.40±16.39^{b}

[a] Means in the same row followed by a similar superscript are not significantly different ($P>0.05$).



(1A) (1B)

Figure 1. EC (1A) and TDS (1B) concentrations during the shrimp-water spinach culture period at low salinity.

hydroponic production systems is EC1.8 or EC2.4, as too high or low EC can induce nutrient stress and suppress growth and quality (Ding *et al*., 2018).

The recommended TDS value for water spinach in the aquaponic system ranges from 800 to 1500 ppm (Rakocy *et al*., 2006). Therefore, regular monitoring is necessary to adjust the conditions to meet the plant's needs. The influence of EC and TDS also affects nutrient uptake and osmosis in water spinach plants (Lennard & Leonard, 2006), making it essential to maintain a balance to promote healthy plant growth.

The EC level in the water will affect the concentration of nutrients available to the plants (de Morais *et al*., 2022). The nutrient concentration in the water may not be sufficient, and water spinach plants can experience nutrient deficiencies when the EC value is low. A high EC value can lead to nutrient excess, potentially causing plant toxicity (de Morais *et al*., 2022; Ding *et al*., 2018; Ferreira*et al*., 2018). The plants will have difficulty absorbing water through the roots due to the significant concentration difference between the roots and the environment when the TDS value of the water is very high. Conversely, when the TDS value is too low, water can enter the plant cells, causing damage and physiological issues (Lennard & Leonard, 2006).

Growth rates, survival, yield, FCR, and water usage

The salinity treatment significantly affected ($p<0.05$) the performance of vannamei shrimp in the aquaponic system under low salinity conditions (Table 2). The survival at 5 ppt salinity was lower than 10 ppt, but the difference was insignificant ($p>0.05$). Growth rate, size of shrimp at harvest, and shrimp yield were higher at 10 ppt salinity compared to 5 ppt, and the difference was statistically significant ($p<0.05$). The average FCR at 10 ppt salinity was lower than at 5 ppt, and both were statistically different. Meanwhile, the total water usage in the 5 ppt salinity treatment was 0.86 ± 0.14 m^3/kg of harvested shrimp-water spinach. This was higher than the 10 ppt salinity treatment at 0.65 ± 0.04 m^3/kg of harvested shrimp-water spinach, calculated in this integrated cultivation.

Aquaponics is a sustainable farming system that combines plant cultivation and fish or shrimp rearing in an integrated system (Rakocy *et al*., 2006). Converting TN and TP into plants is a real success in improving water quality, which has an impact on clean water efficiency. To produce shrimp, up to 4.7 m3/kg of clean water is needed (Mariscal-Lagarda *et al*., 2012). The advantage of water spinach (*Ipomoea aquatica*), which is often grown in hydroponic systems or water cultivation with nutrient solutions (Sugiharta *et al*., 2021), is that they have the flexibility to survive in various extreme conditions and can be planted all year round (Khairuddin, Sikanna, & Sabaruddin, 2017), both rainy and dry seasons, making it suitable for bioremediation and biofiltration (Tiro, Isa, & Iyabu, 2017). Because water spinach grows well at a salinity of 5 ppt, it produces higher growth, survival and biomass compared to a salinity of 10 ppt.

Table 2. Harvest size, yield, feed conversion, growth rate, survival of Vannamei, and water use (mean ± standard deviation) in the experimental shrimp-water spinach culture under low salinity

Variable	Salinity (ppt)	
	5	10
Growth rate (g/week)	0.68 ± 0.07[a]	0.82 ± 0.06[b]
Survival (%)	84.44 ± 7.70[a]	93.33 ± 6.67[a]
Harvest size (g)	3.49 ± 0.34[a]	4.18 ± 0.32[b]
Yield (kg/m^2)	0.37 ± 0.07[a]	0.49 ± 0.03[b]
Food conversion ratio (FCR)	1.28 ± 0.03[a]	1.05 ± 0.05[b]
Water use (m^3/kg shrimp + water spinach)	0.86 ± 0.14[a]	0.65 ± 0.04[b]

[a] Means in the same row followed by similar superscript are not significantly different (P > 0.05)

