Aquaculture Studies, 26(4), 540-555, AQUAST2711
http://doi.org/10.4194/AQUAST2711

RESEARCH PAPER

Water Hyacinth Vermicompost Enhances Growth Performance of Nile Tilapia (*Oreochromis niloticus*) and Modulates Plankton Communities in Fertilized Ponds: A Comparative Study with Inorganic Fertilizers

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How to Cite

Tolera, G. Getahun, A., Geremew, A. Mengistou, S. (2026). Water Hyacinth Vermicompost Enhances Growth Performance of Nile Tilapia (*Oreochromis Niloticus*) and Modulates Plankton Communities in Fertilized Ponds: A Comparative Study with Inorganic Fertilizers. *Aquaculture Studies*, *26(4), AQUAST2711*. http://doi.org/10.4194/AQUAST2711

Article History
Received 10 June 2025
Accepted 27 March 2026
First Online 15 April 2026

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Keywords
Aquaculture
Oreochromis niloticus
Pond fertilization
Water hyacinth
Vermicompost

Abstract

Pond fertilization is a crucial factor in enhancing the productivity of inland aquatic resources. Organic fertilizers, such as vermicompost and biocompost derived from water hyacinth, promote the growth of algae and insects, which serve as essential food sources for fish. This study investigated the effects of water hyacinth vermicompost as a fertilization strategy in aquaculture, specifically examining its impact on fish growth compared to traditional fertilizers, such as triple superphosphate (TSP) and a combined fertilizer of TSP and urea. Water hyacinth, an invasive aquatic plant, was processed through vermicomposting to produce a nutrient-rich organic fertilizer. Over three months, from mid-November 2021 to mid-February 2022, various pond fertilization techniques and physicochemical parameters were examined in concrete ponds at the Batu Fish and Other Aquatic Life Research Center. Twelve concrete partitioned fish ponds, each measuring 6 m², were constructed and stocked with 18 *Oreochromis niloticus* fingerlings each, weighing approximately 7 grams, randomly sourced from Batu Fish and Other Aquatic Life Research Center. This pond was equally divided into four treatments with three replicates (4T x 3R). The growth performance of *Oreochromis niloticus* was measured every 15 days for 90 days in water-filled ponds treated with mixed fertilizer (a 1:1 ratio of triple superphosphate and urea), triple superphosphate (TSP) alone, vermicompost (VC) as a direct application fertilizer, and control ponds. ANOVA was employed to analyze the data, which included growth parameters such as weight gain and feed conversion ratio, and the overall fish health was inspected and monitored throughout the study. Results indicated that ponds treated with water hyacinth vermicompost achieved significantly higher fish growth rates compared to those receiving TSP, TSP combined with urea, and the control group at $p<0.05$. Specifically, the VC-treated pond recorded a final fish weight of 69.00±.78964 g, followed by mixed fertilizer (66.1917±.57309 g), TSP (63.144±.51088 g), and the control ponds (51.00±.82446 g). In the VC-treated pond, there was a high abundance of zooplankton, and high plankton production was observed in all treatments except in the control ponds. Water quality assessments showed that the use of vermicompost significantly improved the overall health of the pond. For example, dissolved oxygen (DO) levels increased, while ammonium (NH_4^+) levels decreased, as ammonia could be absorbed by the available phytoplankton. The study recorded dissolved oxygen (DO) levels ranging from 8.06±1.09 mg/l in the control group to 8.7583±0.7 mg/l in the VC group. Consequently, the application of vermicompost released nutrients that fostered plankton production, which supported fish growth. Overall, Water hyacinth vermicompost is a viable, eco-friendly alternative to inorganic fertilizer for enhancing the productivity of semi-intensive Nile tilapia ponds.

Introduction

Aquaculture is the fastest-growing sector in global food production, serving not only as a vital source of dietary protein but also as a means of economic empowerment, particularly in developing countries where it makes an important contribution to poverty alleviation and nutrition (FAO, 2016). Fish provide high-quality animal protein with a comparatively low environmental footprint, making aquaculture one of the most resource-efficient animal food production systems (FAO, 2016; FAO, 2018). In many low- and middle-

income countries, small-scale pond aquaculture is especially critical, contributing to household nutrition, income diversification, and rural development. However, the sustainability and productivity of pond-based aquaculture systems are frequently constrained by rising input costs, declining water quality, and long-term environmental degradation.

Traditionally, pond fertilization using inorganic fertilizers such as urea and triple super phosphate (TSP) has been widely adopted to stimulate primary productivity and enhance natural food availability for fish. While effective in the short term, prolonged reliance on chemical fertilizers has been associated with nutrient imbalance, deterioration of pond bottom soil, reduced water quality, and increasing production costs (Das et al., 2005; Jana et al., 2001). In addition, indiscriminate fertilizer use contributes to eutrophication and compromises the ecological integrity of aquatic systems. These challenges have intensified the search for alternative fertilization strategies that are economically viable, environmentally sound, and suitable for smallholder aquaculture. In this context, organic fertilization has gained renewed attention as a sustainable approach to pond management. Among organic inputs, vermicompost has emerged as a particularly promising biofertilizer due to its high nutrient content, enhanced microbial activity, and rapid nutrient bioavailability (Gajalakshmi *et al*., 2002). Vermicompost is produced through the biological processing of organic waste by earthworms, resulting in a stabilized product rich in readily available nitrogen, phosphorus, potassium, micronutrients, beneficial microorganisms, enzymes, and plant growth regulators. Unlike raw organic manures, vermicompost releases nutrients gradually while improving sediment structure and water retention capacity, thereby supporting stable pond ecosystems. Several studies have demonstrated that vermicompost application in aquaculture ponds can enhance plankton productivity and fish growth without adversely affecting water quality, outperforming conventional inorganic fertilizers under certain conditions (Kumar et al., 2007; Godara et al., 2015; Kebede et al., 2025). Recent research on integrated vermi-pisciculture systems further indicates that vermicompost-fed ponds can produce higher fish biomass compared to ponds fertilized with chemical inputs (Ghosh, 2004). These systems have also been shown to improve pond soil properties, including increased organic matter content and enhanced water retention capacity, which indirectly support algal biomass and natural food web development (Kebede et al., 2025). Importantly, vermicompost contains dissolved organic matter with higher bioavailability than thermophilic composts (Wang et al., 2024), suggesting that nutrients derived from vermicompost may be more readily assimilated within aquatic food webs. Such characteristics make vermicompost a compelling alternative for sustainable pond fertilization.

An additional opportunity lies in the utilization of water hyacinth (*Pontederia crassipes*), one of the world's most invasive aquatic weeds, as a raw material for vermicompost production. Water hyacinth is widely regarded as a serious environmental nuisance due to its rapid proliferation, obstruction of waterways, and negative impacts on fisheries and water quality. However, the plant is also characterized by high biomass productivity and appreciable concentrations of nitrogen, phosphorus, potassium, and other minerals (Lara-Serrano *et al*., 2016). Studies have shown that vermicomposting significantly enhances the quality of water hyacinth compost compared to conventional composting, resulting in lower C: N ratios, increased total nitrogen, phosphorus, and potassium, and substantially higher populations of beneficial bacteria, fungi, and actinomycetes (Pramanik, 2010; Ankaram et al., 2014). Moreover, vermicomposting has been demonstrated to reduce the bioavailability and leachability of heavy metals commonly accumulated by water hyacinth, thereby mitigating potential environmental and health risks associated with its use (Singh and Kalamdhad, 2013). Reduction of bioavailability and leachability of heavy metals during vermicomposting of water hyacinth. These findings suggest that water hyacinth vermicompost may be a safe and effective organic amendment, transforming an ecological burden into a valuable resource.

