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Effects of organic fertilizers produced from fish pond sediment on growth performances and yield of Malabar and *Amaranthus* vegetables

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The increasing intensification of aquaculture production requires the development of strategies to reduce its environmental impacts such as the pollution caused by the discharge of nutrient-rich sediments into local water bodies. This research was undertaken to investigate and evaluate the effect of using organic fertilizers produced from the pond sludge of freshwater snakehead fish (*Channa striata*) composted with organic amendments of peanut shells and coir fiber on growth performance indices and yields of Malabar spinach (*Basella alba* L.) and *Amaranthus cruentus* (*Amaranthus* L.) vegetables in the dry and wet seasons. An organic fertilizer quality experiment showed that the richest nutrient contents of the produced organic fertilizer were achieved when using 30% sludge mixed with 70% organic amendments (50% peanut shells + 50% coir fiber). This was selected and used for a vegetable cultivation experiment. For the reference treatment, only chemical fertilizer was applied, while in the other four treatments, 25, 50, 75, and 100% of the chemical fertilizer were substituted with the organic fertilizer. A 25–50% reduction in the chemical fertilizer application resulted in better growth performance indices and final yields than the other treatments, including the reference treatment, for both crops. The highest yields of Malabar spinach and *Amaranthus cruentus* vegetables were found in Treatment 3 (50% chemical fertilizer combined with 50% organic fertilizer), followed by Treatment 2 (25% organic fertilizer combined with 75% inorganic fertilizer) ($P < 0.05$). The results show that the reuse of sludge from snakehead fish ponds mixed with agricultural by-products as organic fertilizer for vegetables not only improves vegetable productivity but also reduces the costs of chemical fertilizer and decreases environmental pollution.

KEYWORDS

snakehead fish, sludge/sediment, peanut shells and coir fiber, organic fertilizer, vegetables

Introduction

Aquaculture is one of the fastest-growing industries in Vietnam, contributing to export revenues and increased income for many farmers. Vietnam is ranked the fourth biggest exporter of seafood in the world (FAO, 2020). The export revenue of aquaculture and agricultural products for Vietnam was US$ 40.02 billion (9.3 million tons) in 2019 and accounted for 7.2% of the total national export value, with 70 types of products sold to over 160 countries around the world (VASEP, 2019; MARD, 2020).

The Mekong Delta is a core region for aquaculture in Vietnam where intensive farming of striped catfish (*Pangasianodon hypophthalmus*), whiteleg shrimp (*Litopenaeus vannamei*), giant tiger prawn (*Penaeus monodon*), and giant freshwater prawn (*Macrobrachium rosenbergii*) are currently the most developed sectors. Furthermore, other inland freshwater species such as snakehead (*Channa striata* Bloch, 1973), red tilapia (*Oreochromis sp.*), climbing perch (*Anabas testudineus*), and Asian swamp eels (*Monopterus albus*) are produced at differing levels of intensification and extent in the region. In general, aquaculture in the Mekong Delta plays a crucial role to increase local livelihood income and provide economic benefits to society in the region. It has great potential to continue its current growth and development. However, there are a number of challenges and risks including environmental pollution, harsh weather, and climate change for sustainable growth of the aquaculture sectors (FAO, 2022).

The Binh Duong province, located in the Southeast region of Vietnam, has a well-developed grid of freshwater rivers and canals, which provide a good potential for inland aquaculture development. Due to a large demand for animal protein and fresh vegetables for local consumption, the availability of freshwater and land for aquaculture is decreasing. Snakehead fish is one of the most popular cultured fish species, which has a high economic value, and provides important animal protein and income to local people in the region (Bich et al., 2020; Gustiano et al., 2021). This freshwater fish is a carnivorous species, which is raised in high stocking densities, often fed commercial feeds and trash-fish with a high protein content.

The amount of sludge from fish feces and uneaten feed accumulating in the sediments of fish ponds is quite high with approximately 100–150 kg m^{-3} after a cultivation cycle. Most of the sludge from snakehead fish pond farming is usually discharged untreated directly into rivers and canals, causing water pollution in the province. Currently, there are few solutions to solve the problem of wastewater and sludge from aquaculture farming systems. As the sludge includes uneaten feed and fish feces and has high organic material (OM), nitrogen (N), phosphorus (P), and other macronutrient and micronutrient contents (Thanh et al., 2015; Haque et al., 2016; Da et al., 2020, 2021), one option could be to use it as a fertilizer for improving the productivity of vegetables and other crops. This would reduce the reliance on inorganic fertilizers and reduce the treatment cost of sludge/sediment while reducing the negative impacts and pollution from aquaculture production on the environment. There are a number of studies in Thailand, China, Vietnam, and Bangladesh that have focused on how to recycle wastewater and sludge/sediment from catfish pond farming and composting fish pond sludge/sediment mixed with agriculture waste residues (water hyacinth, rice straws, and weeds/green grass) as organic fertilizers for paddy rice, common vegetables (such as cucumber, water spinach, and Chinese mustard), and fodder grass (Graber and Junge, 2009; Phung et al., 2009; Karak et al., 2013; Da et al., 2015, 2020, 2021; Thanh et al., 2015; Haque et al., 2016).

