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Effect of an *Ipomoea aquatica* Floating Raft on the Water Quality, Antioxidant System, Non-Specific Immune Responses, and Microbial Diversity of *Penaeus vannamei* in an Aquaculture System

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Abstract: Pacific white shrimp (*Penaeus vannamei*) is one of the main shrimp species cultivated around the world. Despite its high yields and easy handling, water pollution from intensive shrimp cultivation remains a serious problem in China. In this study, a compound aquaculture model of *P. vannamei* and water spinach (*Ipomoea aquatica*) was used to investigate the effect of a water spinach floating raft on water quality, antioxidants, non-specific immune response, growth performance, and microbial diversity. The experimental design of this study consisted of two groups with three replicates for each, i.e., control group: aquatic monoculture (AM) system with only *P. vannamei*; treatment group: *P. vannamei-I. aquatica* raft aquaponics (AP) system with a 50% cover ratio with a water spinach floating raft. The experiment lasted for seven weeks. The results show that the concentrations of total phosphorus (TP), total nitrogen (TN), nitrate nitrogen (NO_3^--N), ammonia nitrogen (NH_4^+-N), nitrite nitrogen (NO_2^--N), and active phosphorus (AP) in the AM group were higher than those in the AP group at different sampling times. The water quality index of the AP group was better than that of the AM group, indicating that water spinach can remove the nutrients from aquaculture water bodies. The average daily gain and survival rate of shrimp in the AP group were higher than those in the AM group. The total antioxidant capacity (T-AOC), catalase (CAT), superoxide dismutase (SOD), malondialdehyde (MDA), and acid phosphatase (ACP) in the AP group were better than those in the AM group. The Shannon–Wiener and Simpson indices of the gut, water, and sediment of the AP system were significantly higher than those in the AM system, which implied a higher abundance of microorganisms in the AP system. These results demonstrate that the application of a water spinach floating raft in aquaponics can not only improve the water quality, but also improve the growth performance, antioxidant system, and non-specific immune responses of Pacific white shrimp, while increasing the abundance of microorganisms in the aquaculture system and improving the ecological benefits in terms of the expenditure.

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Key Contribution: *Ipomoea aquatica* floating raft system demonstrated the potential to improve the water quality and microbial diversity in shrimp cultivation.

1. Introduction

In China, pond culture is a long-established culture method [1]. However, high-density stocking and overfeeding not only adversely affect the health of aquatic animals, but also lead to the accumulation of large amounts of feed and feces in ponds [2]. Large quantities of carbon, nitrogen, and phosphorus in feed are utilized inefficiently [3]. These nutrients are carried into natural water bodies during wastewater discharge, resulting in eutrophication of water bodies [4]. In response to these problems, aquaponics systems represent an alternative green development strategy.

Penaeus vannamei belongs to Arthropoda, Crustacea, Decapoda, Penaeidae, *Penaeus* and is native to the Pacific coast of South America [5]. The global production of Pacific white shrimp was 5.81 million tons in 2022, accounting for 51% of the total shrimp production [6]. However, with the rapid development of the industry, agriculture, and aquaculture, the discharge of industrial and domestic sewage and the use of fertilizers have gradually increased, and water quality is deteriorating year by year. With the increase in aquaculture density, especially the accumulation of residual feed in intensive culture systems, in 2010, Chinese mainland aquaculture released 0.9 million tons of phosphorus and 5 million tons of nitrogen into the environment [7]. Aquaculture water quality deterioration is harmful to shrimp, leading to reductions in the immunity and survival of shrimp. Sustainable farming patterns are emerging, e.g., aquaponics, which can absorb the compounds in aquaculture water through plants, so as to alleviate the eutrophication of water. The root system of plants can further increase the attachment area of microorganisms in the water column, and these microorganisms contribute to the degradation of organic matter and further purify the water [8].

Studies have confirmed that many hydroponic plants can have positive effects in aquaponics systems. Water spinach (*Ipomoea aquatica*) is a plant of interest in aquaponics research and a common vegetable in Southeast Asia [9]. Water spinach in high-concentration wastewater has better removal rates in terms of nitrogen and phosphorus [10]. Studies have shown that a concentration of 50 mM NaCl does not affect the germination and growth of water spinach [11]. A mixture of 30:70 seawater and freshwater could promote the growth of water spinach, which further indicates the great potential of water spinach application for shrimp aquaculture effluent treatment [12]. Studies on aquaponics systems consisting of water spinach and shrimp are still unclear. In this study, in view of the considerable economic value and increasing demand for shrimp, an aquaponics system consisting of floating rafts of water spinach and Pacific white shrimp was constructed. The benefits of the aquaponics system were elucidated by measuring water quality indicators, shrimp growth indicators, antioxidant indicators, and system microbial diversity.