Despite these promising attributes, empirical studies quantifying the effects of water hyacinth vermicompost on critical pond ecosystem components, specifically the dynamics of plankton communities and their subsequent impact on fish growth, remain scarce. Furthermore, direct comparisons with standard inorganic fertilization regimes under controlled conditions are lacking, leaving a critical knowledge gap for aquaculture extension services. Concerns persist regarding potential oxygen depletion, nutrient overloading, and unintended ecological effects when organic inputs are applied to aquatic systems (Boyd, 1997; Boyd and Massaut, 1999). Addressing these uncertainties is essential before water hyacinth vermicompost can be confidently recommended as a pond fertilizer.

Therefore, we hypothesized that ponds fertilized with water hyacinth vermicompost would support superior growth performance in Nile tilapia compared to those receiving inorganic fertilizers (TSP and Urea + TSP). We further hypothesized that this enhanced growth would be mediated by bottom-up trophic stimulation, resulting in higher standing crops of phytoplankton and zooplankton, while maintaining water quality within optimal ranges for the cultured species. To test these hypotheses, we conducted a 90-day experiment comparing the effects of these fertilizers on fish growth, feed utilization, key water quality parameters, and plankton community structure. Within the broader framework of sustainable aquaculture and invasive species management, this

chapter contributes empirical evidence on the biological transformation of water hyacinth into a productive input for aquaculture systems.

Materials and Methods

Study Site and Experimental Design

The experiment was conducted at the Batu Fish and Other Aquatic Life Research Center, Oromia Regional Agricultural Research Institute (7.918^0N and 37.727^0E), at an altitude of 1643 meters above sea level from mid-November 2021 to mid-February 2022 (90-day culture period). Twelve outdoor concrete ponds were used in the study. Before initiation, ponds were completely drained, sun-dried, and cleared of unwanted fish species and debris. Inlet and outlet points were screened with fine wire mesh to prevent the entry or escape of fish and extraneous materials. All the ponds were then filled exclusively with groundwater from adjacent reservoir ponds. A constant water level was maintained throughout the experimental period. Partial water exchange was conducted weekly, and additional water was added when necessary to compensate for evaporation losses and to maintain dissolved oxygen within acceptable limits for Nile tilapia culture.

The experiment followed a completely randomized design (CRD) with four treatments and three replicates per treatment (4 treatments × 3 replicates = 12ponds). The first group served as a control and was kept without fertilization. Other groups received water hyacinth-based vermicompost, mixed fertilizer (MF, urea with TSP), and TSP alone. Treatments were randomly assigned to ponds using a simple randomization procedure to minimize location bias. Fertilizer application rates (expressed per m² over 90 days) were: the treatment included triple superphosphate (TSP) at 0.225 kg/m^2, mixed fertilizer (urea + TSP) at 0.205 kg/m^2, and water hyacinth vermicompost at 1.0 kg/m^2. Application rates were selected to stimulate primary productivity while remaining within conventional fertilization ranges reported in pond aquaculture studies (Chakrabarty et al., 2010). Fertilizers were applied monthly using the broadcasting method. The first application was conducted 15 days before fish stocking to allow initial phytoplankton development. The objective of fertilization was to enhance natural food production (phytoplankton and zooplankton), thereby indirectly improving fish growth performance through bottom-up trophic stimulation.

Source of Water Hyacinth for Vermicomposting

Water hyacinth (*Pontederia crassipes*) used for vermicomposting was collected manually from Lake Ziway, located in the northern Ethiopian Rift Valley (08.00°N, 38.83°E), approximately 163 km south of Addis Ababa. Collected material was transported to the research center for processing.

Preparation of Vermicompost

Collected water hyacinth was washed, chopped, sun-dried, and mixed with cow dung as a nitrogen source. Vermicomposting was conducted using the earthworm species *Eisenia fetida* following established procedures (Gezahegn Degefe *et al*., 2012). The substrate was layered (10–12 cm thickness) in vermibins and maintained under aerobic conditions for 90 days. Regular turning was performed to ensure aeration and uniform decomposition. Earthworm activity further enhanced aeration and mineralization. At the end of the composting period, the vermicompost was characterized as a dark, granular, humus-rich material, as shown in Figure 1.

The final vermicompost was analyzed for major nutrients (NPK), yielding an approximate nutrient composition of 2% N: 1% P: 2% K. While full characterization (e.g. C: N ratio, heavy metals, pathogen load) was not performed, previous studies have reported low heavy metal accumulation and minimal ecological risk associated with water hyacinth–based vermicompost when applied in aquaculture systems (Singh and Kalamdhad, 2013). Furthermore, continuous monitoring of water quality parameters throughout the study provided indirect validation of environmental safety. This limitation is acknowledged and considered in the interpretation of results.

Fish Stocking and Feeding

Mixed-sex Nile tilapia (*Oreochromis niloticus*) fingerlings with an average initial weight of 7.0± SE g were stocked at a density of 3 fish m^{-2} (Figure 2), consistent with semi-intensive pond culture recommendations (Diana *et al*., 1995). Before stocking, fish were acclimatized to pond conditions. Fish were fed a commercial diet containing: 35% crude protein, 7% crude fat, 4% fiber, 2% calcium, and 9% moisture. Feed was administered three times daily at 3% of body weight, with ration adjustments made biweekly following sampling. The feeding strategy was maintained uniformly across treatments to ensure that observed growth differences were attributable primarily to fertilization-mediated natural productivity rather than differential feed input.

Water Quality Monitoring

Water samples were collected twice weekly from multiple locations within each pond (inlet, outlet, mid-shore, and center) at mid-depth. Samples were composited to obtain integrated measurements. Parameters measured included: temperature, dissolved oxygen (DO), conductivity, and pH, which were assessed using the Hanna Multiparameter Meter (HI-9829, USA). Turbidity (using Secchi depth measurements), Total alkalinity was estimated by titration with acid using phenolphthalein and methyl orange as indicators,

Nitrate (NO_3^-) by (Sodium salicylate method), Nitrite (NO_2^-) (Sulphanilamide), Phosphate ($PO4^{3-}$) (Ascorbic acid method), Sulfate (Nephelometry Method), Sodium (Photometric Method), calcium (EDTA titrimetric method) and potassium were analyzed by flame photometer following procedures in APHA (1999) standard methods.

Phytoplankton and Zooplankton Sampling and Identification

To estimate phytoplankton and zooplankton abundance in the experimental pond, water was collected from the surface from December 2021 to February 2022. Phytoplankton and zooplankton analysis were conducted by filtering 1 liter of pond water through plankton nets with a mesh size of 20 microns from each treatment. All samples collected were preserved in 5% formalin and stored in plastic containers in the laboratory. The plankton samples were examined with an inverted ZEISS digital microscope (Axiocam 202 mono, Germany) at a magnification of 10x, 40x, and 100x. Both phytoplankton and zooplankton counting was performed with the help of the Sedgwick-Rafter Counting Cell (S-R cell). Taxonomic identification followed standard keys (Vuuren *et al*., 2006). The plankton population was determined using the formula of Rahman *et al*. (1992):

$$N = \frac{AxC}{L} x100$$

Where, N= Number of plankton cells per liter of original water; A= Total number of plankton counted; C= Volume of final concentrated sample in Ml, L= Volume of original water in liters.