The survival rate reached 84.44% with a weekly growth rate of 0.68 g/week, indicating that vannamei shrimp can live and develop well at a salinity of 5 ppt. Several studies show that vannamei shrimp can still grow well at low salinity, even in waters with salinity close to zero ppt (Armenta-Bojórquez *et al*., 2021; Chu & Brown, 2021; Esparza-Leal *et al*., 2009; Fierro-Sanudo *et al*., 2015; Samocha *et al*., 1998; Saoud *et al*., 2003). Aquatic organisms cope with osmoregulatory challenges in low salinities by making finely tuned adjustments at the cellular level to compensate for and control ion and water flux across biological membranes. They decrease membrane permeability to water, change the concentration of osmotic effectors to decrease internal osmolality and change the expression of channels or active membrane carriers. They also use organic osmolytes to increase intracellular osmolality. These mechanisms help them maintain ion homeostasis and avoid water loss, dehydration, and loss of turgor pressure (Kültz, 2015; Rivera-Ingraham & Lignot, 2017). Therefore, the final growth was obtained at 3.49 g at lower salinity and resulted in less than optimal feed utilization with a Feed Conversion Ratio (FCR) of 1.28 and a yield of 0.37 kg/m².

The performance of water spinach

Water spinach produced in the aquaponic system with vannamei shrimp at media salinities of 5 and 10 ppt showed a significant difference ($p < 0.05$). Meanwhile, those produced at 5 ppt salinity were 1.56 times higher than 10 ppt salinity (Table 3). The survival of water spinach at 5 ppt salinity reached 100%, significantly different ($p < 0.05$) from 61.30 ± 0.04% at 10 ppt salinity. The results showed that water spinach grown in the 5 ppt salinity media exhibited better growth performance ($p < 0.05$) in terms of stem height, root length, leaf count, and yield compared to water spinach living in 10 ppt salinity (Table 3). The root length at 5 ppt salinity was 2.25 times longer ($p < 0.05$) than 10 ppt (Table 3). Therefore, the 5 ppt salinity level was more suitable for the growth of water spinach, as evidenced by higher stem height, leaf count, and yield ($p < 0.05$) compared to the 10 ppt salinity level.

The role of water spinach in 5 ppt salinity cannot be separated from the growth of its roots, which experience an increase in length by 17.27 ± 4.84 cm, nearly twice the stem height, which is 9.56 ± 2.43 cm. The roots of the plants spread in various directions and fill the net pots, extending to the bottom of the aquarium. In aquaponic systems, the roots serve as sediment traps that retain coarse particles from fish feed and faeces (Astuti, Hendrawan, & Krismono, 2018). Water spinach roots have aerenchyma, plant tissue containing air spaces larger than usual (Saab & Sachs, 1996). Plants respond differently to low oxygen partial pressure. The root tissue of the plant responds to excess water by forming aerenchyma tissue when submerged. Aerenchyma development will be triggered to enable this plant to withstand critical conditions (Raven, 1996). Water spinach roots form through the lysis of cortex cells from the outer to the inner part, which begins in the third week (Ningsih, Mansyurdin, & Maideliza, 2016). Consequently, the length of the roots can support the tall growth of water spinach stems, reaching 20.65 ± 1.87 cm at a salinity of 5 ppt, which is significantly higher ($p < 0.05$) than the 13.14 ± 0.73 cm at 10 ppt.

The stems of water spinach, which serve as leaf support, can grow well due to sufficient nutrient requirements. The plant growth increases with increasing concentration (Suroso & Antoni, 2017). The height of the stem can support a higher number of leaves, with an average of 8.12 ± 0.67 (at 5 ppt salinity) significantly higher ($p < 0.05$) than 6.01 ± 0.94 at 10 ppt salinity. Leaves function in transportation and light capture for photosynthesis, which converts solar energy into chemicals through stomata. In conditions of excessive water, stomata have a higher density, while in conditions of scarcity, the density is lower. Therefore, stomata adjust to their environmental conditions for survival (Syiam, Amalia, & Putri, 2021). The impact of salinity stress on water spinach plants is evident since survival reaches 100% at a salinity of 5 ppt, while at 10 ppt salinity, it is only 61.33 ± 18.04%. The successful growth and high survival rates are essential for production, which can enhance the role of water spinach in using nutrient loads derived from shrimp aquaculture activities. Water spinach has increased salt tolerance, reducing the adverse effects of salinity on germination and early seedling growth (Ibrahim, Abas, & Zahra, 2019).