2. Materials and Methods

2.1. Pond and Shrimp–Water Spinach Raft Aquaponics System Design

An aquaponics system study based on water spinach (*I. aquatica*) and Pacific white shrimp (*P. vannamei*) was conducted in 6 plastic ponds (length × width × height = 1.6 m × 0.9 m × 0.65 m) at the Teaching and Research Base of South China Agricultural University (Figure 1c). Six plastic ponds, each with a capacity of 800 L, were filled with 5‰ salinity water. The ponds were located indoors, each pond was self-contained, and no water was exchanged throughout the culture experiment. Healthy shrimp (body mass = 0.089 ± 0.0103 g) were collected from Guangdong Liyang Aquaculture Co., Ltd.

from Guangzhou. A total of 100 shrimp from each pond were acclimated for two weeks and maintained under standard conditions (salinity at 5‰, pH at 7.9 ± 0.1, temperature at 22 ± 2 °C, and dissolved oxygen higher than 6 mg/L). Shrimp were then moved to plastic ponds. Shrimp were hand-fed commercial feed to apparent satiation (approximately 4% of body weight per day) two times daily (08:00 and 20:00). *Ipomoea aquatica* is a native species and was purchased from the Teaching and Research Base of South China Agricultural University. The initial biomass of *I. aquatica* was 1.146 kg/m^2 on floating beds. The experimental design included two systems (AP and AM) (Figure 1). The AP system comprised 50% cover of about 0.72 m^2; the *I. aquatica* floating bed was planted on the surface of each plastic pond (Figure 1d). The AM system had no floating bed on the surface of the plastic pond (Figure 1c); this was the control group in this study. Each system included three plastic ponds for three replicates. Shrimp from each plastic pond were measured and weighed individually at the end of the experiment (Figure 1a). In addition, each floating bed production group was measured and weighed individually after the experiment. The overall experimental period lasted for 62 d.

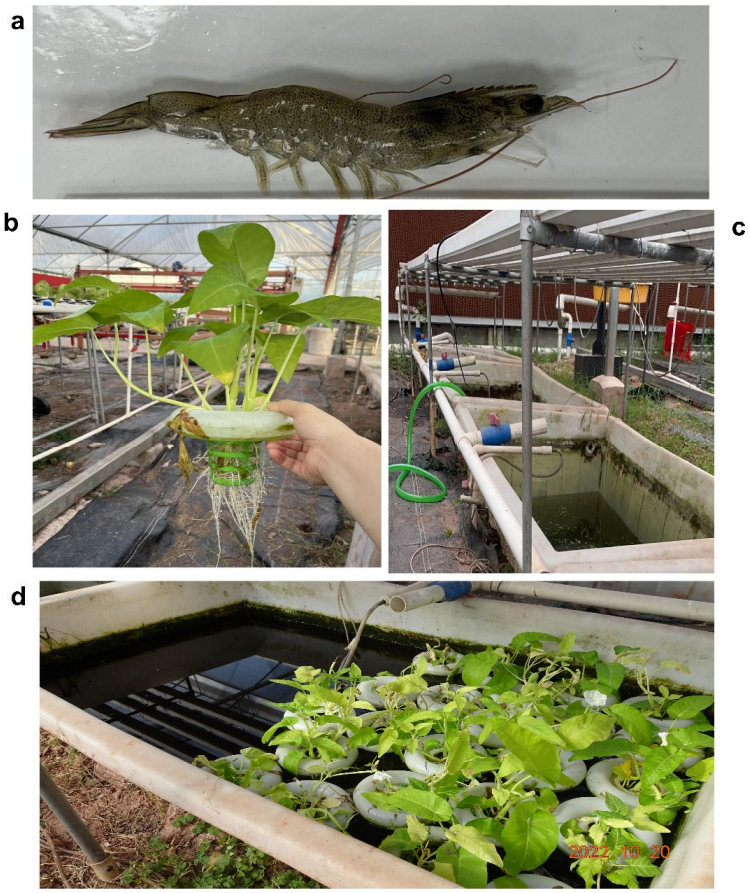

Figure 1. Introduction of the aquaponics system used in this study. The pictures were taken on the final day. (**a**) Pacific white shrimp cultured in the system; (**b**) water spinach from the aquaponics system; (**c**) shrimp aquatic monoculture system without water spinach floating raft; (**d**) shrimp–water spinach raft aquaponics system with 50% plant cover. Each treatment included three plastic ponds for three replicates.

2.2. Water Sample Collection and Measurement of Temperature, pH, TBN, TH, Ca^{2+}, Mg^{2+}, TP, TN, NO_3^--N, NH_4^+-N, NO_2^--N, and AP

Temperature and pH were measured daily, and the water quality of each group was tested weekly, including total base number (TBN), total hardness (TH), Ca^{2+}, and Mg^{2+}. The water indicator collection during the experimental period and water quality analysis

were conducted as described previously [13]. Briefly, water samples were collected using a water column sampler gap once a week. The samples in each pond were taken within 20 cm of the water surface over five locations and were subsequently mixed. A quantity of 500 mL of water from each pond was stored. The samples were kept at 4 °C for analysis within two days. The water quality index total phosphorus (TP), total nitrogen (TN), nitrate nitrogen (NO_3^--N), ammonia nitrogen (NH_4^+-N), nitrite nitrogen (NO_2^--N), and active phosphorus (AP) were measured according to standard methods. The analyses were conducted in triplicate. The relative removal rate was used to estimate the relative capacity for water purification of each treatment for TN, NH_4^+-N, NO_2^--N, NO_3^--N, TP, and AP.

