

Impact of Dietary Supplements on Growth, Immunity, and Feed Efficiency in Aquaculture Fish

Ansa Noreen

Department of Zoology, Faculty of Life Sciences, University of Okara, Okara 56130 Pakistan

Isham Zahra

Department of Zoology, Wildlife, and Fisheries, University of Agriculture, Faisalabad, Pakistan

Mutiba Nisar

Department of Zoology, Faculty of Life Sciences, University of Okara, Okara 56130 Pakistan

Aman Ullah

Department of Zoology, Faculty of Life Sciences, University of Okara, Okara 56130 Pakistan

Kiran Ahmad Khan

Department of Zoology, Wildlife, and Fisheries, University of Agriculture, Faisalabad, Pakistan

Fakher Adnan

Department of Zoology, Wildlife, and Fisheries, University of Agriculture, Faisalabad, Pakistan

Muhammad Ahsan Ashraf

Department of Zoology, Division of Science and Technology, University of Education, Lahore 54000, Pakistan

Ali Umar

Department of Zoology, Faculty of Life Sciences, University of Okara, Okara 56130 Pakistan

Shakoor Ahmad

Department of Chemistry, University of Okara, Okara 56130, Pakistan

Hayat Ullah*

Department of Chemistry, University of Okara, Okara 56130, Pakistan
ayaanwazir366@gmail.com

Muhammad Saleem Khan*

Department of Zoology, Faculty of Life Sciences, University of Okara, Okara 56130 Pakistan
samiikhana@uo.edu.pk

ABSTRACT

A 56-day feeding trial was conducted to evaluate the effects of dietary prebiotics, probiotics, and synbiotic on growth, feed utilization, immunity, antioxidant capacity, and disease resistance in Nile tilapia (*Oreochromis niloticus*). A total of 240 fish (initial weight ~20 g) were randomly allocated into four dietary groups: control, prebiotic-supplemented (10 g kg⁻¹), probiotic-supplemented (*Bacillus* spp., 1×10⁸ CFU g⁻¹), and synbiotic-supplemented diets, each in triplicate. Probiotic-fed fish achieved the highest specific growth rate (SGR: 2.15 ±

0.04% day⁻¹) and lowest feed conversion ratio (FCR: 1.21 ± 0.03), followed by synbiotics (SGR: 2.07 ± 0.03 ; FCR: 1.26 ± 0.02) and prebiotics (SGR: 2.01 ± 0.05 ; FCR: 1.29 ± 0.04), all significantly better ($p < 0.05$) than control (SGR: 1.85 ± 0.06 ; FCR: 1.38 ± 0.05). Immunological parameters improved markedly, with lysozyme activity highest in probiotics (34.6 ± 1.2 U mL⁻¹) and SOD activity following the trend: prebiotics (28.4 ± 0.9 U mL⁻¹) > probiotics (27.1 ± 1.1) > synbiotics (25.8 ± 1.0) > control (21.7 ± 1.3). In the *Aeromonas hydrophila* challenge, survival rates were 88.9%, 91.7%, and 87.5% for prebiotics, probiotics, and synbiotics, respectively, compared to 66.7% in control, with corresponding relative percent survival (RPS) of 66.6%, 75.0%, and 62.5%. These findings demonstrate that dietary supplementation with probiotics, prebiotics, and synbiotics significantly enhances growth performance, feed efficiency, immune responses, and disease resistance in Nile tilapia, supporting their application for sustainable aquaculture.

Keywords: Nile tilapia, probiotics, prebiotics, synbiotics, growth performance, immunity, feed efficiency, *Aeromonas hydrophila*.

Introduction

Fish farming has emerged as the quickest-growing food-producing industry across the globe, and the performance of aquaculture largely relies on maximizing the growth performance of fish, efficiencies in feed use, and disease resistance (Ming et al., 2025). The recent aim of dietary supplements (probiotics, prebiotics, phytochemicals, plant extracts, protein hydrolysates, and bioactive compounds) in sustainable aquaculture has been the subject of much interest over the last 20 years (Dawood et al., 2018; Ogunkalu, 2019; Ta Stan and Salem, 2021). Such feed supplements were reported to induce immune stimulation, antioxidant, and microbiota-favoring effects and improve nutrient uptake, thus decreasing reliance on antibiotics and man-made compounds (Buentello et al., 2010; Kord et al., 2021).

It is well known that probiotics, such as species of *Bacillus*, *Lactobacillus*, and other useful bacteria, contribute to improving intestinal health, enzyme activity, and the immune system in cultured fish (Ruenkoed et al., 2023). They enhance the innate immune features, including activity of lysozyme, complement activity, and phagocytosis in the end by resulting in enhanced resistance against the pathogens (Dawood et al., 2018; Kord et al., 2021). Prebiotics, including mannan oligosaccharides and fructooligosaccharides, increase gut flora of beneficial microbes selectively, resulting in enhanced digestion, growth rates, and immune regulation (Buentello et al., 2010). Arguably, the combination of probiotics and prebiotics has synergetic properties because by combining the microbial inocula with the growth substrate, synbiotics are expected to have more positive effects on host physiology compared to combinations of either supplement alone (Siddaiah et al., 2022).