Vietnam, located in the tropical monsoon region with high agricultural diversity and rich inland aquatic ecosystems, could be considered a potential country for developing large-scale freshwater aquaculture integrated with agriculture, with the aim to reduce production costs and environmental impacts. Malabar spinach and *Amaranthus cruentus* vegetables are popular vegetables cultured on many farms in Vietnam and other Asian countries. These vegetables have rich contents of vitamin A, vitamin C, vitamin K, Iron, and Calcium (Haskell et al., 2004; Makobo et al., 2010). The leaves of the vegetables contain vitamin K, organic acids, carotenoids, bioflavonoids, water-soluble polysaccharides, and betacyanin, and they constitute valuable sources of nutritional and medicinal importance for human health and wellbeing (Adebooye et al., 2008; Ajay et al., 2021). In recent years, the price of chemical fertilizer for agricultural crops and vegetables in Vietnam has dramatically increased, which has led to a large fertilizer deficit (Quynh and Kazuto, 2018). At the same time, the price of agricultural products (vegetables, fruits, and rice production) has remained comparatively low and unprofitable, and there is now a need for farmers to reduce their reliance on expensive chemical fertilizers. Previous studies have reported that the composting of sediment from *Pangasius* catfish pond farming mixed with locally sourced organic residues (rice straw and/or water hyacinth) could be used as organic fertilizers, which could provide an alternative to chemical fertilizers and help to mitigate water pollution, while still improving agricultural production and soil quality (Rahman et al., 2004; Rahman and Yakupitiyage, 2006; Thanh et al., 2015; Da et al., 2020, 2021).

This study aimed to investigate if composting a combination of different proportions of sludge from snakehead fish ponds with agricultural residues (peanut shells and coir fiber) could provide an organic fertilizer that could be used as a substitute for chemical fertilizers. The aim was also to assess how this organic fertilizer affected growth performance indices and yields of Malabar spinach and *Amaranthus cruentus* vegetables.

Materials and methods

Study area and organic amendment materials

The study was carried out in 2021 at a vegetable farm (total farm area is approximately 1,000 m^2) in the Tan Uyen district in the Binh Duong province of the Mekong Delta in Vietnam (Figure 1). Most vegetable farmers in this area practice intensive vegetable farming with multiple cropping throughout the year. The experiment area is dominated by clay-alluvial soil. Sludge/sediment was collected from a snakehead fish pond (an earthen pond of approximately 2,000 m^2) after the fish had been harvested. Peanut shells and coir fiber used as organic amendments were collected from local farms in the Tan Uyen district. High-yielding varieties of Malabar spinach (*Basella alba* L.) and *Amaranthus cruentus* (*Amaranthus* L.) seeds were bought from Thu Dau city in the Binh Duong province. The experiments of the vegetable cultivation were carried out in the dry season (March–June 2021) and the wet season (September–October 2021), and the Malabar spinach and *Amaranthus cruentus* vegetables were grown in an area of 1,000 m^2 using an experimental design as presented in Figures 2, 3.

Research layout

The scope of this study included (1) Collection and chemical analysis of sludge from fish pond farming, organic amendments (Peanut shell and coir fiber), and soil of the experiment (beginning

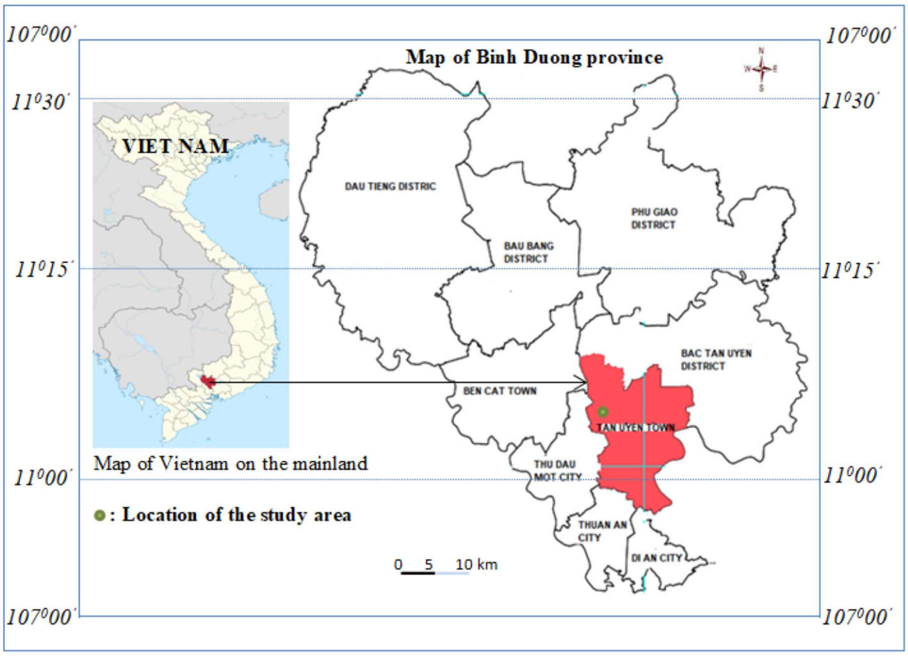

FIGURE 1
Study area in Binh Duong province, Vietnam.