2.3. Growth of P. vannamei and I. aquatica

At the beginning of the experiment, shrimp were moved into ponds. Fifty shrimp were randomly chosen from holding ponds, and we measured their initial weight individually. The initial weight of hydroponic plants was also measured individually before the experiment. At the end of the experiment, shrimp were randomly chosen from each pond and weighed individually. Each floating bed production group was also weighed individually after the experiment. The following equations were used. Growth rate (%) = (Wt-W0)/W0 × 100%, where W0 indicates the weight at the beginning of the experiment and Wt represents the weight of each treatment at the end [14]. Survival rate (%) = St/S0 × 100%, where S0 indicates the initial number of shrimp, while St represents the number of surviving shrimp in each treatment at the end of the experiment.

2.4. Analysis of Antioxidant and Immune Responses of P. vannamei

At the end of the experiment, nine shrimp in each treatment were randomly collected and anesthetized with 50 mg/dm^3 MS-222 in water and were used for hemolymph collection. Hemolymph was collected from the caudal vein, kept at room temperature for 1 h, then centrifuged at 3500 rev/min for 10 min. The resultant serum was stored at −80 °C. Hepatopancreas, gills, and intestines were collected and placed in separate 1.5 mL centrifuge tubes, then stored at −80 °C. The total antioxidant capacity (T-AOC), catalase (CAT), superoxide dismutase (SOD), malondialdehyde (MDA), and acid phosphatase (ACP) activities of serum, hepatopancreas, and gills were measured via the respective assay kits, which were purchased from Nanjing Jiancheng Bioengineering Institute (Nanjing, China).

2.5. Microbial Diversity and Abundance Analysis

At the end of the experiment, sediment samples from the bottom of the pond, shrimp guts, and breeding water were collected; six samples of breeding water, sediment, and shrimp guts of *P. vannamei* were collected. A total of 18 microbial samples were collected for microbial diversity and abundance analysis. For DNA extraction, we collected five shrimp per plastic pond, totaling fifteen shrimp per treatment. DNA was extracted using the Stool DNA Kit (Omega, Norcross, GA, USA) according to the manufacturer's protocol [15]. To determine the diversity and abundance of the bacterial communities in each group, a previous protocol was followed. The V4 region of the 16S rRNA gene was amplified with the 515f/806 r primer via PCR amplification. DNA was amplified as described previously [16]. Sequencing was then conducted on an Illumina MiSeq platform.

2.6. Data Analysis

The data were checked for homoscedasticity using the Hartley homogeneity of variance test. Significant differences among treatments were determined using one-way analysis of variance and least-significant difference tests via SPSS 20.0. A statistical significance level of 0.05 was employed for all analyses ($p < 0.05$ was considered to be significant and $p < 0.01$ to be highly significant). The values and other parameters are shown as means ± standard deviation. Pairs of reads from the original DNA fragments were merged using FLASH [17]. Sequencing reads were assigned to each sample according to the unique barcode for each sample. Sequences were analyzed using the Quantitative Insights into

Microbial Ecology (QIIME 2.0) software package and the UPARSE pipeline. In addition, custom perl scripts were used to analyze alpha (α) diversity as measured via the OUTs, Chao, ACE, Shannon, and Simpson (1-Simpson's index) indices.

3. Results

3.1. A Water Spinach Floating Raft Can Improve the Water Quality of a Shrimp Culture

Throughout the experiment, there was no significant difference in temperature and pH between the experimental group and the control group (Figure 2a,b). Since no warming equipment was used, the water temperature was between 21 °C and 25 °C (Figure 2a). Both pH and temperature ensure the growth of shrimp and water spinach. The results show that from the 5th to the 7th week, the TBN value of the control group was significantly higher than that of the experimental group ($p < 0.05$) (Figure 2c). At the 2nd, 4th, 5th, 6th, and 7th weeks, the TH of the experimental group was significantly lower than that of the control ($p < 0.05$) (Figure 2d). From the 4th to the 7th week, the Mg^{2+} of the experimental group was significantly lower than that of the control group ($p < 0.05$) (Figure 2f). The Ca^{2+} level in the experimental group was significantly lower than that of the control group at the 4th week ($p < 0.05$) (Figure 2e). These results indicate that the concentrations of TBN, TH, Ca^{2+}, and Mg^{2+} were significantly reduced in the aquaponics system, which may be attributed to the growth of water spinach.