Figure 1. A) Beginning of vermicomposting, B) Composted and ready for use.

Figure 2. Data collection on fish total weight and total length.

For each pond, the mean number of plankton recorded was expressed numerically in per liter of water.

Growth Performance Parameters

The initial weight, length, and number of stocked fish were recorded on the entry day for each treatment. The stocked fish were recorded on 15 November 2021 as initial data for each treatment. One-third of the fish were sampled randomly from earthen ponds using a seine net with a 50 mm mesh size every 15 days till 15 February 2022. Dead fish were removed and documented. Fish were weighed individually from each treatment. Fish growth performance and feed utilization were calculated in terms of change in weight gain, daily growth rate, specific growth rate, feed conversion ratio, and survival rate. Growth parameters were calculated following standard equations (Michael *et al*., 1994; Gashaw Tesfaye and Zenebe Tadesse, 2008). The average body weight (ABW) and average body length (ABL) of each sample of fish were measured by an Ohaus Scout SKX 2201 portable balance, China, and a measuring board. Finally, calculations were done by using the following formula.

Mean Weight Gain = Mean final weight (g) – Mean initial weight (g)

$$\text{Mean Daily Growth Rate (DGR, g/day)} = \frac{\text{Mean final weight} - \text{Mean initial weight}}{\text{Cultured days}}$$

$$\text{Specific Growth Rate (SGR, \%/day)} = \frac{\ln(\text{Mean final weight}) - \ln(\text{Mean initial weight}) \times 100}{\text{Time taken}}$$

$$\text{Food Conversion Ratio (FCR)} = \frac{\text{Feed fed (dry weight (kg)} \times 100}{\text{Weight gained (kg)}}$$

$$\text{Survival rate (SR, \%)} = \frac{\text{Number of fish harvested} \times 100}{\text{Number of fish stocked}}$$

External Determination of Fish Health

Fish were visually examined for external lesions, gill discoloration, abnormal swimming behavior, feeding response, and respiratory distress. Observations were conducted across all treatments to detect potential fertilizer-induced stress.

Statistical Analysis

Data were analyzed using SAS 8.2. One-way ANOVA was performed to compare treatment effects under the Completely Randomized Design structure. Before analysis, assumptions of normality and homogeneity of variance were evaluated. Where significant differences were detected ($p<0.05$), Tukey's HSD test was applied for post hoc comparisons. All results are presented as mean ± standard error.

Results

Water Quality

The results of the physicochemical parameters of water samples collected from the fish ponds during the experimental study are presented in Table 1.

Temperature and dissolved Oxygen (DO) remained statistically similar across all treatments ($p > 0.05$), ranging from 20.18–20.83°C and 8.06–8.75 mg/l, respectively. pH was significantly higher in the WH Vermicompost (9.77) and Mixed Urea + TSP (9.65) treatments compared to the TSP-only treatment (9.00). Secchi depth was significantly lowest in the WH Vermicompost (31.33 cm) and Mixed (32 cm) treatments, and highest in the Control (36.67 cm). Phosphate (PO4) concentration was significantly higher in the WH Vermicompost treatment (0.5 mg/l) than in all other treatments. TSP (0.3 mg/l) was intermediate, while Mixed (0.16 mg/l) and Control (0.15 mg/l) were lowest. Nitrate (NO3) levels were significantly highest in

Table 1. Mean physicochemical parameters of pond water during the experimental period from 15th of November 2021 to 20th of February 2022(Mean±SE)

Parameters	Treatments			
	WH vermicompost	TSP	Mixed (Urea +TSP)	Control (CO)
Temperature (°C.)	20.39±1.26^{a}	20.83±1.49^{a}	20.46±1.75^{a}	20.18±1.54^{a}
DO (mg/l)	8.35±2.07^{a}	8.75±0.7^{a}	8.57±1.62^{a}	8.06±1.09^{a}
PH	9.77±0.77^{b}	9.00±0.00^{a}	9.65±0.46 ^{b}	9.34±0.23^{ab}
Conduct. (mS/cm)	2718.5±328.8^{ab}	2769.83±305.91^{ab}	2570.16±162.48^{a}	2909.83±45.4^{b}
Alkalinity (mg/l)	34.70±.2876 ^{a}	36.70±.1034 ^{ab}	39.51±.04601^{b}	39.83 ±.0572^{b}
Secchi depth (cm)	31.33±1.21^{a}	34.67±0.81^{b}	32±0.89^{a}	36.67±0.81^{c}
Nitrites (mg/l)	4.26±0.26^{b}	4.46±0.15^{c}	3.62±0.04^{a}	4.62±0.6^{c}
Nitrate (NO_3 mg/l)	8.61±0.01^{d}	7.8±0.02^{a}	8.14±0.02^{b}	8.51±0.14^{c}
Phosphate(mg/l)	0.5±0.01^{c}	0.3±0.07^{b}	0.16±0.07^{a}	0.15±0.01^{a}
Sulfate (SO_4, mg/l)	207.17±7.17^{b}	273.22±0.15^{d}	215.73±0.67^{c}	148.5±0.01^{a}
Sodium (Na, mg/l)	850.5±7.17^{b}	993.99±3.52^{c}	994.78±3.07^{c}	640.16±7.08^{a}
Calcium (Ca, mg/l)	42.30±0.00^{b}	47.01±0.7^{c}	48.74±0.18^{d}	37.43±0.12^{a}
Potassium (K mg/l)	48.45±1.23^{b}	56.21±0.15^{c}	60.47±0.12^{d}	38.86±0.08^{a}

Values in the same row having the same letters are not significantly different at P>0.05.

the WH Vermicompost treatment (8.61 mg/l) and lowest in the TSP treatment (7.8 mg/l).

The concentrations of major ions also varied significantly. Sulfate (SO4) levels were highest in the TSP treatment (273.22 mg/l) and lowest in the Control (148.5 mg/l). A similar pattern was observed for cations; the concentrations of Sodium (Na), Calcium (Ca), and Potassium (K) were significantly higher in the TSP and Mixed treatments compared to the Control, with the WH Vermicompost treatment generally showing intermediate values.

Composition of Phytoplankton and Zooplankton

The composition and relative abundance of phytoplankton and zooplankton in experimental ponds are presented in Table 2. Plankton composition was very rare for the first week of pond fertilization in every experimental pond. Phytoplankton started appearing in the first week. Likewise, zooplankton appeared after a week in each pond. After that, the experimental pond developed a green color, which is an indication of the development of phytoplankton. Microscopic examination of pond water showed the presence of different species of phytoplankton. The phytoplankton taxa are represented by the blue-green algae, the *Cynophyceae;* the green algae, the *Chlorophyceae;* the *Euglenophyceae;* and the diatoms, the *Bacillariophyceae*. The blue-green algae are represented by two genera, namely *Microcystis* and *Chroococcus* spp.; the green algae are represented by four genera, namely *Chlorella*, *Ankistrodesmus, Sphaerocystis*, and *Chlamydomonas*; *Euglenophyceae* is represented by one genus, the Euglena; and the diatoms by *Tabellaria, Fragilaria, Pinnularia*, and *Navicula*. Among the four phytoplankton groups, *Bacillariophyceae* showed the highest abundance composition during inspection under a microscope in all four treatments on various sampling days, whereas *Cyanophyceae* showed the lowest trend in all the treatments. The phytoplankton abundances were found in increasing order in vats treated with VC, followed by MF, and then by TSP. Zooplankton is represented by four taxa: *Brachionus,* copepods (cyclopoids), rotifers, and *Keratella*. The presence and abundance of these taxa can indicate water quality, nutrient availability, and ecosystem health.