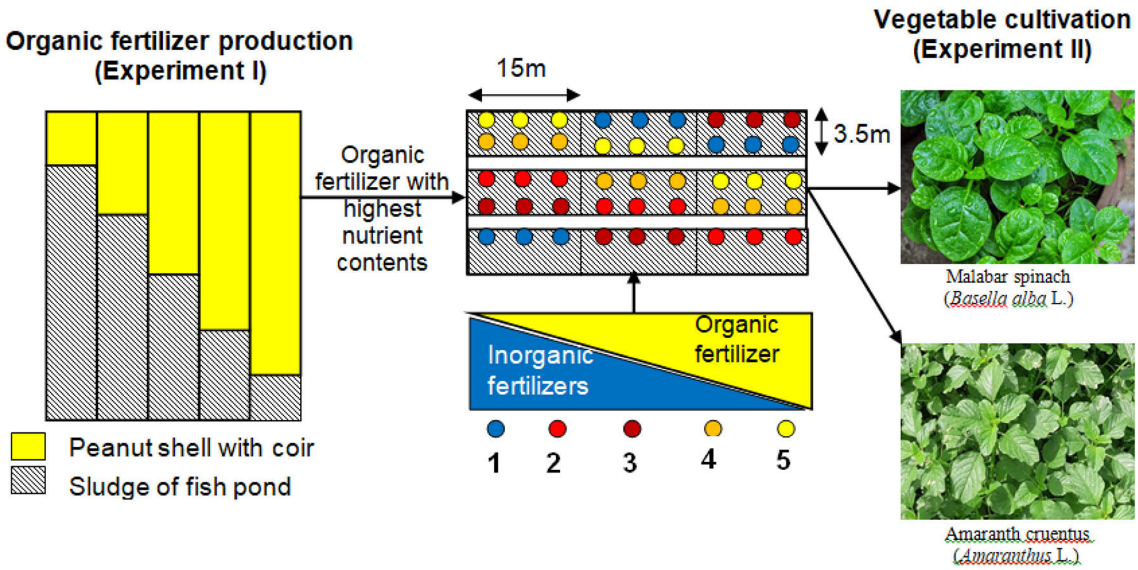

FIGURE 2
Layout of the Malabar spinach (*Basella alba* L.) and *Amaranthus cruentus* (*Amaranthus* L.) vegetables cultivation fertilized by the different organic fertilizer and chemical fertilizer combinations.

and end); (2) Organic fertilizers composted and produced in different proportions (10, 30, 50, 70, and 90%) between sludge/sediment from snakehead fish pond and organic amendments for 95 days; (3) The organic fertilizers of each treatment were analyzed for chemical composition to estimate which organic fertilizer had the richest nutrient concentrations to be used in the vegetable cultivation experiment; (4) Soil preparation for experiment with the organic fertilizer with the highest nutrient content to partly replace inorganic fertilizers for vegetables cultivation of Malabar spinach and *Amaranthus cruentus* in the dry and wet seasons; (5) Conducting growth performance experiment of vegetables treated with different ratios of organic and inorganic fertilizers; (6) Harvest and evaluation of plant growth performance indices and final yield of the vegetable experiment.

Production of organic fertilizers

To determine the optimal ratio of sludge from fish ponds to be mixed with organic amendment materials (50% peanut shell + 50%