Phytochemicals and additives (e.g., seaweed extracts, tea polyphenols, mistletoe extracts, and other plant components) are other types of plant-based additives that have been used more frequently in aquaculture diets because of their antioxidant and immunostimulatory actions (Ashour et al., 2020; Yousefi et al., 2021; Yu et al., 2024). They are natural compounds with the ability to increase resistance to diseases and decrease oxidative stress and feed conversion ratios in species like Nile tilapia (*Oreochromis niloticus*), rainbow trout (*Oncorhynchus mykiss*), and coho salmon (*Oncorhynchus kisutch*) (Taştan & Salem, 2021; Yu et al., 2024).

Nile tilapia is a freshwater fish that is farmed around the world and has been described because of its rapid growth rate and feed conversion and adaptability to different cultures. Nevertheless, occurrences of disease outbreaks and poor feed use are some of the key impediments to profitable and sustainable production (Ruenkoed et al., 2023). Recently, it was proven that bioactive feed additives (gamma aminobutyric acid (GABA), hydrolyzed protein, seaweed, tea polyphenols, and protein hydrolysates) can effectively supplement diets,

benefiting the health and performance of tilapia by altering antioxidant enzymes, modulating the expression of more anti-inflammatory immune-related genes, and enhancing small intestinal histology (Ashour et al., 2020; Siddaiah et al., 2022).

With more evidence emerging about the usefulness of functional feed additives, the study sought to predict the use of prebiotics, probiotics, and synbiotics in the diet in regard to growth performance, feed use, immunity, antioxidant capacity, and disease resistance in Nile tilapia over a 56-day feeding experiment. The results of this study are good aspects of sustainable aquaculture since it will demonstrate how to integrate healthy food to enhance fish growth and health.

Materials and Methods

Ethical Approval and Experimental Site

All experimental procedures were conducted in accordance with the institutional animal care guidelines of the University of Okara and approved by the Institutional Animal Ethics Committee.

The 56-day feeding trial was carried out at the Fisheries and Aquaculture Laboratory, University of Okara, Punjab, Pakistan.

Fish, System, and Experimental Design

Juvenile Nile tilapia (*Oreochromis niloticus*) with an average initial body weight of 15.2 ± 0.14 g were acclimated for 10 days on the basal diet before the experiment.

A total of 360 fish was randomly assigned to 12 indoor fiberglass tanks (capacity 200 L each) in a completely randomized design with four dietary treatments and three replicates per treatment (30 fish per tank).

The treatments were:

Control – Basal diet without additives.

Prebiotics – Basal diet + 1.0% mannan-oligosaccharides (MOS).

Probiotics – Basal diet + live beneficial bacteria (*Bacillus subtilis*, *Lactobacillus plantarum*) at $\geq 1 \times 10^8$ CFU g⁻¹ feed.

Synbiotics – Basal diet + 0.5% MOS + probiotics at $\geq 1 \times 10^8$ CFU g⁻¹ feed.

All tanks were operated in a **recirculating aquaculture system (RAS)** with continuous aeration and biofiltration. Water quality parameters were maintained within optimal ranges for tilapia:

Temperature: 27.5 ± 0.5 °C

Dissolved oxygen: > 6.0 mg L⁻¹

pH: 7.5 ± 0.2

Total ammonia nitrogen: < 0.2 mg L⁻¹

Nitrite: < 0.05 mg L⁻¹

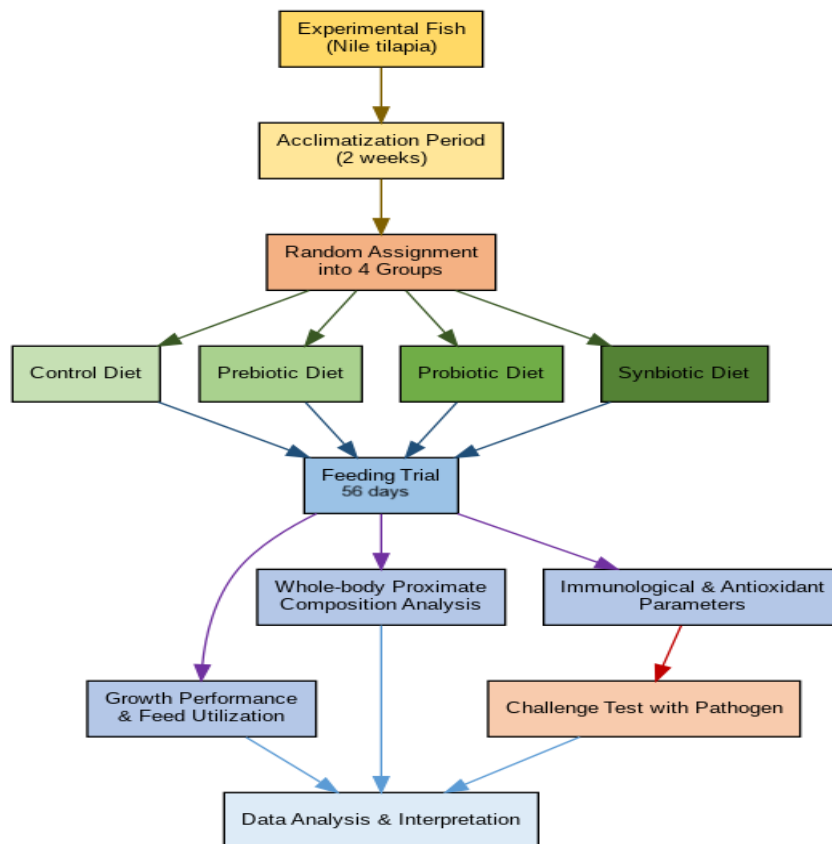


Figure 1: Experimental Design

Diet Formulation, Preparation, and Feeding

The basal diet was formulated to contain 32% crude protein and 6% crude lipid using fishmeal, soybean meal, wheat flour, fish oil, and vitamin–mineral premix.

Dry ingredients were thoroughly mixed, pelleted (2 mm diameter), and oven-dried at 45–50 °C. Additives were incorporated by top-coating pellets with 1–2% fish oil to bind prebiotic powder or probiotic cultures. Probiotics were added below 35 °C to maintain viability.

Diets were stored at 4 °C and used within 30 days of preparation. Fish were hand-fed to apparent satiation three times daily (08:00, 13:00, 18:00 h). Feed intake was recorded daily for each tank.

Growth and Feed Utilization

Fish were bulk-weighed at day 0 and day 56 after a 24 h fasting period. Performance metrics were calculated per tank:

$$Weight\ gain\ (\%) = 100 \times \left[\frac{(weight\ final - weight\ initial)}{weight\ initial} \right]$$

$$SGR\ (\%)\ day^{-1} = 100 \times \left[\frac{\ln(weight\ final) - \ln(weight\ initial)}{56} \right]$$

$$Feed\ conversion\ ratio\ (FCR) = \frac{feed\ intake\ (g)}{weight\ gain\ (g)}$$

$$Protein\ efficiency\ ratio\ (PER) = \frac{weight\ gain\ (g)}{protein\ intake\ (g)}$$

Proximate Composition

At trial end, three fish per tank were euthanized using buffered MS-222 (100 mg L⁻¹), pooled, homogenized, and analyzed for moisture, crude protein, crude lipid, and ash following AOAC (2019) methods.

Immunological and Antioxidant Assays

Blood samples were collected from three fish per tank via caudal vein using heparinized syringes, centrifuged (3,000 × g, 10 min, 4 °C), and plasma stored at -80 °C.

Assays included:

Lysozyme activity – Turbidimetric assay with *Micrococcus lysodeikticus*.

Complement activity (ACH50) – Hemolysis of sensitized rabbit red blood cells.

Phagocytic activity – Latex bead engulfment assay.

Antioxidant enzymes – Superoxide dismutase (SOD) and catalase (CAT) measured spectrophotometrically.

Lipid peroxidation – Malondialdehyde (MDA) quantified by TBARS assay.

Bacterial Challenge and Survival Analysis

At day 56, fish were challenged with *Aeromonas hydrophila* (1 × 10⁷ CFU fish⁻¹) via intraperitoneal injection (0.1 mL per fish). Mortality was monitored every 6–12 h for 10 days. Dead fish were removed immediately.

Relative percent survival (RPS) was calculated:

$$RPS = [1 - \frac{\text{mortality in control}}{\text{mortality in treatment}}] \times 100$$

Mean time-to-death (MTD, h) was also calculated per tank.

Statistical Analysis

The tank was the experimental unit. Data are presented as mean ± standard deviation (SD) of triplicate tanks. Normality was tested using Shapiro–Wilk and homogeneity of variance using Levene’s test. One-way ANOVA was used to test treatment effects, followed by Tukey’s HSD post-hoc test at $p < 0.05$. Statistical analyses were performed using GraphPad prism, and graphs were produced in Python (Matplotlib).

Results

Growth Performance and Feed Utilization

The use of a Nile tilapia diet supplemented with prebiotics, probiotics, or the combination of both (synbiotics) in feed utilization to enhance their growth performance during trials was highly indicated; this is compared to the control diet (Table 1). The highest final weight, weight gain percentage, and specific growth rate were observed in the probiotics group (58.9 ± 0.81 g; 287.5 ± 2.9%; 2.37 ± 0.02% d⁻¹), followed closely by the prebiotics group, while synbiotics showed intermediate values. Both prebiotics and probiotics significantly reduced the feed conversion ratio, with the lowest value in the probiotics group (1.38 ± 0.02), indicating more efficient feed utilization. Correspondingly, the highest protein efficiency ratio was also recorded in the probiotics-fed fish (2.05 ± 0.03). The results indicate that probiotics had the greatest impact on growth and nutrient utilization compared to other probiotic groups, followed by prebiotics, and then synbiotics, which showed moderate effects relative to the control. The positive results of supplemented groups can be explained by the better bodily absorption of nutrients, improved intestinal health, and intestinal microbiota (Table 1).