Growth Performance of Fish

The growth performance of fish was evaluated based on several factors: weight gain, specific growth rate, food conversion ratio, and survival rate, as summarized in Table 3. There were no significant differences in the mean initial length and weight among the treatment groups, including the control groups. However, the treatment using vermicompost (VC) demonstrated a significantly higher growth rate ($p<0.05$) compared to the other treatments. The VC group exhibited the highest growth increments and total weight gains, followed by the MF and TSP treatments, while the control groups showed the lowest growth rates. By the end of the experiment, the mean weight gain of fish in the VC treatment was significantly higher at 62±.5 g, compared to 59±.5 g in the MF treatment and 56±.5 g in the TSP treatment. The control groups had the lowest mean weight gain, of 44±.5 g. The mean specific growth rate (SGR) of tilapia across the different treatments ranged from 2.20±.0087% to 2.54±.005% per day. The highest SGR value of 2.54±.005% per day was recorded in the VC treatment, while the lowest, at 2.20% per day, was observed in the control ponds. The food conversion ratios were recorded as follows: 1.39±.07 for the VC treatment, 1.54±.06 for the TSP treatment, 1.46±.05 for the MF treatment, and 1.96±.05 for the

Table 2. Phytoplankton and zooplankton identified in the treatment ponds

Phytoplankton Group	Treatments			
	WH Vermicompost	TSP	Mixed F (Urea +TSP)	Control
Cyanophyceae (Blue green algae)	*Microcystis*$^{+++}$ *Chroococcus sp.*$^{++}$	*Microcystis*$^{+}$ *Chroococcus sp.*$^{+}$	*Microcystis*$^{+}$ *Chroococcus sp.*$^{+}$	*Microcystis*$^{+}$ *Chroococcus sp.*$^{+}$
Chlorophyceae (Green algae)	*Chlorella*$^{++}$ *Ankistrodesmus*$^{+}$ *Sphaerocystis*$^{+}$ *Chlamydomonas*$^{++}$	*Chlorella*$^{++}$ *Ankistrodesmus*$^{+}$ *Sphaerocystis*$^{+}$ *Chlamydomonas*$^{++}$	*Chlorella*$^{++}$ *Ankistrodesmus*$^{+}$ *Sphaerocystis*$^{+}$ *Chlamydomonas*$^{++}$	*Chlorella*$^{++}$ *Ankistrodesmus*$^{+}$ *Sphaerocystis*$^{+}$ *Chlamydomonas*$^{++}$
Euglenophyceae	*Euglena*$^{++}$	*Euglena*$^{++}$	*Euglena*$^{++}$	*Euglena*$^{++}$
Bacillariophyceae (Diatoms)	*Tabellaria*$^{++}$ *Fragilaria*$^{+++}$ *Navicula*$^{+++}$ *Pinnularia*$^{++}$	*Tabellaria*$^{++}$ *Fragilaria*$^{+}$ *Navicula*$^{++}$ *Pinnularia*$^{+}$	*Tabellaria*$^{++}$ *Fragilaria*$^{+}$ *Navicula*$^{+++}$ *Pinnularia*$^{++}$	*Tabellaria*$^{++}$ *Fragilaria*$^{+}$ *Navicula*$^{++}$ *Pinnularia*$^{+}$
Zooplankton Group	Cop.(Cyclopoids)$^{+++}$ Rotifera^{++} *Brachionus*$^{+++}$ *Keratella*$^{+}$	Cyclopoids^{++} Rotifera^{++} *Brachionus*$^{++}$ *Keratella*$^{+}$	Cyclopoids^{++} Rotifera^{++} *Brachionus*$^{++}$ *Keratella*$^{+}$	Cyclopoids^{++} Rotifera^{++} *Brachionus*$^{+}$ *Keratella*$^{+}$
Phytoplankton density (cells L^{-1})	$2.84\times10^{6}\pm2.3\times10^{5a}$	$1.68\times10^{6}\pm1.5\times10^{5c}$	$2.21\times10^{6}\pm1.9\times10^{5b}$	$0.95\times10^{6}\pm0.8\times10^{5d}$
Shannon-Wiener diversity indices (H')	2.84 ± 0.21^{a}	2.23 ± 0.18^{c}	2.51 ± 0.19^{b}	1.95 ± 0.15^{d}
Zooplankton density (ind. L^{-1})	1580 ± 142^{a}	890 ± 76^{c}	1120 ± 98^{b}	520 ± 45^{d}
Copepods (45-55%) ind. L^{-1})	870 ± 78^{a}	400 ± 38^{c}	560 ± 51^{b}	240 ± 43^{d}
Zooplankton diversity (H')	2.12 ± 0.18^{a}	1.68 ± 0.14^{c}	1.89 ± 0.16^{b}	1.41 ± 0.12^{d}

Note: $^{+++}$Most abundant, $^{++}$ Abundant, $^{+}$ Rare

control ponds. The survival rates for the fish were generally high, ranging from 94±.58% to 100.0±.0%. This indicates that applying vermicompost at a rate of 1 kg/m² every 90 days can enhance tilapia growth in ponds. The overall health of the fish was assessed through random sampling from all ponds. Notably, the fish in the pond treated with water hyacinth vermicompost were in excellent condition, displaying normal physical appearances in their eyes, fins, opercula, and gills. The fish in the control ponds also show good health.

Discussions

This study demonstrates that water hyacinth vermicompost is a highly effective organic fertilizer for Nile tilapia ponds, significantly enhancing fish growth performance compared to conventional inorganic fertilizers (TSP and TSP + Urea) and unfertilized controls. The results support our hypotheses that vermicompost mediates its beneficial effects through bottom-up trophic stimulation, enhancing plankton communities and maintaining favorable water quality rather than through direct nutrient supplementation alone. These findings align with and extend previous research on vermicompost application in aquaculture (Chakrabarty et al., 2008; Kumar et al., 2007) while providing novel evidence specifically for water hyacinth-based vermicompost in semi-intensive tilapia culture.

Water Quality Dynamics

All physicochemical parameters measured throughout the 90-day experiment remained within acceptable ranges for Nile tilapia culture (Boyd, 2017; El-Sherif & El-Feky, 2009), confirming that the tested fertilization regimes did not compromise environmental conditions for fish health. This is particularly significant for vermicompost application, as concerns persist regarding potential oxygen depletion or nutrient overloading associated with organic inputs in aquatic systems (Boyd & Massaut, 1999). Our findings counter these concerns and are consistent with Garg et al. (2008), who reported that vermicompost application at appropriate rates maintains water quality within safe limits for carp culture.

Dissolved oxygen (DO) concentrations ranged from 8.06±1.09 mg/L in control ponds to 8.75±0.7 mg/L in TSP-treated ponds, with no significant differences among treatments ($p > 0.05$). The consistently high DO levels (>5 mg/L) across all treatments exceed the minimum requirement of 3 mg/L for optimal tilapia growth (Abdel-Tawwab et al., 2015). Notably, VC-treated ponds maintained DO levels (8.35±2.07 mg/L) comparable to inorganic treatments, similar to findings by Chakrabarty et al. (2009), who observed no oxygen depletion in vermicompost-fertilized carp ponds. This can be attributed to the stabilized nature of vermicompost, which undergoes aerobic decomposition during production, resulting in reduced biochemical oxygen demand upon application (Gajalakshmi & Abbasi, 2004). Furthermore, the enhanced phytoplankton abundance in VC ponds likely contributed to oxygen production through photosynthesis during daylight hours (Hargreaves & Tucker, 2004), creating a self-sustaining oxygen regime.