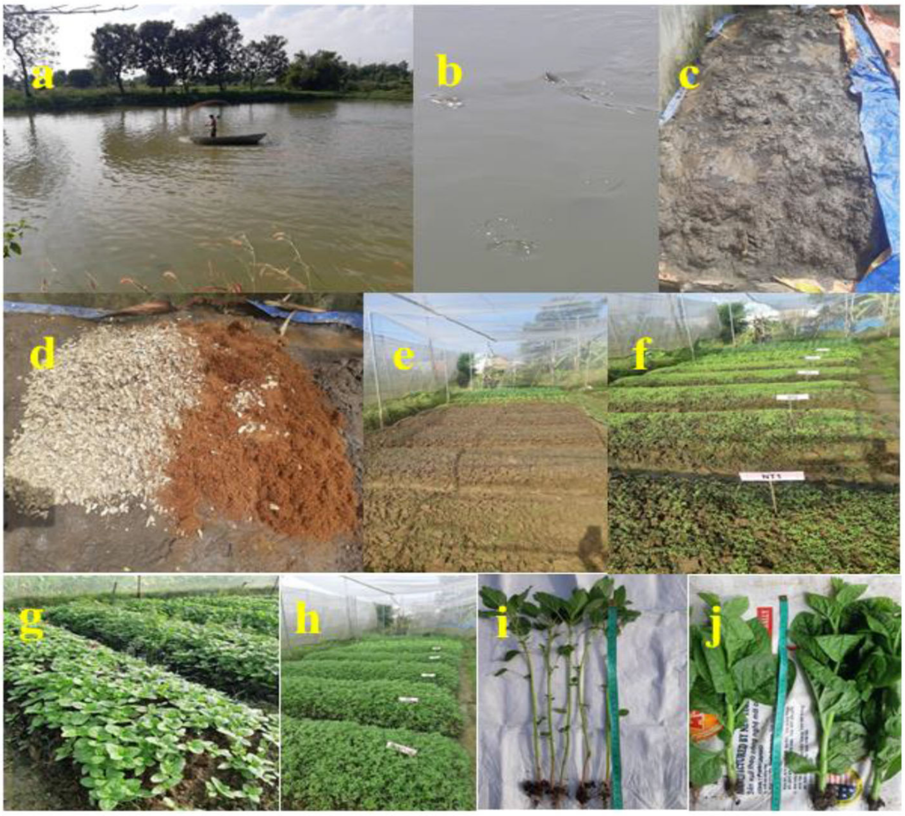

FIGURE 3
Schematic outline of organic fertilizer production, experimental vegetable cultivation, experimental management, and harvesting. **(a)** Snakehead fish pond farming. **(b)** Sludge/sediment is collected from fish pond. **(c)** Sludge of fish pond is sun-dried. **(d)** Sludge/sediment mixed with peanut shells+coir fiber. **(e)** Experimental plots and soil preparation. **(f)** *Malabar spinach and Amaranthus cruentus* planting. **(g)** Malabar spinach at 20-day after planting. **(h)** Amaranth after 20 days of planting. **(i)** Harvested *Malabar spinach* vegetable. **(j)** Harvested *Amaranthus cruentus* vegetable.

coir fiber), an experiment was designed with five treatments and three replicates for each treatment as follows: Treatment 1 (reference treatment): 10% sludge + 90% organic amendment; Treatment 2: 30% sludge + 70% organic amendment; Treatment 3: 50% sludge + 50% organic amendment; Treatment 4: 70% sludge + 30% organic amendment; Treatment 5: 90% sludge + 10% organic amendment (Figure 4).

All treatments were incubated in plastic bags for approximately 95 days. The experimental organic fertilizers were produced following the composting methods recommended by Hien (2003) and Thanh and Ty (2022). To each treatment of compost, the microbial fungal inoculum was added (*TRICODHCT-LUA VON*: 80% *Trichoderma asperellum* spp. with 20% *Trichoderma atroviride* Karsten) to increase the composting process.

Assessment of vegetable growth under different fertilizer treatments

Soil preparation and vegetable cultivation

The experimental soil was prepared by plowing. Soil samples were collected for chemical composition analysis at the beginning and the end of the experiment. Seeds of Malabar spinach and *Amaranthus cruentus* vegetables were soaked in warm water at 40–45°C for 60 min and incubated on wet paper for 24 h for their germination. The germinated seeds were raised in nursery trays and pots for approximately 2–3 days before they were transferred and planted in the soil plots of the experiments. The planting distance was 15 × 15 cm (approximately 2.5 kg of seeds 1,000 m^{-2}). The plants were irrigated by well water daily at 7:00 a.m. and 4:00 p.m.

Malabar spinach and *Amaranthus cruentus* vegetables were cultivated in three replicated plots for each of the five fertilization treatments and during two consecutive cropping cycles (dry and wet seasons). Thus, a total of 15 plots for five treatments of each experiment of plant cultivation were used. Each plot area of the experiment was approximately 52 m^2 (3.5 m width × 15 m length × 0.3 m height) (Figure 2).

Growth of malabar spinach and *Amaranthus cruentus* vegetables under different fertilizer treatments

This experiment tested the use of different organic–chemical fertilizer ratios on Malabar spinach and *Amaranthus cruentus* vegetables. The organic fertilizer from Treatment 4, which was found to have the highest concentration of nutrients, was used in combination with different quantities of chemical fertilizer to fertilize the vegetables in the wet and dry seasons. Five different treatment levels, Treatment 1 (reference treatment)–Treatment 5, representing a gradient from 100% chemical fertilizers to 100% organic fertilizers,