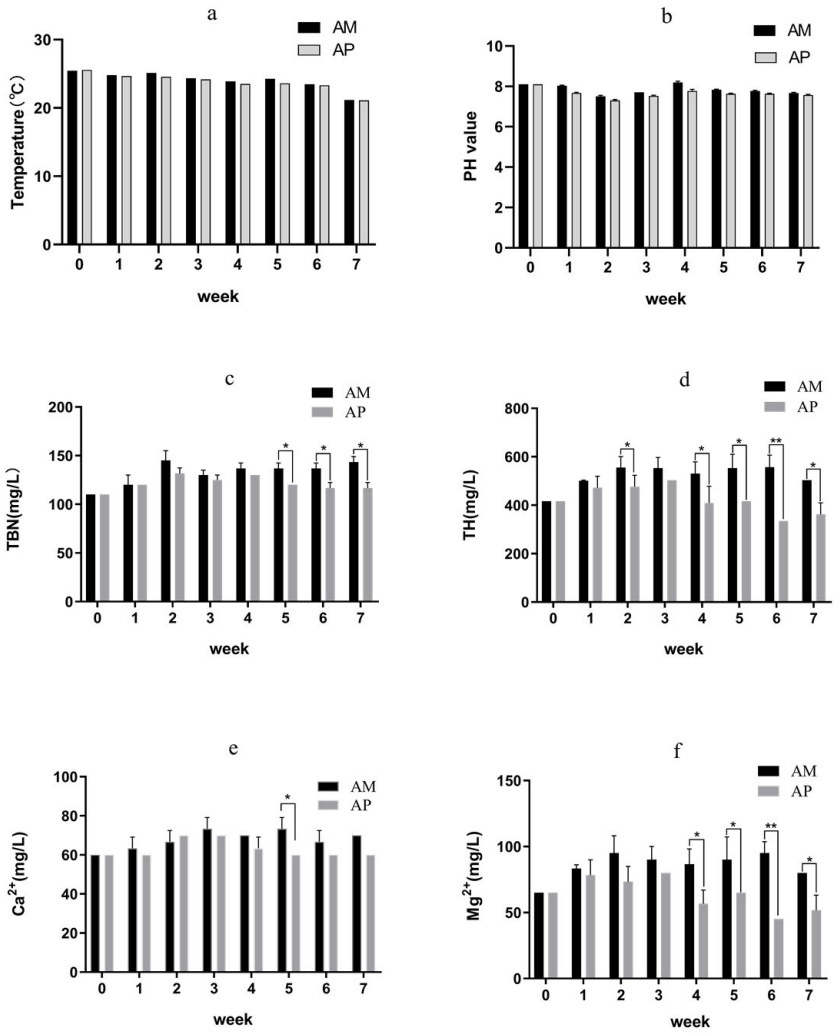

Figure 2. The modulation of water quality including temperature, pH, TBN, TH, Ca^{2+}, and Mg^{2+} in AP and AM systems at different times. (**a**) Temperature, (**b**) pH, (**c**) total base number (TBN), (**d**) total hardness (TH), (**e**) calcium (Ca^{2+}), and (**f**) magnesium (Mg^{2+}) ($n = 3$; * $p < 0.05$; ** $p < 0.01$).

Other water quality indicators, including TN, NH4+-N, NO_2^--N, NO_3^--N, TP, and active phosphorus (AP) were also tested weekly. The results show that from the 2nd to the 7th week, the TN of the control group was significantly higher than that of the experimental group ($p < 0.05$) (Figure 3a). At the 2nd, 4th, 5th, 6th, and 7th weeks, the NH_4^+-N of the experimental group was significantly lower than that of the control group ($p < 0.05$) (Figure 3b). From the 2nd to the 7th week, the NO_2^--N of the experimental group was significantly lower than that of the control group ($p < 0.05$) (Figure 3c). At the 3rd, 4th, and 7th weeks, the NO_3^--N of the experimental group was significantly lower than that of the control group ($p < 0.05$) (Figure 3d). From the 3rd to the 7th week, the components of TP and active phosphorus (AP) in the experimental group were significantly lower than those of the control group ($p < 0.05$) (Figure 3e,f). The above results show that the aquaponics system can significantly reduce the ammonia and nitrite nitrogen concentrations in the water column, which is favorable for healthy aquaculture. TP and active phosphorus (AP) concentrations were significantly decreased in the aquaponics system, which might also be related to the need for phosphorus for the growth of water spinach.