Table 3. Survival, height, root length, number of leaves, and yield (mean ± standard deviation) of water spinach in the experimental shrimp–water spinach culture

Variable	Salinity (ppt)	
	5	10
Survival (%)	100.00 ± 0.00[a]	61.30 ± 18.04[b]
Plant height gain (cm)	9.56 ± 2.43[a]	1.97 ± 0.53[b]
Root length gain (cm)	17.27 ± 4.84[a]	7.67 ± 0.23[b]
Number of leaves	6.12 ± 0.67[a]	4.01 ± 0.94[b]
Yield (kg/m^2)	1,163.22 ± 41.71[a]	743.38 ± 42.90[b]

[a] Means in the same row followed by similar superscript are not significantly different ($P > 0.05$)

Waste load of N and P sourced from shrimp feed

In the aquaponic system of shrimp-water spinach cultivation, the salinity treatment did not significantly affect ($p > 0.05$) the retention of N and P and the N and P waste load per kg of harvested shrimp. Therefore, vannamei shrimp survived up to a salinity of 5 ppt and were considered euryhaline. The P waste load showed a significant difference ($p < 0.05$), reaching 13.5206 ± 0.7030 gP per kg and 11.0660 ± 0.7031 gP per kg harvested shrimp at 5 ppt and 10 ppt salinity. N and P waste loads were higher in the 5 ppt salinity treatment than 10 ppt. This was related to the performance of shrimp cultivation and water spinach under the two salinity conditions.

The salinity of the media is one of the critical environmental parameters in shrimp and plant cultivation in aquaponic systems because both cultured species have different tolerance levels to salinity. This characteristic affects the growth performance of both species and, consequently, influences the waste load generated. Changes in media salinity can affect the waste load generated by the feed given to the shrimp, as it is related to the shrimp's metabolic processes. Shrimp are osmoregulatory animals, which means they regulate the balance of water and salt in their bodies. Changes in salinity can affect the activity level of these osmoregulators. At low salinities, shrimp must allocate more energy to cope with osmoregulatory challenges, requiring more feed intake and energy for regulating these osmoregulatory processes, resulting in more waste production (J. Li, Xu, Li, & Zhang, 2019; Rivera-Ingraham & Lignot, 2017).

This is evident in shrimp growth, survival rates, and harvest size, which are lower at a salinity of 5 ppt compared to shrimp at a salinity of 10 ppt. Changes in salinity can also impact the shrimp's appetite. At a salinity of 5 ppt, shrimp have a reduced appetite compared to a salinity of 10 ppt. This is reflected in the significantly higher FCR of 1.28 ± 0.03, which is significantly different from the FCR at the 10 ppt treatment, which is 1.05 ± 0.05. This means that less feed is consumed, which, in turn, can increase the amount of unconsumed feed, becoming a waste burden during cultivation. The TN (Total Nitrogen) waste load from feed in the 5 ppt salinity treatment is not significantly different from the 10 ppt salinity treatment, but the TP (Total Phosphorus) waste load differs significantly between the 5 and 10 ppt salinity treatments. Syah *et al.* (2006) reported nutrient retention values for N and P at 33.14% TN and 16.46% TP, respectively, in the cultivation of vannamei shrimp with a stocking density of 50 individuals/m² in earthen ponds, with waste loads of 62.74 gN/kg shrimp and 61.53 gP/kg shrimp feed. Meanwhile, at a stocking density of 500 individuals/m² in concrete ponds, N and P retention were 38.71% and 16.59%, with waste loads of 50.12 gTN/kg shrimp and 15.73 gTP/kg shrimp (Syah *et al.*, 2014). On the other hand, Hangsheng *et al.* (2008) obtained N and P retention values in vannamei shrimp cultivation using a recirculation system at 22.27% and 9.79%, respectively. The variations in nutrient retention and waste loads observed in these studies are influenced by various factors, including farming management practices (such as feed quality and feeding regimes) (Jannathulla *et al.*, 2019; Zhou *et al.*, 2020). Water quality, especially media salinity (Kumlu *et al.*, 2010), and the overall performance of the cultivation, which is characterized by parameters like FCR, growth, SR, and production (Lim *et al.*, 2021; Ponce-Palafox *et al.*, 2019).