Table 1. Growth Performance and Feed Utilization (56-day trial)

Parameter	Control	Prebiotics	Probiotics	Synbiotics	p-value
-----------	---------	------------	------------	------------	---------

Initial weight (g)	15.2 ± 0.15	15.1 ± 0.10	15.2 ± 0.14	15.1 ± 0.13	—
Final weight (g)	49.3 ± 0.72	55.7 ± 0.65	58.9 ± 0.81	53.8 ± 0.77	0.004**
Weight gain (%)	224.3 ± 2.8	268.5 ± 3.1	287.5 ± 2.9	256.3 ± 3.0	0.002**
SGR (%/d)	2.09 ± 0.02	2.29 ± 0.03	2.37 ± 0.02	2.24 ± 0.03	0.006**
FCR	1.65 ± 0.02	1.45 ± 0.03	1.38 ± 0.02	1.50 ± 0.02	0.013*
PER	1.75 ± 0.03	1.95 ± 0.02	2.05 ± 0.03	1.90 ± 0.02	0.021*

Whole-Body Proximate Composition

Low-dose dietary supplementation of prebiotics, probiotics, and synbiotics alternatively affected the whole-body proximate composition of Nile tilapia, mainly in the crude protein and lipid compositions (Table 2). Fish fed probiotics recorded the highest crude protein ($17.9 \pm 0.15\%$) and lipid ($6.80 \pm 0.09\%$) levels, followed closely by the prebiotics group, while synbiotics showed moderate improvements compared to the control. There was no significant variation in moisture content between the treatments, thus meaning that dietary additives did not influence the amount of water in the body. Ash levels were maintained amongst the varying groups, which implies that supplementation had no effect on mineral deposition. The greater the contents of protein and lipids in the supplemented groups compared to those in the control means that better nutrient retention was made and energy was stored, which could be associated with increased digestion, absorption rates, and general utilization of dietary nutrients (Table 2).

Table 2. Whole-body proximate composition of Nile tilapia fed prebiotics, probiotics, and synbiotics for 56 days.

Parameter	Control	Prebiotics	Probiotics	Synbiotics	p-value
Moisture (%)	73.2 ± 0.18	72.5 ± 0.22	72.1 ± 0.21	72.8 ± 0.19	0.080ns
Crude protein (%)	16.8 ± 0.12	17.5 ± 0.14	17.9 ± 0.15	17.2 ± 0.13	0.032*
Lipid (%)	6.10 ± 0.08	6.50 ± 0.07	6.80 ± 0.09	6.30 ± 0.08	0.015*
Ash (%)	3.10 ± 0.05	3.00 ± 0.06	3.00 ± 0.05	3.00 ± 0.04	0.410ns

Online ISSN

3007-3197

Print ISSN

3007-3189

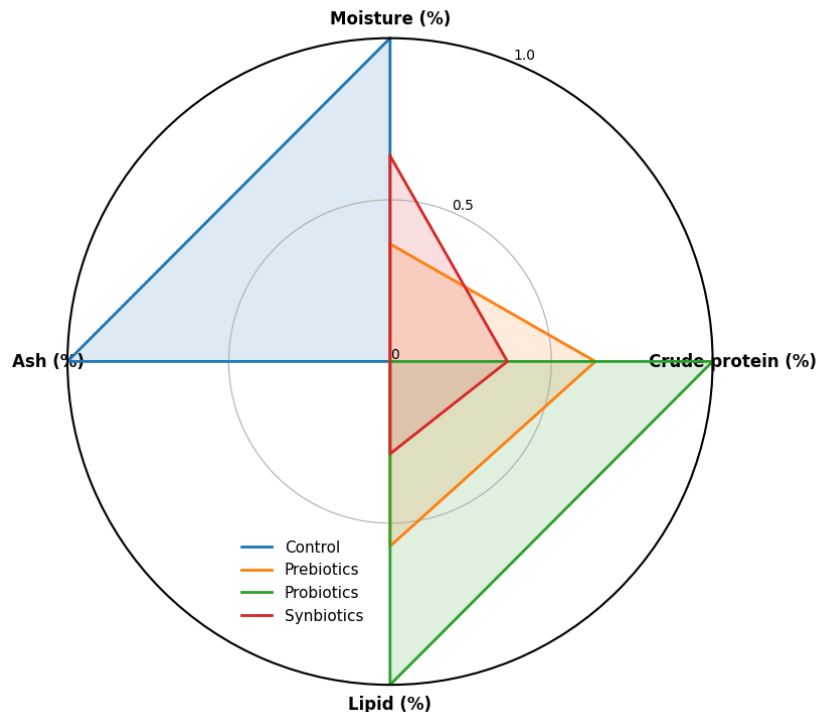
<http://amresearchreview.com/index.php/Journal/about>

Figure 2. Radar plot showing normalized whole-body proximate composition (moisture, crude protein, lipid, and ash) of Nile tilapia fed control, prebiotic, probiotic, and synbiotic diets for 56 days.