Water temperature remained stable across treatments (20.18-20.83°C), reflecting the groundwater source and consistent environmental conditions. While these temperatures are suboptimal for maximum tilapia growth (optimum 28-32°C; El-Sayed, 2006; Azaza et al., 2008), the uniformity across treatments ensures that observed growth differences reflect fertilization effects rather than thermal variation. The ability of tilapia to maintain differential growth rates under suboptimal temperatures underscores the nutritional contribution of natural food enhanced by vermicompost, consistent with observations by Liti et al. (2005) in fertilized Kenyan ponds.

pH values ranged from 9.00±0.00 (TSP) to 9.77±0.77 (VC), exceeding the typically recommended upper limit of 9.0 for aquaculture (Boyd & Tucker, 2012). However, no fish stress or mortality was observed, suggesting acclimation to local conditions or adequate

Table 3. Growth parameters of tilapia obtained from different treatments

Parameters	Treatments			
	WH Vermicompost	TSP	Mixed F (Urea+TSP)	Control
Fertilizer added (kg)	6	1.35	1.215	0
Initial Fish Weight (g)	7.00±.78964^{a}	7.144±.51088^{a}	7.1917±.57309^{a}	7.00±.82446^{a}
Final Fish Weight (g)	69.00±.78964^{a}	63.144±.5108^{c}	66.1917±.5730^{b}	51.00±.8244^{d}
Initial Fish length(cm)	8.433±.4633^{a}	8.3944±.1379^{a}	8.4120±.3490^{a}	8.400±.4232^{a}
Final Fish length (cm)	13.900±.5652^{a}	13.944±.1464^{a}	13.914±.1115^{a}	12.833±.057^{b}
SGR (% per day)	2.54±.005^{a}	2.495±.0087^{a}	2.44±.0087^{a}	2.20±.0087^{b}
Daily growth rate (g/d)	0.688±.0009^{a}	0.655±.0004^{a}	0.622±.0004^{a}	0.488±.0004^{b}
Weight gained (g)	62.0±.5^{a}	56.0±.5^{a}	59.0±.5^{a}	44.0±.5^{b}
Feed given in (g)	86.40±.005^{a}	86.40±.005^{a}	86.40±.005^{a}	86.40±.005^{a}
Food Conversion Ratio	1.39±.07^{a}	1.54±.06^{b}	1.46±.05^{ab}	1.96±.05^{c}
Survival rate (%)	94.0±.58^{a}	94.0±.58^{a}	94.0±.58^{a}	100.0±.0^{b}
Nutrient content (NPK)	2-1-2	0-46-0	46-0-0+0-46-0	-
Overall fish health	Normal (very good condition)	Normal	Normal	Normal (good condition)

Results in the same row having the same letters are not significantly different at P>0.05.

buffering capacity. Similar pH ranges (8.5-9.5) were reported by Wurts and Durborow (1992) in productive aquaculture ponds without adverse effects. The elevated pH likely resulted from intensive photosynthetic activity removing CO2, particularly in VC and MF treatments, where phytoplankton abundance was highest. Total alkalinity (34.7-39.8 mg/L as CaCO3) fell within the low-to-medium productivity range (Moyle, 1946), comparable to values reported by Santhosh and Singh (2007) for productive tropical ponds. The slightly higher alkalinity in control and MF ponds may reflect reduced photosynthetic demand for CO2.

Nutrient dynamics revealed treatment-specific patterns with important ecological implications. Phosphate concentrations were significantly higher in VC-treated ponds (0.5±0.01 mg/L) compared to all other treatments ($p<0.05$), while nitrate showed a distinct hierarchy: VC (8.61 mg/L) > Control (8.51 mg/L) > MF (8.14 mg/L) > TSP (7.8 mg/L). These patterns reflect fundamental differences in nutrient release kinetics between organic and inorganic fertilizers.

Inorganic fertilizers (TSP and MF) deliver nutrients in highly soluble forms, creating immediate but transient availability peaks (Boyd, 2017). TSP, containing 46% P2O5 as water-soluble monocalcium phosphate, rapidly releases phosphate that can be quickly taken up by phytoplankton or fixed into insoluble calcium phosphates in high-pH waters (Masuda & Boyd, 1994). This may explain the paradoxically lower measured phosphate in TSP-treated ponds despite high application rates, rapid biological uptake, and chemical precipitation likely removed dissolved phosphate before sampling. Similar findings were reported by Diana et al. (1991), who observed rapid phosphorus disappearance from the water column following TSP application in Thai fish ponds. Conversely, the combination of urea and TSP in MF treatment provided both nitrogen and phosphorus, promoting more balanced phytoplankton growth and explaining intermediate phosphate levels, consistent with Knud-Hansen et al. (1991).

Vermicompost, by contrast, functions as a slow-release fertilizer. Its organic matrix retains nutrients that become bioavailable through microbial mineralization (Atiyeh et al., 2002). The significantly higher phosphate in VC ponds suggests sustained release throughout the experimental period, maintaining elevated concentrations despite continuous biological uptake. This slow-release characteristic is particularly valuable in aquaculture, where pulsed nutrient inputs from inorganic fertilizers can lead to boom-bust cycles in phytoplankton production, followed by crashes that deplete oxygen and release ammonia (Boyd & Tucker, 2012; Hargreaves, 1998). Our results align with Edwards (1993), who advocated for organic fertilizers in tropical ponds precisely for their sustained nutrient release properties.

The elevated nitrate in control ponds (8.51 mg/L) relative to TSP (7.8 mg/L) and MF (8.14 mg/L) is unexpected but may reflect nitrification of ammonia derived from supplemental feed and fish excretion in the absence of competing phytoplankton uptake. In fertilized ponds, vigorous phytoplankton growth assimilates inorganic nitrogen rapidly, potentially reducing ambient nitrate concentrations despite higher total nitrogen inputs (Hargreaves, 1998). This interpretation is supported by the inverse relationship between phytoplankton abundance (highest in VC) and nitrate accumulation (lowest in TSP), consistent with observations by Teichert-Coddington and Green (1993) in Honduran fish ponds.

Conductivity values (2570-2910 µS/cm) were elevated across all treatments, reflecting the groundwater source and potential mineral accumulation. While these values exceed typical freshwater ranges (<1000 µS/cm; Boyd, 2017), tilapia are euryhaline and tolerate broad salinity ranges (Stickney, 2000). The significantly lower conductivity in MF ponds (2570 µS/cm) compared to controls (2910 µS/cm) may indicate greater nutrient uptake by phytoplankton, removing dissolved ions from the water column, a phenomenon also noted by Boyd (1990) in fertilized ponds.

Secchi depth measurements (31.3-36.7 cm) fell within the optimal range for fish ponds (30-60 cm; Bhatnagar & Devi, 2013; Almazán & Boyd, 1978), indicating moderate phytoplankton densities without excessive turbidity. The significantly lower Secchi depth (higher turbidity) in VC ponds (31.3 cm) compared to controls (36.7 cm) reflects greater phytoplankton standing crops, consistent with nutrient enrichment and supporting our hypothesis of enhanced primary productivity. These values are comparable to those reported by Diana et al. (1995) for optimally fertilized tilapia ponds in Asia.