Nutrient budget

The importance of nutrient budgets in shrimp ponds is to understand the source and sink of nitrogen, which affects pond water quality and effluent impact. It helps determine the contribution of the pond bottom soil to the accumulation of sediment and phosphorus and its potential contribution of nitrogen to the pond system. Additionally, nitrogen budgets can provide insights into the nutrient utilization efficiency and sustainability of shrimp farming systems (Dien *et al.*, 2018; Funge-Smith & Briggs, 1998; Sahu *et al.*, 2013).

The factors that influence the nitrogen budget in intensive shrimp farming include the nitrogen content in shrimp feeds, the amount of nitrogen converted to harvested shrimp, the amount of nitrogen remaining in the sediment, the amount of nitrogen discharged to the environment, and the amount of nitrogen lost to the atmosphere via denitrification or volatilization of ammonia (Chaikaew *et al.*, 2019; Jackson *et al.*, 2003).

They showed that the primary nitrogen entering the aquaponic-water spinach system at 5 ppt salinity was from feed N (5.2880 ± 0.8594 g), followed by filling the water with the most negligible contribution of 0.0086 ± 0.0013 g (Table 5). The principal loss occurred through deposition into shrimp biomass, accounting for 56.20%, followed by water spinach at 28.14%, released into the cultivation media, and discharged water at 15.26% and 0.24%. The Nitrogen budget in the 10 ppt salinity treatment resulted in higher total input and output of nitrogen than the 5 ppt. The nitrogen taken up by water spinach in the 5 ppt was higher than the 10 ppt salinity treatment. This was related to the growth performance of water spinach, which thrived better in 5 ppt salinity and used N, resulting in higher water spinach biomass than those in 10 ppt. The amount of un-identified N was less than 1%, likely dissolved in water discharge during cultivation, originating from the release of feed N to the culture media.

A relatively similar response was shown in the P budget pattern. The input and output of P were relatively higher at 10 ppt salinity compared to 5 ppt (Table 6). Meanwhile, the highest contributor of P was from feed P, and the output components, which were deposited in the shrimp carcass, reached 34.80%. This was followed by 39.08%, 25.12%, and 1% P released into the culture media, deposited in the water spinach biomass, and found in water discharge at

Table 5. Nitrogen budget in the aquaponic system of shrimp-water spinach culture

Variable	Salinity (ppt)	
	5	10
Feed (g)	5.2880 ± 0.8594	5.7388 ± 0.1410
Water intake (g)	0.0086 ± 0.0013	0.0079 ± 0.0021
N Input (g)	5.2966	5.7467
Shrimp (g)	2.9837 ± 0.6698	3.1329 ± 0,2205
Water-spinach (g)	1.4940 ± 0.0398	1.2662 ± 0.0526
Release to culture media (g)	0.8102 ± 0.2454	1.3397 ± 0.1412
Water discharge (g)	0.0213 ± 0.0018	0.0173 ± 0.0026
N Output (g)	5.3093	5.7561
Un-identified	0.0127	0.0094

[a] Means in the same row followed by similar superscript are not significantly different ($P > 0.05$)

harvest. The group of unidentified P was less than 1%, originating from P in the feed released to the culture media and dissolved in water discharge during cultivation.