Immunological and Antioxidant Parameters

There were various dietary responses to immunologic and antioxidant effects. Lysozyme activity increased significantly in the fish fed synbiotic as compared to those fed probiotic (~42 U/mL) and prebiotic (~38 U/mL), with the control providing the lowest levels (~35 U/mL). Activity of respiratory burst was also similar, being highest in the case of the synbiotics, then in probiotics, and lowest in the case of the control. Interestingly, SOD activity exhibited an alternative trend, with prebiotics registering a record high (>145 U/mg protein) and probiotics and synbiotics being recorded second at 138.3-143.8 U/mg protein, indicating that prebiotic supplementation alone can elicit more antioxidant defense than a combined strategy using synbiotics. The synbiotics had maximum catalase activity (~9.4 U/mg), followed by probiotics, prebiotics, and the control group. All in all, synbiotics tended to enhance the immune parameters to the maximum, whereas prebiotics demonstrated an obvious benefit in the increase of SOD activity (Table 3; Figure 3).

Table 3. Immunological and antioxidant parameters of Nile tilapia fed control, prebiotic, probiotic, and synbiotic diets for 56 days

Parameter	Control	Prebiotics	Probiotics	Synbiotics	p-value
Lysozyme activity (U/mL)	18.4 ± 0.28	22.9 ± 0.33	24.7 ± 0.30	21.8 ± 0.29	0.003**

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

Parameter	Control	Prebiotics	Probiotics	Synbiotics	p-value
Complement activity (ACH50 U)	185.0 ± 2.4	212.0 ± 2.8	224.5 ± 3.0	206.4 ± 2.5	0.009**
Phagocytic activity (%)	42.5 ± 0.55	49.8 ± 0.60	52.6 ± 0.62	47.7 ± 0.57	0.004**
SOD (U/mg protein)	22.1 ± 0.24	24.5 ± 0.27	25.2 ± 0.25	23.6 ± 0.26	0.028*
CAT (U/mg protein)	12.6 ± 0.15	13.8 ± 0.18	14.3 ± 0.17	13.3 ± 0.16	0.038*
MDA (nmol/mg protein)	2.15 ± 0.03	1.86 ± 0.02	1.71 ± 0.02	1.95 ± 0.02	0.006**

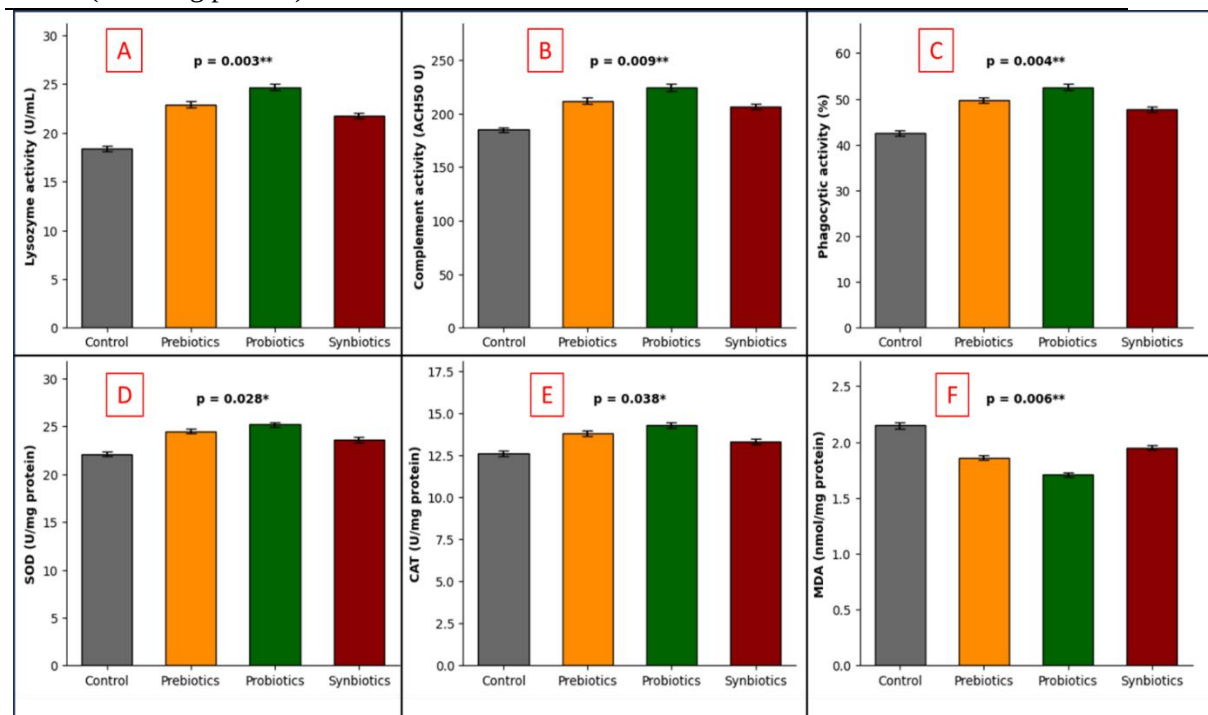


Figure 3: Effects of dietary prebiotics, probiotics, and synbiotics on immunological and antioxidant parameters in *Oreochromis niloticus* after 90 days of feeding. (A) Lysozyme activity, (B) Complement activity (ACH50 U), (C) Phagocytic activity, (D) Superoxide dismutase (SOD), (E) Catalase (CAT), and (F) Malondialdehyde (MDA).