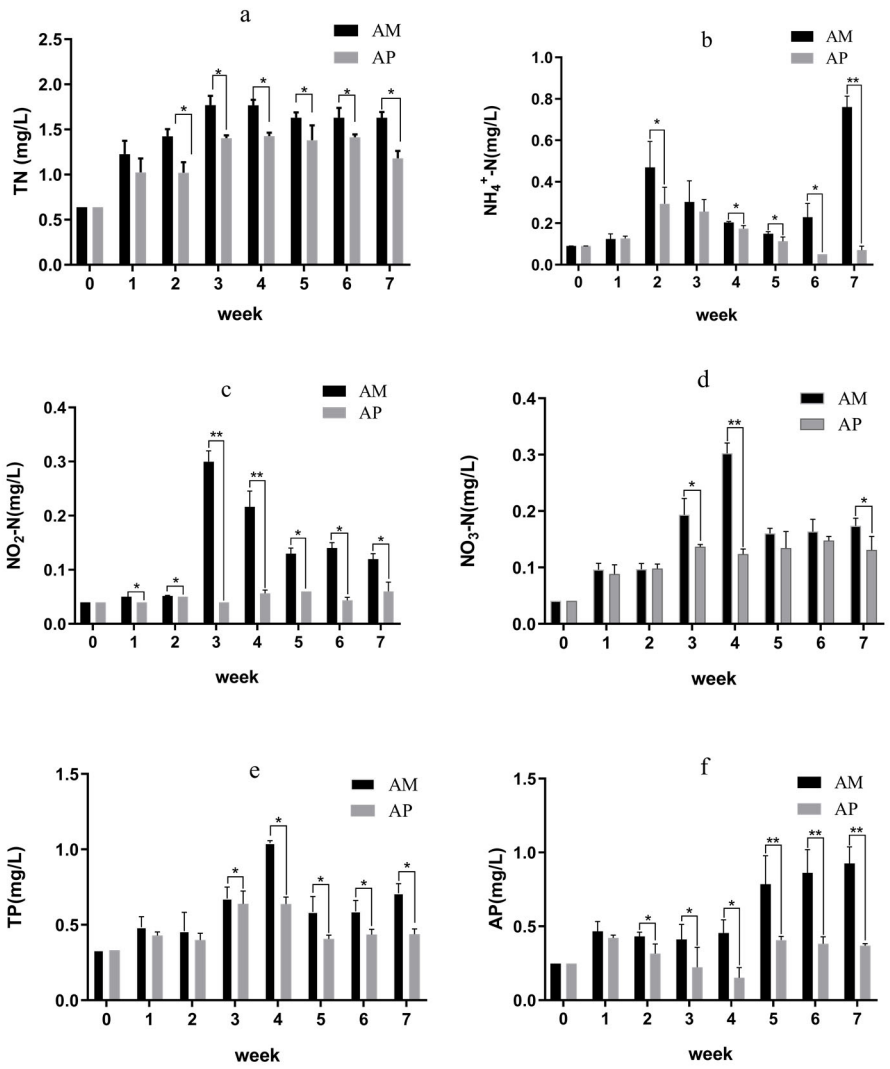

Figure 3. The modulation of water quality including TN, NH_4^+-N, NO_2^--N, NO_3^--N, TP, and AP in the aquaponics system and the aquatic monoculture system at different sampling weeks. (**a**) Total nitrogen (TN), (**b**) ammonia nitrogen (NH_4^+-N), (**c**) nitrite (NO_2^--N), (**d**) nitrate (NO_3^--N), (**e**) total phosphorus (TP), and (**f**) active phosphorus (TP) ($n = 3$; * $p < 0.05$; ** $p < 0.01$).

3.2. The Water Spinach Raft Aquaponics System Improved the Production Performance of Shrimp

In order to further understand the impact of the AP system on the growth performance, the survival rate, relative growth rate, and total harvest weight of shrimp and water spinach in the AP and AM systems were measured. During the experiment, the water spinach in the system was harvested twice. The first harvest of water spinach in each pond was 1640.6 ± 52.201 g. The final harvest of water spinach in each pond was 1206.3 ± 40.869 g. Throughout the entire experimental period, we harvested 8538 g of water spinach from three ponds of the AP system. The growth data for shrimp show that the final weight of shrimp in the AP system was significantly higher than that in the AM system. The survival rate of shrimp in the AP system was also significantly higher than that in the AM system. These results show that the AP system improved the growth performance of shrimp significantly (Table 1). Compared to the AM system, the AP system also produced over 8000 g of water spinach.

Table 1. Growth performance of shrimp and water spinach. Different letters represent significant differences between groups ($p < 0.05$).

Data per Pond	AP Water Spinach	AP Shrimp	AM Shrimp
Initial weight (g/pond)	231 ± 5.507	0.089 ± 0.0102	0.089 ± 0.0102
First harvest weight (g/pond)	1640.6 ± 52.201	/	/
Final weight (g/pond)	1206.3 ± 40.869	1.878 ± 0.178 [a]	1.166 ± 0.376 [b]
Relative growth rate (%)	1232.03	2110.11 [a]	1310.11 [b]
Survival rate (%)	100	76 [a]	71 [b]
Total harvest weight (g)	8538	142.728 [a]	82.786 [b]

3.3. The Antioxidant and Non-Specific Immune Response of Shrimp Were Improved in the AP System

In order to further explore the effect of the aquaponics system on the antioxidation and non-specific immune indicators of shrimp, hepatopancreas, gill, and muscle were sampled after seven weeks and the enzyme activity of T-AOC, CAT, SOD, MDA, and ACP was detected. The results show that the hepatopancreas T-AOC, CAT, SOD, and ACP of the AP system were significantly higher than those of the AM system (Figure 4c,e). The hepatopancreas MDA of the AP system was significantly lower than that of the control group (Figure 4d). MDA in the hepatopancreas and spleen of the AP system was significantly lower than that of the AM system (Figure 3d). CAT in the hepatopancreas and kidney of the AP system was significantly higher than that of the AM system (Figure 3c). CAT in the gill of the AP system was significantly higher than that of the AM system (Figure 3b). MDA in the gill of the AP system was significantly lower than that of the AM system (Figure 3d). These results indicate that the antioxidant and non-specific immune indicators of shrimp under the aquaponics system seem to be better than those under the aquatic monoculture system.

3.4. The Microbial Diversity and Abundance Analysis Were Different between the AP and AM Systems

To further understand the microbial diversity of the two different systems, shrimp guts, breeding water, and sediment were collected for microbial diversity and abundance analysis at the seventh week. As shown in Table 2, a total of 44 phyla, 115 orders, 346 orders, 861 families, 1672 genera, and 2244 species of microorganisms were detected in all samples. The Shannon–Wiener and Simpson indices of the gut, water, and sediment of the AP system were significantly higher than those in the AM system, which implied a higher abundance of microorganisms in the AP system (Table 3). Among these three samples, the Shannon–Wiener and Simpson indices of the sediment were the highest, which implied that the microbial abundance of the sediment in the system was higher than that of the shrimp gut and water sample.