Plankton Community Structure and Dynamics

The plankton community represents the critical trophic link between fertilizer inputs and fish production in semi-intensive aquaculture (Milstein, 1992; Schroeder, 1978). Our results demonstrate that the fertilization regime fundamentally influences not only plankton abundance but also community composition and diversity, with cascading effects on fish growth performance. The quantitative assessment of plankton density and diversity provides robust evidence for treatment effects that extend beyond the qualitative observations common in earlier studies (e.g., Saha et al., 2002).

Phytoplankton abundance and composition varied significantly among treatments, with VC ponds supporting the highest densities and the most diverse community. Mean phytoplankton density in VC ponds ($2.84 \times 10^6 \pm 2.3 \times 10^{5a}$ cells L^{-1}) significantly exceeded MF ($2.21 \times 10^6 \pm 1.9 \times 10^{5b}$ cells L^{-1}), TSP ($1.68 \times 10^6 \pm 1.5 \times 10^{5c}$ cells L^{-1}), and control ponds ($0.95 \times 10^6 \pm 0.8 \times 10^{5d}$ cells L^{-1}) ($p<0.05$). This hierarchy mirrors the fish growth

results, strongly supporting the bottom-up trophic transfer mechanism. Similar findings were reported by Chakrabarty et al. (2008), who observed 40-60% higher phytoplankton densities in vermicompost-treated carp ponds compared to inorganic fertilizer treatments.

The dominance of Bacillariophyceae (diatoms) across all treatments, particularly in VC ponds, has important nutritional implications. Diatoms are considered high-quality food for filter-feeding fish and zooplankton due to their appropriate size, digestibility, and essential fatty acid content, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (Müller-Navarra et al., 2000; Brett & Müller-Navarra, 1997). The abundant genera *Navicula*, *Fragilaria*, and *Tabellaria* are typically associated with nutrient-rich, well-oxygenated waters and serve as high-quality forage. Their predominance in VC ponds suggests that vermicompost creates conditions favoring nutritionally valuable algal groups over less desirable cyanobacteria, consistent with findings by Das et al. (2005) in organically-fertilized ponds. Chlorophyceae (green algae), represented by *Chlorella*, *Ankistrodesmus*, *Sphaerocystis*, and *Chlamydomonas*, formed the second most abundant group. These genera are typical of eutrophic waters and contribute substantially to primary production (Reynolds, 2006). *Chlorella*, in particular, is widely used as live feed in aquaculture due to its high protein content (50-60% dry weight) and digestibility (Becker, 2004). The presence of *Chlamydomonas*, a motile flagellate capable of vertical migration, suggests dynamic water column conditions that may enhance nutrient cycling, as described by Sommer et al. (2012) in productive aquatic systems. Euglenophyceae (*Euglena* spp.) occurred at moderate abundance, particularly in VC and MF treatments. Euglenophytes are often associated with organic-rich environments (Wolowski & Walne, 2006) and can supplement fish nutrition through their high protein and vitamin content (Takeuchi et al., 1997). Their presence at moderate levels in VC ponds is consistent with observations by Jana et al. (2001) in manured aquaculture ponds.

Cyanophyceae (blue-green algae), represented by *Microcystis* and *Chroococcus*, showed the lowest abundance among phytoplankton groups but were notably more prevalent in VC ponds than in other treatments. While some cyanobacteria produce toxins and are considered undesirable (Paerl & Otten, 2013), their presence at moderate levels in diverse communities may not pose risks. The co-dominance of diatoms and green algae likely suppressed excessive cyanobacterial proliferation through competitive exclusion (Tilman et al., 1982; Smith, 1983). This balanced community structure is a key indicator of ecosystem health and contrasts with the cyanobacteria-dominated blooms often associated with inorganic fertilizer overuse (Smith, 2003; Hargreaves, 1998).

Shannon-Wiener diversity indices (H') for phytoplankton were highest in VC ponds (2.84 ± 0.21^{a}), followed by MF (2.51 ± 0.19^{b}), TSP (2.23 ± 0.18^{c}), and controls (1.95 ± 0.15^{d}). Greater diversity typically confers ecosystem stability and resilience to perturbation (McCann, 2000), suggesting that vermicompost fosters more robust plankton communities better able to maintain productivity throughout the production cycle. These diversity values are comparable to those reported by Mustapha (2009) for productive tropical reservoirs and exceed those typically found in intensively fertilized ponds (Milstein et al., 1992).

Zooplankton community response to fertilization treatments was equally pronounced and followed patterns consistent with phytoplankton availability. Total zooplankton density in VC ponds (1580 ± 142^{a} individuals L^{-1}) significantly exceeded MF (1120 ± 98^{b} ind. L^{-1}), TSP (890 ± 76^{c} ind. L^{-1}), and control ponds (520 ± 45^{d} ind. L^{-1}) ($p<0.05$). Copepods (Cyclopoida) dominated all treatments, comprising 45-55% of total zooplankton abundance, followed by Rotifera (25-30%), *Brachionus* (15-20%), and *Keratella* (5-10%). This taxonomic composition is typical of fertilized tropical ponds (Fernando, 1994) and similar to that reported by Saha et al. (2002) in manure-fertilized carp nurseries.

The dominance of copepods, particularly Cyclopoids, is ecologically significant. Copepods are nutritionally superior to many other zooplankton due to their high protein content (50-70% dry weight) and essential fatty acid profiles rich in EPA and DHA (Evjemo et al., 2003; Sargent et al., 1999). Nile tilapia, particularly during juvenile stages, actively forage on copepods, and their availability can substantially reduce dependence on formulated feeds (El-Sayed, 2006; Getachew, 1987). The significantly higher copepod abundance in VC ponds (870 ± 78^{a} ind. L^{-1}) compared to MF (560 ± 51^{b} ind. L^{-1}), TSP (400 ± 38^{c} ind. L^{-1}), and CO (240 ± 43^{d} ind. L^{-1}) represents a substantial increase in high-quality natural food availability, consistent with the findings of Kumar et al. (2007) in vermicompost-fertilized polyculture ponds.

Rotifers, particularly Brachionus spp., were also more abundant in VC ponds. Rotifers are an important first food for fish larvae and small fingerlings due to their appropriate size and slow movement (Lubzens et al., 1989). Their presence throughout the study period indicates sustained suitable conditions for zooplankton production, similar to observations by Jana and Chakrabarty (1993) in manured nursery ponds. The higher abundance of Brachionus in VC ponds compared to other treatments likely contributed to the superior growth of smaller size classes of tilapia. The positive relationship between fertilizer type and zooplankton abundance operates through two mechanisms: direct effects on phytoplankton prey availability and indirect effects on water quality and habitat suitability. The sustained nutrient release from vermicompost supported consistent phytoplankton production, which in turn maintained higher zooplankton carrying capacity. In contrast, the pulsed nutrient inputs from inorganic fertilizers may have created feast-famine cycles in phytoplankton production, limiting

zooplankton populations that require stable food supplies to complete their life cycles (Sommer et al., 2012; Lampert, 1988). This interpretation is supported by the lower coefficient of variation in plankton densities over time in VC ponds compared to inorganic treatments (data not shown), consistent with the "stability" argument advanced by Oglesby (1977) for naturally productive aquatic systems.

Zooplankton diversity (H') followed patterns similar to phytoplankton: VC ponds (2.12±0.18) > MF (1.89±0.16) > TSP (1.68±0.14) > control (1.41±0.12). Higher diversity in zooplankton communities is associated with more efficient energy transfer through the food web and greater resilience to environmental fluctuations (Duffy et al., 2007). The particularly low diversity in control ponds reflects resource limitation, as only the most competitive species persist under low-food conditions, consistent with predictions from ecological theory (Tilman, 1982).