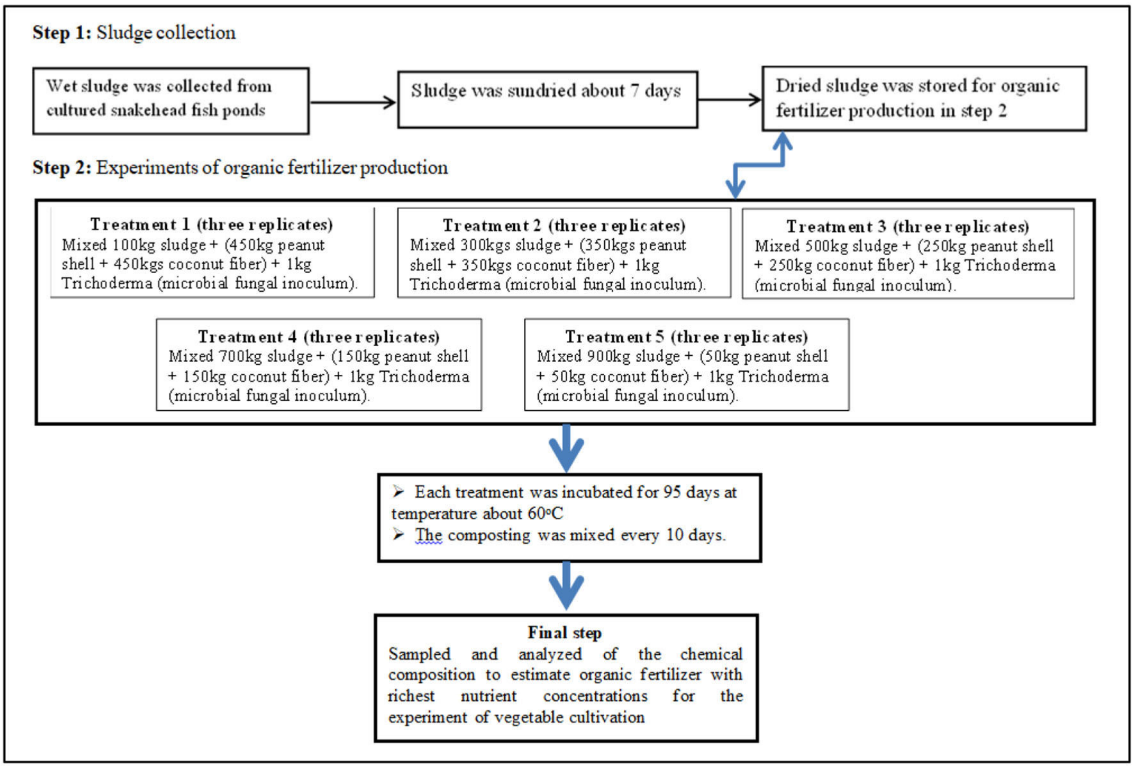

FIGURE 4
Layout of the compositing method applied and used in experimental organic fertilizer production (Hien, 2003).

TABLE 1 Proportion of inorganic and organic fertilizers used for Malabar spinach (*Basella alba* L.) and *Amaranthus cruentus* (*Amaranthus* L.) vegetables experiment.

Treatments	Experimental fertilizer	Amount of N:P:K (ha^{-1})
Reference treatment	100% inorganic fertilizer	55 kg N: 75 kg P: 60 kg K
Treatment 2	75% inorganic fertilizer + 25% (organic fertilizer of treatment T5)	(41 kg N: 56 kg P: 45 kg K) + 0.5 tons of organic fertilizer
Treatment 3	50% inorganic fertilizer + 50% (organic fertilizer of treatment T5)	(28 kg N: 38 kg P: 30 kg K) + 1.0 ton of organic fertilizer
Treatment 4	25% inorganic fertilizer + 75% (organic fertilizer of treatment T5)	(14 kg N: 19 kg P: 15 kg K) + 1.5 tons of organic fertilizer
Treatment 5	100% organic fertilizer	20 tons of organic fertilizer

The final organic fertilizer was produced from Treatment 4 [30% sludge + 70% organic materials (including 50% peanut shell and 50% coir)]. It was used and applied for the experiment of Malabar spinach (*Basella alba L.*) and Amaranth cruentus (*Amaranthus* L.) vegetables production. The inorganic fertilizer in Treatment 1 (Reference treatment) and organic fertilizers in Treatment 5 used for the experiments in both seasons were recommended by the Agricultural Extension Center of Ho Chi Minh City (2009).

were used (Table 1 and Figure 2). The organic fertilizers were added to the soil plot of each plant before planting, while the inorganic fertilizers were added to the soil plot 15 days after sowing (DAS). The total amounts of N:P:K of the chemical and organic fertilizers applied in each treatment are presented in Table 1.

Data collection and measurement

During the vegetable cultivation period of both the dry and wet seasons, growth performance indices including plant length, the length of leaves, the width of leaves, and the number of leaves in each treatment were measured at 10, 20, and 30 DAS in each crop cycle. The final yields of Malabar spinach and *Amaranthus cruentus* vegetables for each treatment were harvested by hand and weighed at the end of the cultivation season. The edible weight without plant roots of each treatment was measured and weighed.