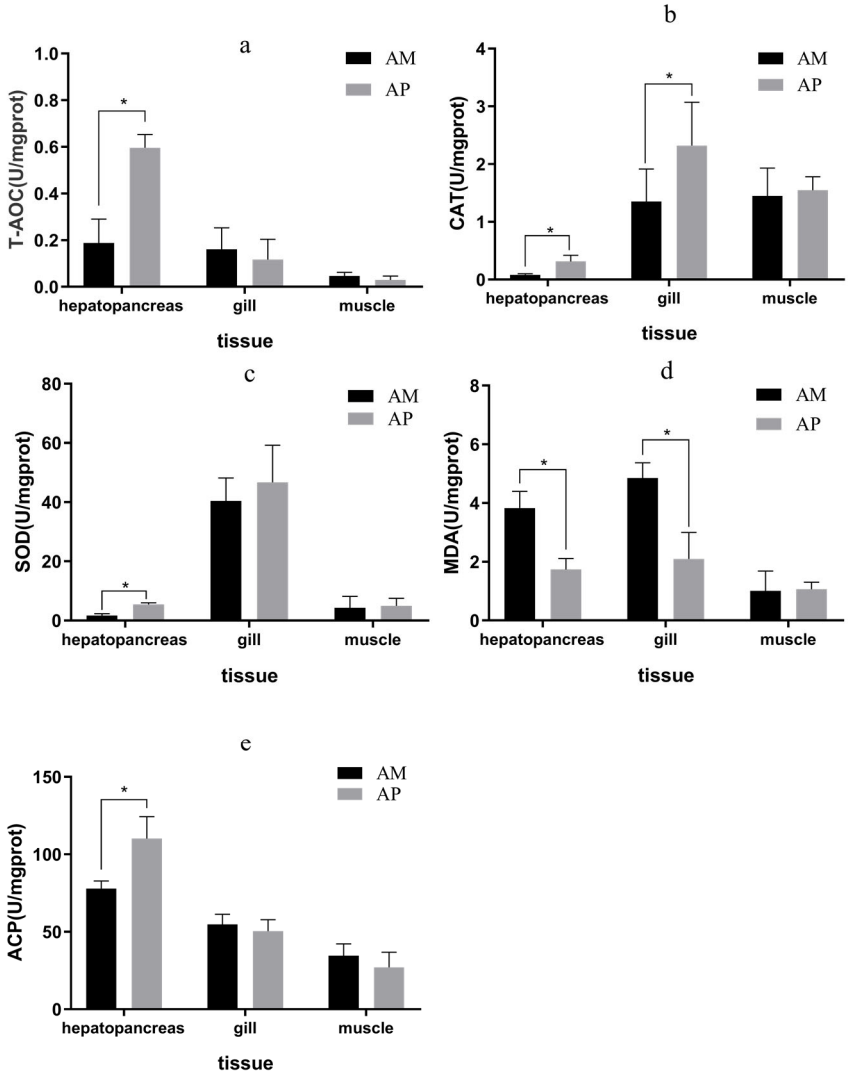

Figure 4. Non-specific immune responses of hepatopancreas, gills, and muscles in AP and AM systems. (**a**) Total antioxidant capacity (T-AOC), (**b**) catalase (CAT), (**c**) superoxide dismutase (SOD), (**d**) malondialdehyde (MDA), and (**e**) acid phosphatase (ACP) ($n = 3$; * $p < 0.05$).

Table 2. Composition of microbial communities in shrimp gut, water, and sediment.

Sample	Groups	Phylum	Class	Order	Family	Genus	Species
Gut	AP system	34	87	222	377	619	664
	AM system	32	84	210	393	594	638
Water	AP system	37	92	244	434	720	780
	AM system	34	87	209	372	588	664
Sediment	AP system	38	87	217	386	612	780
	AM system	33	81	206	372	573	638

As shown in Figure 5, *Proteobacteria*, *Cyanobacteria,* and *Bacteroidetes* were the top three species in terms of relative abundance, with *Proteobacteria* having the highest percentage. Different sample types present differences at the phylum classification level; the relative abundance of *Proteobacteria* in water samples and shrimp gut samples was higher than in the sediment samples. Additional phyla also presented in the AP and AM systems, such as *Firmicutes*, *Actinobacteriota*, *Chloroflexi*, *Acidobacteriota*, *Gemmatimonadota*, and *Desulfobacterota*.

Table 3. Microbial diversity and abundance analysis of shrimp guts, breeding water, and sediment based on alpha (α) diversity analysis. Different letters represent significant differences between groups ($p < 0.05$).