The mechanistic link between enhanced plankton communities and fish growth is well-established in aquaculture ecology (Milstein, 1992; Diana et al., 1995; Schroeder, 1978). Nile tilapia is an omnivorous filter-feeder capable of efficiently grazing phytoplankton and zooplankton throughout its life cycle (Getachew Tefera, 1987; Bowen, 1982). In semi-intensive systems, natural food can contribute 30-60% of total tilapia nutrition, even when supplemental feed is provided (Diana et al., 1995; Liti et al., 2005; El-Sayed, 2006). The superior plankton production in VC ponds effectively subsidized fish nutrition, reducing metabolic demand on formulated feed and improving overall growth efficiency. This interpretation is supported by the lower FCR in VC ponds (1.39±.07) compared to other treatments, indicating better conversion of total inputs (feed + natural food) into fish biomass, consistent with findings by Chakrabarty et al. (2008) and Kumar et al. (2007).

Fish Growth Performance

The growth performance data provide compelling evidence for the superiority of water hyacinth vermicompost as a pond fertilizer. Final mean weight of tilapia in VC ponds (69.00±0.79 g) significantly exceeded MF (66.19±0.57 g), TSP (63.14±0.51 g), and control (51.00±0.82 g) treatments ($p<0.05$), representing a 35% increase over controls and 9% increase over the next best treatment (MF). These differences emerged progressively over the 90-day culture period, with divergence accelerating during the final month as treatment effects accumulated. Similar growth enhancements were reported by Ghosh (2004) in vermicompost-fertilized carp ponds (28% increase over controls) and by Kebede et al. (2025) in integrated vermi-pisciculture systems in Ethiopia.

Weight gain followed the same hierarchy: VC (62.0±0.5 g) > MF (59.0±0.5 g) > TSP (56.1±0.5 g) > control (44.0±0.5 g). The 41% higher weight gain in VC compared to controls, despite identical supplemental feeding rates, unequivocally demonstrates the contribution of fertilizer-induced natural productivity. Importantly, VC outperformed both inorganic treatments despite having lower immediately available nutrient concentrations, underscoring the importance of sustained nutrient release and food web development over instantaneous nutrient availability. These results align with the conceptual framework proposed by Edwards (1993), who argued that organic fertilizers often outperform inorganic options in tropical ponds due to their multiple trophic pathways.

Specific growth rate (SGR) in VC ponds (2.54±.005% day^{-1}) compared favorably with published values for Nile tilapia under semi-intensive culture. Workagegn and Gjoen (2012) reported SGR of 2.59-2.73% day^{-1} for different tilapia strains in earthen ponds in Ethiopia, nearly identical to our findings. Ashagrie Gibtan et al. (2008) observed lower values (0.79-1.03% day^{-1}) under extensive conditions in Ethiopian reservoirs, highlighting the importance of fertilization. The SGR achieved in our study approaches those reported for intensively fed systems (2.8-3.2% day^{-1}; Abdel-Tawwab et al., 2006; El-Sayed, 2006), indicating that vermicompost-mediated natural productivity effectively supplements nutritional inputs. The progressive decline in SGR across treatments (VC > MF > TSP > control) mirrors the plankton abundance gradient, reinforcing the causal relationship between natural food availability and growth performance established by Diana et al. (1995).

Daily growth rate (DGR) ranged from 0.488±0.0004 g day^{-1} (control) to 0.688±.0009 g day^{-1} (VC). These values are comparable to Liti et al. (2005), who reported 0.6-0.9 g day^{-1} for tilapia in fertilized ponds with supplemental feeding in Kenya, but lower than optimally-fed systems (1.5-2.5 g day^{-1}; El-Sayed, 2006). The suboptimal water temperatures (20-21°C) during our study likely constrained absolute growth rates, as tilapia growth increases exponentially with temperature up to 30°C (Azaza et al., 2008; Stickney, 2000). The persistence of treatment differences under thermal stress highlights the robustness of the vermicompost effect. Our DGR values substantially exceed those reported by Ogunji et al. (2008) for unfertilized systems (0.16-0.23 g day^{-1}) and are within the range observed by Workagegn and Gjoen (2012) for Ethiopian tilapia strains.

Feed conversion ratio (FCR) showed significant improvement with vermicompost application. The FCR of 1.39±0.07 in VC ponds indicates highly efficient feed utilization, substantially better than control ponds (1.96±0.05) and marginally better than MF (1.46±0.05) and TSP (1.54±0.06). These values fall within the optimal range for tilapia (1.4-1.8; Awad, 2017; Jauncey & Ross, 1982) and are considerably lower than FCRs reported for some on-farm formulated diets (2.6-3.0; Liti et al., 2005; Ogunji et al., 2008). The low FCR in VC ponds implies that natural food organisms contributed substantially to meeting nutritional requirements, reducing the

proportion of supplemental feed required for each unit of growth. This has direct economic implications, as feed typically represents 50-70% of operating costs in semi-intensive aquaculture (El-Sayed, 2006; Shang, 1990). Similar FCR improvements with vermicompost were reported by Chakrabarty et al. (2008), who observed FCR reductions from 2.1 to 1.5 in carp culture.

Survival rates exceeded 94±0.58% in all treatments, with 100.0±0.0% survival in control ponds. High survival confirms that water quality remained within tolerable limits and that no acute disease outbreaks occurred. The slightly lower (though statistically non-significant) survival in fertilized ponds (94%) may reflect the challenges of maintaining water quality at higher fish densities and feeding rates, as fertilized ponds supported larger fish biomass with correspondingly higher metabolic waste production. Similar survival rates (90-100%) are commonly reported in well-managed tilapia culture (El-Sayed, 2006; El-Sherif et al., 2011), and our values compare favorably with those of Ashagrie Gibtan et al. (2008) in Ethiopian ponds.

Fish health assessment revealed no external abnormalities in any treatment, with VC ponds supporting fish in "excellent condition" based on visual inspection of eyes, fins, opercula, and gills. This qualitative observation, while not a substitute for rigorous health assessment, provides initial evidence that vermicompost application does not compromise fish welfare. The normal appearance of all anatomical features corresponds to descriptions by Geode (1988) for healthy tilapia. Future studies should incorporate quantitative health indicators, including condition factor (K), hepatosomatic index, and blood chemistry profiles, as recommended by Abdel-Tawwab et al. (2015), to validate these observations.

Mechanisms Underlying Vermicompost Performance

The superior performance of water hyacinth vermicompost can be attributed to several interacting mechanisms that distinguish it from inorganic fertilizers. These mechanisms operate synergistically to enhance pond productivity while maintaining environmental quality.

Unlike soluble inorganic fertilizers that rapidly dissolve and become subject to chemical fixation or washout, vermicompost releases nutrients gradually through microbial mineralization (Atiyeh et al., 2002). This slow-release characteristic maintains more stable nutrient concentrations in the water column, supporting consistent phytoplankton production without the boom-bust cycles characteristic of pulsed fertilizer applications (Boyd & Tucker, 2012; Hargreaves, 1998). The sustained availability of phosphate and nitrate in VC ponds (Table 1) supports this interpretation and is consistent with the conceptual model of Edwards (1993) for organic fertilizers in tropical ponds. Vermicompost adds organic matter that serves multiple functions beyond nutrient supply. It provides substrate for bacterial growth, enhancing microbial loop processes that recycle nutrients and produce microbial protein available to filter-feeding organisms (Moriarty, 1997; Schroeder, 1978). These bacteria themselves serve as direct food for tilapia and zooplankton (Beveridge et al., 1989), adding another trophic pathway for nutrient transfer. Organic matter may also chelate micronutrients, maintaining their bioavailability in high-pH water where they would otherwise precipitate (Chen et al., 2004). Similar mechanisms have been invoked to explain the superior performance of manures over inorganic fertilizers in traditional Asian aquaculture (Little & Muir, 1987).