Laboratory analysis of soil, organic amendment, and organic fertilizers

Soil samples used for analyses were taken on two diagonals at the experimental plot. Once dry, the samples were thoroughly mixed, and three samples (1 kg each) were collected and stored separately in labeled plastic bags for chemical analyses. The chemical analyses of soil, fish pond sludge, peanut shell, and coir fiber were carried out at the laboratory of Thu Dau Mot University, Binh Duong district. The pH was determined using a 1:5 soil:water suspension (McLean, 1982); TN and the effective N were analyzed using the Kjeldahl method. TP

TABLE 2 Chemical composition of sludge from snakehead fish (*Channa striata* Bloch, 1973) pond, agricultural organic amendments, and organic fertilizer production.

Nutrient parameters	Sludge	Peanut shell	Coir	Soil of experiment	
				Beginning	End
pH	6.80	-	5.10	4.80	5.20
Organic carbon (C %)	5.51	21.20	9.80	5.10	5.20
Total N (% N)	0.54	5.00	0.55	0.14	0.16
Total P (% P_2O_5)	0.46	0.11	0.32	0.11	0.14
Total K (% K_2O)	0.21	4.32	0.40	1.30	1.34
Effective N (mg kg^{-1})	0.20	–	0.16	0.12	0.14
Effective P (mg kg^{-1})	0.12	–	0.09	0.09	0.10
Effective K (mg kg^{-1})	0.10	–	0.09	0.58	0.57

TABLE 3 Chemical composition of organic fertilizer production.

Nutrient parameters	Experimental organic fertilizer production				
	Treatment 1	Treatment 2	Treatment 3	Treatment 4*	Treatment 5
Organic carbon (% C)	5.64^{c}	8.33^{bc}	11.13^{b}	15.57^{a}	12.33^{ab}
Total N (% N)	0.65^{d}	0.85^{c}	1.11^{b}	1.28^{a}	1.14^{b}
Total P (% P_2O_5)	0.90^{a}	0.60^{c}	0.68^{b}	0.65^{bc}	0.64^{bc}
Total K (% K_2O)	0.22^{b}	0.23^{b}	0.23^{b}	0.38^{a}	0.24^{b}
C/N	8.67	9.84	10.00	12.13	10.85

Treatment 1 (Reference treatment): 90% sludge + 10% organic materials (included 50% peanut shell and 50% coir fiber); Treatment 2: 70% sludge + 30% organic materials (included 50% peanut shell and 50% coir fiber); Treatment 3: 50% sludge +50% organic materials (included 50% peanut shell and 50% coir fiber); Treatment 4: 30% sludge + 70% organic materials (included 50% peanut shell and 50% coir fiber); Treatment 5: 10% sludge + 90% organic materials (included 50% peanut shell and 50% coir fiber). Mean with different superscript letters within rows are significantly different ($P < 0.05$).

*The organic fertilizer of Treatment 4 was selected and used for the Malabar spinach (*Basella alba L.*) and Amaranth cruentus (*Amaranthus L.*) vegetables experiment.

and effective P were measured using the spectrophotometry method (ISO 11261:1995, 1995), TK was measured by hydrofluoric acid digestion (Bartels, 1996), and SOC by Walkley–Black wet oxidation method (Walkley and Black, 1934). All soil analysis methods are, unless alternatively referenced, described by Houba et al. (1995).

Data analysis

All data of plant growth performance indices between each treatment at 10, 20, and 30 DAS of the Malabar spinach and *Amaranthus cruentus* vegetable experiments were entered in Microsoft Excel 2010 before the statistical analysis by IBM SPSS STATISTIC program, version 2020. All collected data were statistically analyzed by the general linear model (ANOVA), using Pairwise Comparison and Tukey's *post-hoc* tests for treatment comparisons ($P \leq 0.05$ level of significance) (IBM SPSS Statistic, 2020).

Results

Chemical composition of soil, sludge, organic amendments, and organic fertilizers

The chemical composition of the organic fertilizers and experimental soil was found to be slightly different before and after the experiment (Table 2). The organic carbon (OC%) in peanut shells, waste sludge, and coir fiber were significantly different, with 21.2, 5.5, and 9.8%, respectively. Total N (%) in sludge and coir fiber showed a similar percentage (0.5%) but was almost 10 times lower than in the peanut shell material (5%). At the end of the experiment, the effective N and P in the soil had increased slightly while the effective K had decreased (Table 2). The results showed that the mineral nutrient composition in the soil was significantly changed by adding organic fertilizer.