Index	Sample	AP	AM
Shannon–Wiener index	Guts	8.7425 [a]	8.5342 [b]
	Water	8.9987 [a]	8.8721 [b]
	Sediment	9.5536 [a]	8.7655 [b]
Simpson index	Guts	0.9695 [a]	0.9740 [a]
	Water	0.9785 [a]	0.9768 [b]
	Sediment	0.9919 [a]	0.9792 [b]

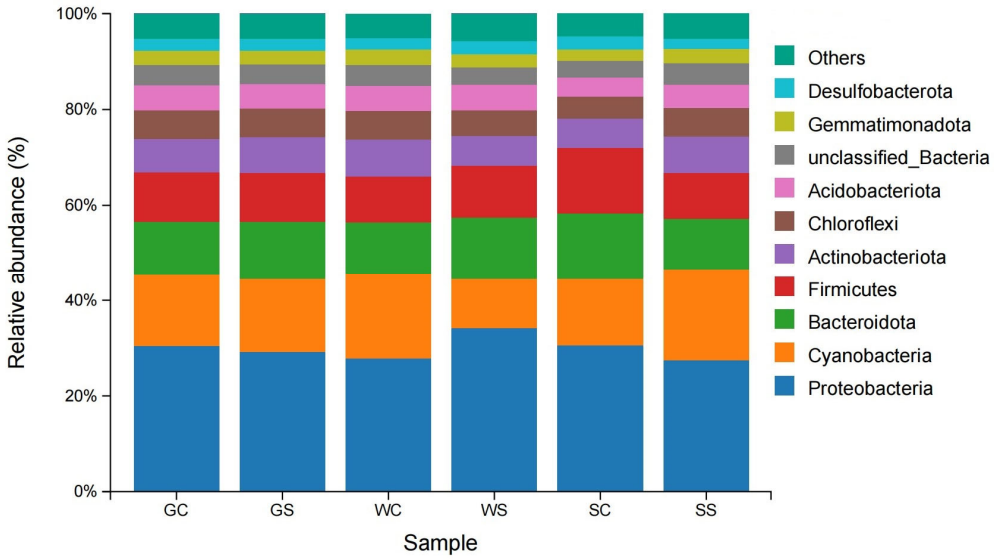

Figure 5. Dominant bacterial phyla and relative abundance analysis in shrimp guts, breeding water, and sediment content samples in different treatments. GC represents shrimp guts from the AM system, GS represents shrimp guts from the AP system, WC represents breeding water from the AM system, WS represents breeding water from the AP system, SC represents sediment from the AM system, and SS represents sediment from the AP system.

4. Discussion

As pH is an important water quality index in aquaculture, pH stability is vital for the growth of aquatic animals, plants, and microorganisms. Abnormally high pH values can enhance ammonia toxicity and affect shrimp growth. Abnormal decreases in pH can easily lead to acidosis in fish and shrimp, causing physiological hypoxia in aquatic animals [13]. Studies have shown that the pH value of water is determined by the content and decomposition degree of organic matter in water and the balance system of free carbon dioxide and calcium carbonate, while free carbon dioxide in water mainly depends on plant photosynthesis, respiration, and the oxidative decomposition of organic matter [18]. In this study, the pH of the AP and AM systems stayed within a physiologically safe range during the whole farming process. The optimum temperature for the growth of *P. vannamei* was 23–30 °C [18]. In this study, there was no significant difference in temperature between the experimental group and the control group, which is consistent with previous studies [13].

The modification of nitrogen and phosphorus is a vital factor for water eutrophication [19]. Water eutrophication leads to fishery reduction, environmental destruction, and reductions in species diversity [20]. Studies have shown that the roots of aquatic plants can not only remove particulate phosphorus and phosphorus-containing organic debris in water via adsorption and interception, but also directly remove phosphorus through adsorption and enrichment, while dissolved organophosphates and inorganic phosphorus

in water can be directly assimilated and then used for the synthesis of substances needed for life [21]. The main sources of nitrogen for aquatic plants are dissolved organic and inorganic nitrogen, and absorbed ammonium nitrogen is used directly for amino acid synthesis. Absorbed nitrate nitrogen can only be utilized after metabolic reduction [22]. In this research, from the 2nd to the 7th week, the TN of the AM system was significantly higher than that of the AP system. From the 3rd to the 7th week, the components of TP and AP in the AP system were significantly lower than those of the AM system. This suggests that regular harvesting of water spinach is effective in removing nitrogen and phosphorus from the culture system. In addition, the growth of water spinach can effectively absorb calcium and magnesium in the water body, which is conducive to the total alkalinity and total hardness of the water body to maintain relative stability [23].

Ammonia nitrogen is a combined nitrogen composed of free ammonia and ammonium ions; free ammonia is highly toxic to aquatic organisms [24]. When ammonia levels exceed the tolerance limits of shrimp, they inhibit hemolymph antimicrobial activity, molting, and growth, thereby attenuating the innate immune response of shrimp [25]. Studies on shrimp and ammonia have shown that as ammonia concentration increases, the levels of bacteriolytic and antibacterial activities decrease [26]. Similar results have been found for nitrite nitrogen; as the nitrite nitrogen concentration increases, shrimp survival decreases [27]. During the experimental period, the NH_4^+-N, NO_2^--N, and NO_3^--N of the AP system were significantly lower than those of the AM system. Ammonia and nitrite nitrogen are toxic to shrimp, and excessive levels may result in shrimp mortality. Through aquaponics experiments with cherry tomato, lettuce, and basil, it was found that compared with a hydroponics system, the aquaponics system produced significantly less environmental waste and had a higher utilization rate of nitrogen and phosphorus [28]. Similar results were also found in an aquaculture–koi symbiotic system [29]. A study of Ipomoea aquatica and grass carp showed that Ipomoea aquatica had obvious removal effects for ammonium nitrogen and nitrous nitrogen [30].