The more diverse phytoplankton and zooplankton communities in VC ponds provide superior nutrition compared to less diverse communities. Different algal groups produce distinct fatty acid profiles (Brett & Müller-Navarra, 1997; Ahlgren et al., 1990), and mixed diets often support better growth than monospecific diets due to nutritional complementarities (Demott & Müller-Navarra, 1997). The abundance of diatoms in VC ponds may be particularly significant given their high EPA content, which is essential for fish growth and health (Sargent et al., 1999; Watanabe, 1982). Zooplankton grazing on diverse phytoplankton assemblages themselves accumulate more balanced fatty acid profiles, further enhancing nutritional quality transfer to fish (Evjemo et al., 2003). The use of water hyacinth as feedstock for vermicompost production addresses two challenges simultaneously: managing an invasive aquatic weed that degrades freshwater ecosystems throughout Ethiopia and the tropics (Patel, 2012; Gichuki et al., 2012), and providing a low-cost fertilizer input for smallholder aquaculture. This dual benefit aligns with circular economy principles and sustainable development goals, enhancing the practical significance of the research. Studies by Singh and Kalamdhad (2013) and Mukhopadhyay (2023) have further demonstrated that vermicomposting reduces heavy metal bioavailability in water hyacinth, addressing potential concerns about toxin transfer through the food chain.

Implications for Aquaculture Development

Our findings have important implications for sustainable aquaculture development, particularly in resource-limited settings. Water hyacinth vermicompost offers a low-cost, locally producible alternative to imported inorganic fertilizers, reducing external input dependence and improving farm profitability. The transformation of an invasive weed into a productive resource creates dual benefits: controlling an environmental nuisance while supporting food production. This aligns with the concept of "integrated pest management" applied to invasive species (Patel, 2012) and with principles of ecological intensification in agriculture (Cassman, 1999). The

improved FCR in vermicompost-treated ponds has particular economic significance. Feed typically represents the highest variable cost in semi-intensive aquaculture, accounting for 50-70% of operating expenses (El-Sayed, 2006; Shang, 1990). By enhancing natural food production, vermicompost reduces the proportion of nutritional requirements that must be met by formulated feed, potentially improving farm profitability. For smallholder farmers with limited access to commercial feeds, vermicompost may enable productive aquaculture with minimal external inputs, as suggested by Little and Muir (1987) for traditional Asian systems. The environmental benefits of vermicompost use also merit consideration. Inorganic fertilizer production is energy-intensive and contributes to greenhouse gas emissions (Woods et al., 2010; Pelletier et al., 2007). By substituting locally-produced organic fertilizers for industrially-manufactured chemicals, aquaculture systems can reduce their carbon footprint. Furthermore, the slow-release characteristics of vermicompost reduce nutrient losses to surrounding waterways, mitigating eutrophication risks associated with aquaculture effluents (Boyd & Tucker, 2012; Hargreaves, 1998). This environmental compatibility is increasingly important as aquaculture faces scrutiny over its ecological impacts (Naylor et al., 2000). From a policy perspective, our results support investments in vermicomposting extension programs that train farmers to convert locally available organic wastes, including invasive water hyacinth, into valuable aquaculture inputs. Such programs could simultaneously address invasive species management, waste utilization, and food security objectives, representing efficient use of development resources. Similar programs have proven successful in integrated agriculture-aquaculture systems in Asia (Prein, 2002; Edwards et al., 1988) and could be adapted to African contexts.

Conclusions and Recommendations

This study provides compelling evidence that water hyacinth vermicompost is a superior and sustainable alternative to conventional inorganic fertilizers for semi-intensive Nile tilapia pond culture. By enhancing plankton productivity and diversity, vermicompost significantly improved fish growth, final weight, and feed conversion ratio while maintaining excellent water quality. The process successfully transforms an ecologically problematic weed into a valuable resource, aligning with principles of circular economy and sustainable aquaculture.

The key conclusions from this research are:-

- ❖ Tilapia in VC-treated ponds achieved significantly higher final weights (69.0 g), weight gains (62.0 g), and specific growth rates (2.54% day^{-1}) compared to fish in MF, TSP, and control treatments ($p<0.05$).
- ❖ The FCR of 1.39 in VC ponds was substantially better than controls (1.96) and marginally better than inorganic treatments (1.46-1.54), indicating more efficient conversion of total inputs into fish biomass.
- ❖ VC ponds supported significantly higher densities of phytoplankton (2.84×10^6 cells L^{-1}) and zooplankton (1580 in. L^{-1}), with greater diversity and dominance of nutritionally valuable groups (diatoms, copepods) compared to other treatments.
- ❖ All measured physicochemical parameters remained suitable for tilapia culture throughout the experiment, addressing concerns about potential negative impacts of organic fertilization.
- ❖ Water hyacinth, an invasive weed threatening Ethiopian water bodies, can be converted through vermicomposting into a valuable aquaculture input, creating dual benefits for ecosystem management and food production.

Based on these conclusions, the following recommendations are forwarded:-

- ✓ Water hyacinth vermicompost at a rate of 1 kg/m² (10 t/ha) per production cycle, applied monthly with the first application 15 days before fish stocking, is recommended for semi-intensive Nile tilapia culture in ponds.
- ✓ This fertilization regime should be combined with supplemental feeding at 3% body weight daily to achieve optimal growth performance and feed efficiency.
- ✓ Farmers should be trained in simple vermicomposting techniques to convert locally available water hyacinth into fertilizer, reducing dependence on purchased inorganic inputs and controlling invasive weeds.
- ✓ Pond water quality should be monitored regularly, particularly during the first weeks after fertilization, to ensure conditions remain within acceptable ranges.
- ✓ Conduct long-term studies over complete production cycles (6-8 months) and multiple cycles to evaluate cumulative effects on pond sediment health, nutrient dynamics, and fish productivity.
- ✓ Perform detailed nutrient-budget analyses to quantify nitrogen and phosphorus utilization efficiencies in vermicompost-fed ponds, identifying pathways for improving nutrient retention.
- ✓ Undertake dose-response studies to establish optimal vermicompost application rates for different production objectives and environmental conditions.
- ✓ Investigate the microbial and biochemical mechanisms by which vermicompost influences plankton community dynamics and fish nutrition, including potential probiotic effects.

- ✓ Conduct a comprehensive economic analysis, including vermicompost production costs, application labor, and sensitivity to input price fluctuations, to determine profitability compared to current practices.
- ✓ Compare water hyacinth vermicompost with other organic and integrated nutrient management strategies to identify the most effective and sustainable approaches for different farming contexts.

Ethical Statement

All experimental procedures involving fish were conducted in accordance with national and institutional guidelines for the care and use of animals in research.

Funding Information

The authors received no financial support for the research, authorship, and/or publication of this article.

Author Contribution

First Author: Writing the manuscript. Second Author: Data Organizer and arranging for the second draft. Third Author: Data curation. Fourth Author: Cross Checking and reviewing.

Conflict of Interest

The authors declare that there is no conflict of interest.

Acknowledgement

The author acknowledges Batu Fish and Other Aquatic Life Research Center.

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