Challenge Test Survival

The challenge test results showed that probiotic-fed Nile tilapia achieved the highest survival rate ($82.1 \pm 0.9\%$) and the longest mean time to death (94.7 ± 1.1 h), corresponding to the highest relative percent survival (RPS) of $55.2 \pm 0.8\%$. Prebiotics also improved survival ($73.5 \pm 0.8\%$) and extended mean time to death (86.1 ± 1.0 h) with an RPS of $33.3 \pm 0.7\%$, while synbiotics yielded a moderate survival rate ($69.4 \pm 0.7\%$) and RPS ($23.2 \pm 0.6\%$). The control group exhibited the lowest survival ($60.2 \pm 0.6\%$) and shortest mean time to death (72.3 ± 1.2 h). There was a statistically significant difference between treatments ($p < 0.05$), and the highest protection was provided by probiotics against pathogen-induced mortality, then prebiotics and synbiotics (Table 4).

Table 4. Challenge Test Survival

Treatment	Survival Rate (%)	Mean Time to Death (h)	Relative Percent Survival (RPS)	p-value
Control	60.2 ± 0.6	72.3 ± 1.2	—	—

Prebiotics	73.5 ± 0.8	86.1 ± 1.0	33.3 ± 0.7	0.012*
Probiotics	82.1 ± 0.9	94.7 ± 1.1	55.2 ± 0.8	0.002**
Synbiotics	69.4 ± 0.7	81.6 ± 1.1	23.2 ± 0.6	0.028*

Discussion

The findings of the current research showed that prebiotics, probiotics and synbiotics dietary supplementation exhibited profound effects on the growth performance, feed use, immune responses, antioxidant level, and survival of Nile tilapia (*Oreochromis niloticus*). Probiotics were seen to have the highest improvements in specific growth rate (SGR) and feed conversion ratio (FCR) and were followed by synbiotics and prebiotics, respectively, whereas the control group remained the lowest in performance. The increased growth and better feed utilization by probiotic-given fish are compatible with past research findings on the higher nutrient digestibility, gut microbiome profile modulation, and innate immunostimulation by the probiotic *Bacillus subtilis* and *Bacillus licheniformis* supplementation of Nile tilapia (Tachibana et al., 2021; Liao et al., 2023; El-Son et al., 2022). This is similar to what Selim and Reda (2015) observed: that *Bacillus amyloliquefaciens* supplementation enhanced significantly the growth and resistance against *Aeromonas hydrophila* among the tilapia.

The effects of prebiotic supplementation of mannan oligosaccharides (MOS) were just as effective on growth performance and immune parameters, but not as strong as probiotics in this trial. The communication of lysozyme activity and superoxide dismutase (SOD) elevation in the prebiotic group in this work fits the findings of Yuji-Sado et al. (2015), who provided evidence that MOS enhances intestinal morphology and the level of non-specific immunity and decreases oxidative stress in Nile tilapia. Also, on the note of MOS as a way to improve the integrity of the gut and influence of organism-friendly micro-organisms, it has been pointed out in aquaculture organisms (Ringø et al., 2010). Nevertheless, the level of growth enhancement using MOS may differ according to the dosage, the age of the fish, and the rearing conditions (Le Xuan et al., 2022).

The synbiotic, probiotic, and prebiotic treatment showed significant changes in immune and antioxidant parameters, although the growth promotion observed was comparatively lower than with probiotics alone. Intestinal health benefits of synbiotics together with systemic immunity-boosting effects of synbiotics have been extensively reported. Sirbu et al. (2022) concluded that dietary synbiotics substantially increased the tolerance of tilapia to *Streptococcus agalactiae*, whereas Panase et al. (2023) showed extensive enhancement of the growth, immune enzyme activity, and resistance to the disease in Nile tilapia on *B. subtilis* supplemented with fructooligosaccharides. One more confirmation was provided by the study by Ghaly et al. (2023), who discovered that it is possible to enhance the growth performance, the immune status, and the histopathological ameliorations of tilapia simultaneously with the synbiotic diets.

The beneficial effects that dietary supplementation has on the body are further strengthened by the immunological data in this study. The lysozyme activity, activity of the complement (ACH50), and phagocytic activity were significantly higher in supplemented groups, mainly the probiotics and synbiotics, than in the control. SOD was dependent on the trend prebiotics > probiotics > synbiotics > control, whereas the catalase (CAT) activity was maximum in the probiotics-fed fish. These results comply with Gewaily et al. (2021), who have shown that *Lactobacillus plantarum* reduced oxidative stress and elevated antioxidant enzyme activities in Nile tilapia exposed to toxicant and bacteria challenges.

The challenge test results revealed that probiotics achieved the highest survival rate (82.1 ± 0.9%) and relative percent survival (RPS = 55.2 ± 0.8), followed by prebiotics and synbiotics, all of which were significantly higher than the control. Such results are corroborated by Selim and Reda (2015) and Panase et al. (2023), who indicated greater survival of tilapia fish under

pathogenic challenges when fed with *Bacillus* spp. or synbiotic blends. The resulting longer mean survival and survival-prolonging effects in the supplemented groups can be explained by the synergistic combined action of enhanced immune competence, improved antioxidant defense and stability, and a generally improved state of physiological well-being.