When the load of nitrogen and phosphorus exceeds the self-purification capacity of the water body, this can lead to the appearance of eutrophication of the water body, resulting in algae blooms. When algae die and decompose, they need to consume a large amount of oxygen, and a variety of toxic and harmful substances are produced during the decomposition process, thus hindering the growth of fish [31]. In our experiment, the final weight of shrimp in the AP system was significantly higher than that in the AM system. The survival rate of shrimp in the AP system was also significantly higher than that in the AM system. Dissolved organic phosphorus and inorganic phosphorus in water can be directly assimilated for the synthesis of substances needed for water spinach. The results of this study indicate that the improvement in shrimp growth was attributed to water quality improvement by water spinach.

Almost all cells have a complete antioxidant system for eliminating the by-products of metabolism (oxygen free radicals) and preventing the damage caused by oxygen free radicals to cell bodies [32]. As a line of defense in the antioxidant system, SOD can catalyze the conversion of superoxide free radicals and singlet oxygen free radicals generated in the metabolism or tissue reactions into hydrogen peroxide and oxygen, thereby reducing the risk of potentially harmful superoxide anions [33]. The total antioxidant capacity (T-AOC) depends on antioxidant systems and non-enzymatic systems. The enzymes include glutathione peroxidase (CSH-Px), superoxide dismutase (SOD), and catalase (CAT) [34]. In our experiment, the hepatopancreas T-AOC activity of the AP system was significantly higher than that of the AM system. A similar phenomenon was observed for hepatopancreatic CAT and SOD. The hepatopancreatic CAT and SOD activities of shrimp in the AP system were significantly higher than those in the AM system. The gill CAT activity of shrimp in the AP system was significantly higher than that of shrimp in the AM system. T-AOC, CAT, and SOD are critical components of the primary antioxidant system and are commonly used to indicate the body's antioxidant capacity. The activity levels of ACP reflect the metabolic capacity and immune capacity. Hepatopancreatic ACP activity of shrimp in the

AP system was significantly higher than that of shrimp in the AM system. The results of the present study suggest that the aquaponics system is beneficial for improving the antioxidant capacity of shrimp. Lipid peroxidation occurs through the action of free radicals produced by non-enzymatic systems, and the oxidation end-product is MDA [35]. The production of MDA affects the activity of the mitochondrial respiratory chain complex and enzymes in the mitochondria [36]. The results of this study show that the hepatopancreas and gill MDA of the AP system was significantly lower than that of the AM system, which reflected that the level of cellular damage in shrimp of the AP system was lower than that of the AM system.

Intestinal microorganisms and their own flora structure play an important role in the development and growth of aquatic animals. The intestinal microorganisms of shrimp are closely related to their nutritional metabolism, gastrointestinal development, and immune defense [37]. Studies have shown that in the larval stage, the gastrointestinal tract of shrimp is not fully developed and the immune system is still relatively incomplete. When the shrimp directly ingests food from water, it begins to form its own microbial flora [38]. The bacteria in the gut of *Penaeus vanna* can be found in the aquatic environment [39]. A similar phenomenon is seen in the intestinal flora of *Penaeus longicaeus* [40,41]. A study of the bacteria in the gut and sediment of *Sticostis Japonicus* showed that the number of bacterial populations changes with the seasons, indicating that the bacterial strains are intrinsically correlated [42]. The results of our study show that there were 44 categories, 115 classes, 346 classes, 861 families, and 1672 genera detected in the water samples, sediment, and gut of *P. vannamei*, which indicated that the environment had a close relationship with the intestinal microorganisms of *P. vannamei*. From the distribution of each taxonomic level, the most common microorganisms exist between the water and guts. This pattern can also be found from the perspective of microbial community diversity. Microbial community diversity plays an important role in maintaining ecological functions. A low diversity of microbial communities may result in poor functional stability, increasing the risk of biological diseases. Studies have shown that a higher α diversity in aquaculture water is more conducive to the stability of the water environment and the development of shrimp calves; lower diversity may lead to disease in shrimp calves [43,44].

Previous studies have shown a correlation between the Shannon index and shrimp health, suggesting that the Shannon index could be regarded as a health indicator of *P. vannamei* [45]. In the present study, the diversity index of sediments was significantly higher than that of water and gut samples, implying that most of the intestinal flora may be of environmental origin. Intestinal microbial diversity is considered to be a biomarker representing host health and metabolic capacity [46]. The bacterial diversity of the AM system was lower than that of the AP system, indicating that microbial diversity plays a vital role in the regulation of animals.

5. Conclusions

The *Ipomoea aquatica* floating raft system investigated in this study improved the water quality in a shrimp culture. The contents of TN, NH_4^+-N, NO_2^--N, NO_3^--N, and TP were significantly lower in the AP system than those of AM system. The antioxidant indices of shrimp in the AP system were better than those in the AM system, suggesting that the application of water spinach floating rafts has the potential to promote shrimp health. The growth indicators of shrimp in the AP system were better than those of the AM system, implying that the aquaponics culture system seems to have better economic benefits. The Shannon–Wiener index and Simpson index of the gut, water, and sediment of the AP system were significantly higher than those in the AM system, which implied a higher abundance of microorganisms in the AP system.

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Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

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