Table 3 shows the chemical composition of the organic fertilizer produced from the five different mixtures of sludge from the snakehead fish pond and organic amendments. The results showed that Treatment 1 (reference treatment) had the lowest nutrient content (5.64% OC, 0.65% TN, 0.90% TP, and 0.22% TK), while Treatment 4 had the highest nutrient content (15.57% OC, 1.28% TN, 0.65% TP, and 0.38% TK) compared with the other treatments ($P < 0.05$). Therefore, Treatment 4 was used for the growth performance experiments of Malabar spinach and *Amaranthus cruentus* vegetable cultivation. The C/N ratios of the produced organic fertilizer ranged between 8.7 and 12.1 among treatments.

Evaluation of growth performance indices of vegetables

The growth performance indices of Malabar spinach and *Amaranthus cruentus* vegetables are presented in Table 4. The

TABLE 4 Growth performance indices of Malabar spinach (*Basella alba* L.) and *Amaranthus cruentus* (*Amaranthus* L.) vegetables treated with experimental fertilizers in the wet and dry seasons at 10, 20, and 30-day after sowing (DAS).

DAS	Plant indices	Malabar spinach vegetable					*Amaranthus cruentus* vegetable				
		Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5
		Dry season					**Dry season**				
10	Plant length (cm)	6.2 ± 0.6^{b}	6.2 ± 0.6^{b}	6.3 ± 0.6^{a}	6.0 ± 0.6^{c}	5.9 ± 0.6^{c}	6.3 ± 0.1^{b}	6.3 ± 0.1^{b}	6.4 ± 0.6^{a}	6.2 ± 0.1^{c}	6.1 ± 0.6^{d}
	Leaf length (cm)	3.1 ± 0.1^{c}	3.2 ± 0.1^{b}	3.4 ± 0.6^{a}	3.1 ± 0.1^{c}	2.8 ± 0.6^{d}	2.2 ± 0.1^{c}	2.3 ± 0.1^{b}	2.6 ± 0.1^{a}	2.3 ± 0.1^{b}	1.9 ± 0.6^{d}
	Leaf width (cm)	2.6 ± 0.1^{c}	2.7 ± 0.1^{b}	2.8 ± 0.1^{a}	2.7 ± 0.6^{b}	2.4 ± 0.1^{d}	1.7 ± 0.1^{c}	1.8 ± 0.1^{b}	2.0 ± 0.1^{a}	1.8 ± 0.6^{b}	1.5 ± 0.1^{d}
	Leaf number	5	5	5	5	5	4	4	4	4	4
20	Plant length (cm)	19.2 ± 0.6^{bc}	19.4 ± 1.2^{b}	19.8 ± 1.5^{a}	19.3 ± 0.6^{b}	19.1 ± 0.6^{c}	19.0 ± 0.6^{bc}	19.3 ± 1.1^{b}	19.7 ± 1.1^{a}	19.2 ± 0.6^{b}	19.0 ± 0.6^{c}
	Leaf length (cm)	7.2 ± 0.1^{b}	7.3 ± 0.6^{b}	7.4 ± 0.1^{a}	7.2 ± 1.2^{b}	7.0 ± 0.6^{c}	4.1 ± 0.1^{b}	4.2 ± 0.6^{b}	4.3 ± 0.1^{a}	4.1 ± 1.2^{b}	3.9 ± 0.6^{c}
	Leaf width (cm)	6.1 ± 0.1^{b}	6.2 ± 0.1^{ab}	6.3 ± 0.1^{a}	6.1 ± 1.2^{b}	5.7 ± 1.5^{c}	3.2 ± 0.1^{b}	3.3 ± 0.1^{ab}	3.4 ± 0.1^{a}	3.2 ± 1.2^{b}	2.8 ± 1.5^{c}
	Leaf number	10	10	10	10	10	9.0^{b}	9.0^{b}	10^{a}	9.01^{b}	9.0^{b}
30	Plant length (cm)	30.1 ± 0.6^{c}	32.1 ± 0.1^{b}	33.8 ± 0.9^{a}	32.0 ± 0.1^{b}	30.1 ± 1.0^{d}	30.2 ± 0.6^{c}	31.2 ± 0.6^{b}	32.7 ± 1.5^{a}	31.1 ± 0.6^{b}	29.4 ± 0.3^{d}
	Leaf length (cm)	12.9 ± 0.1^{c}	13.1 ± 0.6^{b}	13.4 ± 0.6^{a}	13.0 ± 0.6^{c}	12.0 ± 0.1^{d}	5.9 ± 0.1^{b}	6.1 ± 1.0^{b}	6.6 ± 0.1^{a}	6.1 ± 0.1^{b}	5.2 ± 0.4^{c}