The components that contribute to N and P input in high salinity intensive vannamei shrimp ponds are dominated by feed, amounting to around 78% and 51% (Funge-Smith & Briggs, 1998). A similar observation was reported by (Syah *et al.*, 2014), who found that N and P input contributors in intensive vannamei shrimp ponds were feed, constituting 61% for N and 88% for P. In contrast, in low salinity aquaponic systems between water spinach plants and shrimp, N input is converted into shrimp 35.0%, and converted into plants in stems 2.3%, leaves 3.6%, root 11.3%, in water media 3.6%, detritus 20.5% and others 23.7% (Liu *et al.*, 2022), and P shrimp 32.0%, and converted into plants in stems 3,8%, leaves 5,0%, root 15.9%, in water media 8,5%, detritus 17,1% and others 17,6%. Using kale plants was able to reduce 73% and 76% of organic suspended solids, 23% and 18% of total phosphorus (TP), and 24% and 21% of total phosphorus (TP). total nitrogen (TN) for WW and DSW, respectively. Reduction of TN and TP in the system implies excellent efficiency in nutrient use and, consequently low environmental impact (Alarcón-Silvas *et al.*, 2021; Endut *et al.*, 2010).

Table 6. Phosphor budget in the aquaponic system of shrimp-water spinach culture

Variable	Salinity (ppt)	
	5	10
Feed (g)	1.5283 ± 0.2484 [a]	1.6585 ± 0.0407[a]
Water intake (g)	0.0087 ± 0.0006	0.0092 ± 0.0003
P Input (g)	1.5370	1.6677
Shrimp (g)	0.5372 ± 0.1142 [a]	0.5837 ± 0.0375[b]
Water-spinach (g)	0.3878 ± 0.0170 [a]	0.3062 ± 0.0073[b]
Release to culture media (g)	0.6032 ± 0.1314	0.7687 ± 0.0135
Water discharge (g)	0.0154 ± 0.0022	0.0115 ± 0.0042
P Output (g)	1.5437	1.6700
Un-identified	0.0067	0.0023

[a] Means in the same row followed by similar superscript are not significantly different ($P > 0.05$)

Nitrogen (N) and phosphorus (P) conversion in managing water quality is the key to successful cultivation. The ecological advantage is clean water efficiency; the less water added, the less likely the entry of disease contamination will be minimized. This information allows farmers to implement management strategies that can increase nutrient use efficiency and reduce nutrient loss without polluting clean water sources. Several studies share the same view (Chaikaew *et al.*, 2019; Chen *et al.*, 2015; Nagaraju, 2022; Vinothkumar *et al.*, 2021). By measuring nutrient inputs and outputs, farmers can determine the potential impact of pond management practices on water quality. This knowledge can guide them in making decisions regarding feed management, water exchange, and sediment management to maintain optimal water quality conditions for shrimp growth and minimize environmental impacts (Dien *et al.*, 2018; Funge-Smith & Briggs, 1998).

Efficiency of water spinach

The role of water spinach in using N and P from the waste load of vannamei shrimp cultivation reached 65.31 ± 7.62% and 39.55 ± 4.37% at 5 ppt salinity, and 48.67 ± 3.34% and 28.48 ± 0.33% at 10 ppt (Figure 3). The salinity treatment had a significant effect ($p < 0.05$) on the efficiency of water spinach in taking up N and P from the cultivation media. There was also a trend of decreasing efficiency in nutrient uptake with increasing salinity. The uptake of N and P by water spinach was 34.17% and 38.85% higher at 5 ppt salinity compared to 10 ppt. This was related to the biomass production of water spinach in each treatment.

Under 10 ppt salinity conditions, water spinach is expected to experience difficulty taking nitrogen from the cultivation media. Therefore, the deposition of nitrogen nutrients in the plant may decrease, leading to suboptimal growth and impacting water spinach productivity. A salinity of 10 ppt can also affect the availability and uptake of phosphorus in water spinach. Phosphorus is an essential nutrient for plant growth, and when its availability is limited due to high salinity, the plant may experience phosphorus deficiency. This can result in slow growth and reduced deposition of phosphorus nutrients in water spinach. Nutrient retention of N and P in the plant biomass is higher at 5 ppt salinity compared to 10 ppt. Higher salinity can reduce nutrient absorption in water spinach (Ferreira *et al.*, 2020; Uçgun *et al.*, 2020).