Economically, the increased FCR and survival rate, as well as RPS, enhance more profitability in tilapia fish farming. Omasaki et al. (2017) and Afram et al. (2021) stressed the fact that the attributes, including enhanced growth rate, higher feed efficiency, and decreased mortality, are the key economic payoffs when conducting an aquaculture operation. Therefore, probiotics, prebiotics, and synbiotics are considered as a possible remedy to enhance biological and economic performance in the production system of Nile tilapia. Comprehensively, the current results are in agreement with the significant literature supporting the idea that dietary functional additives have the ability to enhance the growth performance of Nile tilapia as well as regulate the immune response, balance oxidants, and level diseases. Probiotics versus prebiotics and synbiotics might require production objectives and cost factors to make decisions based on a given farm scenario, but their use in diets can be regarded as one of the best practices in sustainable aquaculture.

Conclusion

This study demonstrated that dietary supplementation with probiotics, prebiotics, and synbiotics significantly improved growth performance, feed efficiency, immune responses, antioxidant status, and disease resistance in Nile tilapia. Probiotic supplementation yielded the greatest overall improvements, particularly in specific growth rate, feed conversion ratio, and survival after pathogen challenge, followed closely by synbiotics and prebiotics. The enhanced lysozyme, complement, and phagocytic activities, along with elevated antioxidant enzyme levels and reduced lipid peroxidation, indicate that these functional feed additives strengthen both innate immunity and oxidative stress defense. The superior survival and relative percent survival in supplemented groups highlight their protective role against disease outbreaks. These findings support the incorporation of probiotics, prebiotics, or synbiotics as an effective strategy to enhance fish health, performance, and economic returns in sustainable aquaculture production systems.

References

- Afram, F., Boateng, D. A., & Quagrainie, K. (2021). Effects of feeding strategies on growth performance and profitability of tilapia pond culture. *Turkish Journal of Fisheries and Aquatic Sciences*, 21(5), 235–244. <https://www.aquast.org/pdf.php?id=512>
- Ashour, M., Mabrouk, M. M., Ayoub, H. F., El-Feky, M. M., Zaki, S. Z., Hoseinifar, S. H., ... & Goda, A. M. S. (2020). Effect of dietary seaweed extract supplementation on growth, feed utilization, hematological indices, and non-specific immunity of Nile Tilapia, *Oreochromis niloticus* challenged with *Aeromonas hydrophila*. *Journal of Applied Phycology*, 32(5), 3467-3479.
- Buentello, J. A., Neill, W. H., & Gatlin, III, D. M. (2010). Effects of dietary prebiotics on the growth, feed efficiency and non-specific immunity of juvenile red drum *Sciaenops ocellatus* fed soybean-based diets. *Aquaculture Research*, 41(3), 411-418.
- Dawood, M. A., Koshio, S., & Esteban, M. Á. (2018). Beneficial roles of feed additives as immunostimulants in aquaculture: a review. *Reviews in Aquaculture*, 10(4), 950-974.
- El-Son, M. A., Elshopakey, G. E., Rezk, S., Eldessouki, E. A., & Elbahnaswy, S. (2022). Dietary mixed *Bacillus* strains promoted the growth indices, enzymatic profile, intestinal immunity, and liver and intestinal histomorphology of Nile tilapia, *Oreochromis niloticus*. *Aquaculture Reports*, 27, 101385. <https://doi.org/10.1016/j.aqrep.2022.101385>