Water spinach (*Ipomoea aquatica*) is essential in aquaponic systems with shrimp and can play a role in phytoremediation (Love *et al.*, 2015), namely removing or reducing contaminants. This plant can absorb excess nutrients and metabolic waste fish or shrimp produce. Water spinach maintains water quality by absorbing these nutrients and reducing potentially toxic substances, such as leftover feed, faeces, and shrimp metabolites. The plant takes nutrients such as nitrogen and phosphorus from aquaponic water for its growth and development. Furthermore, water spinach offers continuity of nutrient cycling by taking nutrients and returning cleaner water to the aquaponic system (Pantanella *et al.*, 2012; Rakocy *et al.*, 2006). The plant provides habitat and hiding places for fish or shrimp in aquaponics systems (Love *et al.*, 2015). It forms dense root networks, offering a place for aquatic organisms to seek shelter. Water spinach stabilizes the substrate and enhances biodiversity in the aquaponics system. According to Endut *et al.* (2011), water spinach is more effective than green mustard in reducing nutrients in the utilized aquaponics system. This superiority is attributed to its root structure, which offers a more significant number of attachment sites for microbes, extends the residence time of wastewater, acts as a trap for suspended particles, possesses a more extensive root surface for pollutant adsorption, and facilitates absorption and assimilation within the plant tissue.

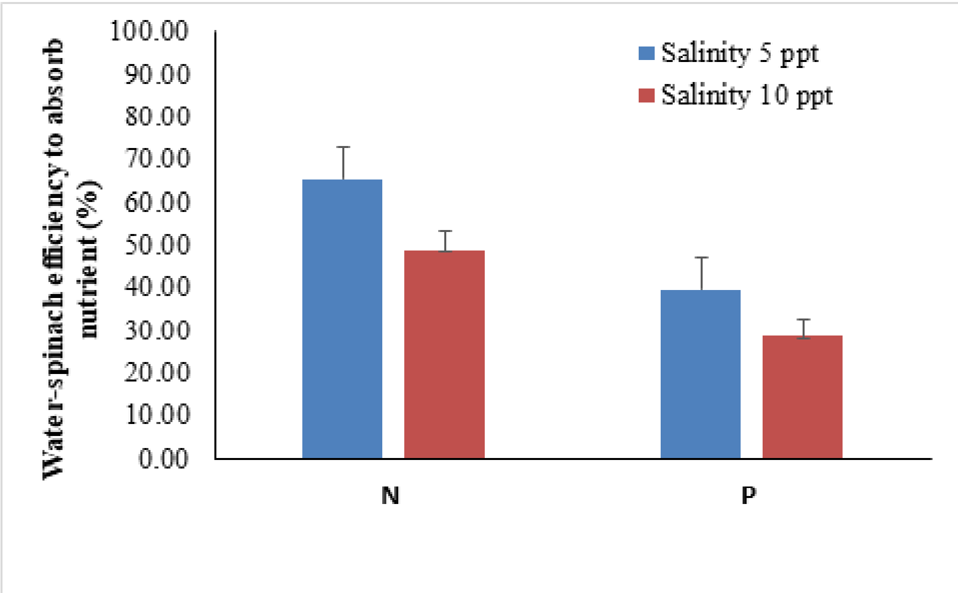


Figure 3. The efficiency of water spinach in utilizing the N and P waste load in low-salinity shrimp-water spinach aquaponic media.

In this research, the role of water spinach at 5 ppt salinity showed a significantly higher efficiency at 34.17%, and 38.85%, in absorbing N and P compared to 10 ppt salinity. Salinity affects nutrient absorption in plants, so it becomes a limiting factor (Kimera & Dawood, 2023), thus affecting growth (Sihotang, 2021; Yousif *et al.*, 2010). Plants experience leaf aging more quickly because photosynthesis is disrupted (Kusmiyati *et al.*, 2014; Rochmania, 2021). Plants experience leaf aging more quickly, photosynthesis and root growth are disrupted (Junandi *et al.*, 2019). This information is crucial for developing water spinach in managing wastewater from shrimp and fish aquaculture on a larger scale, using aquaponic systems. The functions of plants in low salinity aquaponics include: improving water quality (Armenta-Bojórquez *et al.*, 2021; T. Li *et al.*, 2021) and increasing income (Zacharof *et al.*, 2019). The environmentally friendly management of aquaculture waste entails refraining from directly discharging N and P waste into water bodies. The waste should be converted into productive plants that hold significant economic value. This approach mitigates pollution and harnesses the potential of waste by transforming it into valuable resources through plant utilization. The conversion reduces N and P waste in aquaculture water media (Goddek *et al.*, 2019; Yang & Kim, 2019), helping clean wastewater and minimising eutrophication's negative impacts in water bodies.

Integrating vannamei shrimp and water spinach aquaponics at low salinities in a single cultivation unit can be technically performed and scaled up to become a profitable enterprise. Meanwhile, the nutrient conversion process from aquaculture waste to valuable plant biomass supports circular economy activities. Floating aquaponic systems that integrate vannamei shrimp and water-spinach at low salinity are considered efficient in the use of cultivated land, and can be developed on coastal lands exposed to seawater to produce sustainable shrimp and vegetables throughout the year for the fulfilment of food security. In Bangladesh, aquaponics is cost-effective for food security and household income of coastal farms (Sunny *et al*., 2019). Aquaponics is one of the promising solutions to overcome poor water quality sourced from aquaculture activities, limited water availability and reduced fertile soil and plays a role in increasing healthy local organic food production with short supply chains in urban areas (Diatin *et al*., 2021).

FUTURE PROSPECTIVES

Some emerging trends in aquaponics that impact the prospects of this system include:

a) Integration of Interdependent Aquaculture and Hydroponics: The integration of aquaculture and hydroponics, known as aquaponics, is gaining popularity due to its dual benefits of reduced nutrient supplementation, water treatment, and improved profit by producing two cash crops simultaneously within the system.

b) Socio-economic and Environmental Prospectives: Aquaponics is being endorsed by governments, scientists, and populations as a sustainable food production method that addresses global challenges such as climate change, land and water quality diminution, rising fertilizer costs, and energy concerns. It is seen as a practical enterprise for arid conditions and urban settings and a livelihood strategy for food security and income generation among the rural poor.

c) Flocponics: An alternate type of aquaponics integrating biofloc technology with hydroponics is in the initial stage of development, and research efforts are needed to standardize setup and design experiments to enhance system productivity.

d) Climate-Smart Agriculture Approach: Aquaponics is recognized as a critical intervention in climate-smart agriculture, enhancing sustainable food security and economic development by effectively using land and water resources, nutrient and wastewater recycling, reducing pollution from aquaculture discharge, and mitigating greenhouse gas emissions. It is considered a promising tool to mitigate climate change and adapt to diverse conditions with proper management.

e) Organic Production Sector: There is a growing recognition of the feasible role of aquaponics in the organic production sector. Discussions are ongoing to blend principles of organic aquaculture and horticulture to benefit consumers, entrepreneurs, and the environment. Aquaponics is seen as a prospective ecological approach to the global food crisis and environmental impacts, offering sustainable and ecological intensification compared to standalone hydroponics and aquaculture.

These trends indicate a positive trajectory for aquaponics, showcasing its potential to address various challenges in food production, sustainability, and economic development. By leveraging these emerging trends, aquaponics can continue to evolve as a viable and sustainable food production system with promising prospects.

CONCLUSION

In conclusion, the water salinity significantly affected the production performance of both vannamei shrimp and water spinach. It also had a significant impact on the absorption efficiency of N in water spinach but did not show a significant difference for P. The vannamei shrimp and water spinach thrived well at a salinity of 5 ppt, making it the recommended optimal condition for integrated cultivation. These two species were compatible and complemented each other's role in developing low-salinity aquaponics.

Further research should provide more specific data and information regarding the impact of salinity on product quality and nutrient deposition of N and P in water spinach, as well as the mineral requirements for shrimp and water spinach aquaponics at low salinity levels.

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Conflict of interest statement

The author declares that there is no conflict of interest in this scientific writing.

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