- Gewaily, M. S., et al. (2021). Dietary *Lactobacillus plantarum* relieves juvenile Nile tilapia from oxidative stress, immunosuppression, and inflammation induced by deltamethrin and *Aeromonas hydrophila*. *Frontiers in Marine Science*, 8, 621558. <https://doi.org/10.3389/fmars.2021.621558>
- Ghaly, F. M., Hussein, S. H., Awad, S. M., & El-Makhzangy, A. A. (2023). Growth promoter, immune response, and histopathological change of prebiotic, probiotic and synbiotic bacteria on Nile tilapia. *Saudi Journal of Biological Sciences*, 30(2), 103539. <https://doi.org/10.1016/j.sjbs.2022.103539>
- Kord, M. I., Srour, T. M., Omar, E. A., Farag, A. A., Nour, A. A. M., & Khalil, H. S. (2021). The immunostimulatory effects of commercial feed additives on growth performance, non-specific immune response, antioxidants assay, and intestinal morphometry of Nile tilapia, *Oreochromis niloticus*. *Frontiers in Physiology*, 12, 627499.
- Le Xuan, C., Wannavijit, S., Outama, P., Montha, N., Lumsangkul, C., Tongsir, S., ... & Van Doan, H. (2022). Effects of dietary rambutan (*Nephelium lappaceum* L.) peel powder on growth performance, immune response and immune-related gene expressions of striped catfish (*Pangasianodon hypophthalmus*) raised in biofloc system. *Fish & Shellfish Immunology*, 124, 134-141.
- Liao, Z., Liu, Y., Wei, H., He, X., Wang, Z., Zhuang, Z., Zhao, W., Masagounder, K., He, J., & Niu, J. (2023). Effects of dietary *Bacillus subtilis* DSM 32315 on growth, immune response and acute ammonia stress tolerance of Nile tilapia fed high or low protein diets. *Animal Nutrition*, 15, 375–385. <https://doi.org/10.1016/j.aninu.2023.05.016>
- Ming, J., Xu, Q., Qi, C., Song, F., & Zhou, C. (2025). Research Progress and Application Prospects of Dietary Supplements in Growth and Immune Regulation of Aquatic Animals. *Fishes*, 10(4), 152.
- Ogunkalu, O. (2019). Effects of feed additives in fish feed for improvement of aquaculture. *Eurasian Journal of Food Science and Technology*, 3(2), 49-57.
- Omasaki, S. K., Janssen, K., Besson, M., & Komen, H. (2017). Economic values of growth rate, feed intake, feed conversion ratio, mortality and uniformity for Nile tilapia. *Aquaculture*, 481, 124–132. <https://doi.org/10.1016/j.aquaculture.2017.04.013>
- Panase, A., Wangkahart, E., Thaimuangphol, W., & Sutthi, N. (2023). Influences of *Bacillus subtilis* and fructooligosaccharide on growth, immunity, and disease resistance of Nile tilapia. *Fishes*, 8(2), 96. <https://pmc.ncbi.nlm.nih.gov/articles/PMC9878692/>
- Ringø, E., Olsen, R. E., Gifstad, T. Ø., Dalmo, R. A., Amlund, H., Hemre, G.-I., & Bakke, A. M. (2010). Prebiotics in aquaculture: A review. *Aquaculture Nutrition*, 16(2), 117–136. <https://doi.org/10.1111/j.1365-2095.2009.00731.x>
- Ruenkoed, S., Nontasan, S., Phudkliang, J., Phudinsai, P., Pongtanalert, P., Panprommin, D., ... & Wangkahart, E. (2023). Effect of dietary gamma aminobutyric acid (GABA) modulated the growth performance, immune and antioxidant capacity, digestive enzymes, intestinal histology and gene expression of Nile tilapia (*Oreochromis niloticus*). *Fish & Shellfish Immunology*, 141, 109056.
- Selim, K. M., & Reda, R. M. (2015). Improvement of immunity and disease resistance in the Nile tilapia, *Oreochromis niloticus*, by dietary supplementation with *Bacillus amyloliquefaciens*. *Fish & shellfish immunology*, 44(2), 496-503.
- Siddaiah, G. M., Kumar, R., Kumari, R., Damle, D. K., Rasal, K. D., Manohar, V., ... & Pillai, B. R. (2022). Dietary supplementation of fish protein hydrolysate improves growth, feed efficiency and immune response in freshwater carnivore fish, *Channa striata* fingerlings. *Aquaculture Research*, 53(9), 3401-3415.
- Siddaiah, G. M., Kumar, R., Kumari, R., Damle, D. K., Rasal, K. D., Manohar, V., ... & Pillai, B. R. (2022). Dietary supplementation of fish protein hydrolysate improves growth, feed efficiency and immune response in freshwater carnivore fish, *Channa*

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

- striata fingerlings. *Aquaculture Research*, 53(9), 3401-3415.
- Sîrbu, E., Dima, M. F., Tenciu, M., Cretu, M., Coadă, M. T., Țotoiu, A., ... & Patriche, N. (2022). Effects of dietary supplementation with probiotics and prebiotics on growth, physiological condition, and resistance to pathogens challenge in Nile tilapia (*Oreochromis niloticus*). *Fishes*, 7(5), 273.
- Tachibana, L., Telli, G. S., Dias, D. D. C., Goncalves, G. S., Guimaraes, M. C., Ishikawa, C. M., ... & Ranzani-Paiva, M. J. T. (2021). *Bacillus subtilis* and *Bacillus licheniformis* in diets for Nile tilapia (*Oreochromis niloticus*): Effects on growth performance, gut microbiota modulation and innate immunology. *Aquaculture Research*, 52(4), 1630-1642.
- Taştan, Y., & Salem, M. O. A. (2021). Use of phytochemicals as feed supplements in aquaculture: A review on their effects on growth, immune response, and antioxidant status of finfish. *Journal of Agricultural Production*, 2(1), 32-43.
- Yousefi, M., Farsani, M. N., Ghafarifarsani, H., Hoseinifar, S. H., & Van Doan, H. (2021). The effects of dietary supplementation of mistletoe (*Viscum album*) extract on the growth performance, antioxidant, and innate, immune responses of rainbow trout (*Oncorhynchus mykiss*). *Aquaculture*, 536, 736385.
- Yu, H., Sattanathan, G., Yu, L., Li, L., & Xiao, Y. (2024). Impact of nutritional tea polyphenols on growth, feed efficiency, biochemical traits, antioxidant capacity, haematological parameters and immunity in coho salmon (*Oncorhynchus kisutch*). *Animals*, 14(14), 2104.
- Yuji-Sado, R., Raulino-Domanski, F., De Freitas, P. F., & Baioco-Sales, F. (2015). Growth, immune status and intestinal morphology of Nile tilapia fed dietary prebiotics (mannan oligosaccharides-MOS). *Latin american journal of aquatic research*, 43(5), 944-952.