	Leaf width (cm)	8.2 ± 1.0^{c}	8.5 ± 0.6^{b}	8.7 ± 0.1^{a}	8.5 ± 1.0^{b}	7.9 ± 0.6^{d}	4.2 ± 1.0^{cd}	4.5 ± 1.5^{bc}	4.9 ± 0.4^{a}	4.5 ± 1.0^{b}	4.1 ± 0.3^{d}
	Leaf number	13^{c}	14^{b}	15^{a}	13^{c}	13^{c}	12^{b}	13^{b}	13^{a}	12^{b}	12^{b}
DAS	Plant indices	**Wet season**					**Wet season**				
10	Plant length (cm)	6.3 ± 0.6^{b}	6.3 ± 0.6^{b}	6.4 ± 0.6^{a}	6.2 ± 0.6^{bc}	6.1 ± 1.1^{c}	6.2 ± 0.1^{b}	6.2 ± 0.6^{bc}	6.3 ± 0.5^{a}	6.1 ± 0.1^{cd}	6.0 ± 0.6^{d}
	Leaf length (cm)	3.2 ± 0.1^{c}	3.3 ± 0.1^{b}	3.5 ± 0.6^{a}	3.2 ± 0.1^{c}	2.8 ± 0.6^{d}	2.1 ± 0.1^{c}	2.2 ± 0.1^{b}	2.5 ± 0.1^{a}	2.2 ± 0.1^{b}	1.8 ± 0.6^{d}
	Leaf width (cm)	2.7 ± 0.1^{c}	2.8 ± 0.1^{b}	2.9 ± 0.1^{a}	2.8 ± 0.6^{b}	2.6 ± 0.6^{d}	1.6 ± 0.1^{c}	1.7 ± 0.1^{b}	1.9 ± 0.1^{a}	1.7 ± 0.6^{b}	1.4 ± 0.1^{d}
	Leaf number	5	5	5	5	5	4	4	4	4	4
20	Plant length (cm)	19.3 ± 0.6^{c}	19.5 ± 1.2^{b}	19.9 ± 1.5^{a}	19.4 ± 0.6^{bc}	19.2 ± 0.1^{c}	19.0 ± 0.6^{bc}	19.2 ± 1.1^{b}	19.6 ± 1.5^{a}	19.1 ± 0.6^{b}	18.9 ± 0.6^{c}
	Leaf length (cm)	7.3 ± 0.1^{b}	7.4 ± 0.6^{b}	7.5 ± 0.1^{a}	7.3 ± 1.0^{b}	7.2 ± 0.6^{c}	4.0 ± 0.1^{b}	4.1 ± 0.6^{b}	4.2 ± 0.1^{a}	4.0 ± 1.2^{b}	3.8 ± 0.6^{c}
	Leaf width (cm)	6.2 ± 0.1^{b}	6.3 ± 0.1^{ab}	6.4 ± 0.1^{a}	6.3 ± 0.6^{ab}	5.9 ± 1.7^{c}	3.1 ± 0.1^{b}	3.2 ± 0.1^{ab}	3.3 ± 0.1^{a}	3.1 ± 1.2^{b}	2.7 ± 1.5^{c}
	Leaf number	10	10	10	10	10	9^{b}	9^{b}	10^{a}	9^{b}	9^{b}
30	Plant length (cm)	31.2 ± 0.6^{c}	32.2 ± 0.1^{b}	33.0 ± 1.0^{a}	32.1 ± 0.6^{b}	30.2 ± 0.6^{d}	30.1 ± 0.6^{c}	31.1 ± 0.6^{b}	32.6 ± 2.0^{a}	31.0 ± 0.6^{b}	29.1 ± 1.5^{d}
	Leaf length (cm)	13.0 ± 0.1^{c}	13.2 ± 0.6^{b}	13.5 ± 0.6^{a}	13.1 ± 0.6^{c}	12.1 ± 0.1^{d}	5.8 ± 0.1^{c}	6.0 ± 1.0^{b}	6.5 ± 0.1^{a}	6.0 ± 0.1^{b}	4.9 ± 0.6^{d}
	Leaf width (cm)	8.3 ± 1.0^{c}	8.6 ± 0.6^{b}	8.8 ± 0.1^{a}	8.6 ± 1.0^{b}	8.0 ± 0.6^{d}	4.1 ± 1.0^{c}	4.4 ± 1.5^{b}	4.8 ± 0.6^{a}	4.4 ± 1.0^{b}	3.9 ± 0.6^{d}
	Leaf number	14^{b}	14^{b}	15^{a}	14^{b}	14^{b}	12^{b}	12^{b}	13^{a}	12^{b}	12^{b}

Treatment 1 (Reference treatment): 100% inorganic fertilizer, Treatment 2: 75% inorganic fertilizer + 25% organic fertilizer, Treatment 3: 50% inorganic fertilizer + 50% organic fertilizer, Treatment 4: 25% inorganic fertilizer + 75% organic fertilizer, and Treatment 5: 100% organic fertilizer. DAS, Day after sowing. The mean with different superscript letters within rows is significantly different ($P < 0.05$).

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TABLE 5 Final yield and edible weight of Malabar spinach (*Basella alba* L.) and *Amaranthus cruentus* (*Amaranthus* L.) vegetables of each treatment in the dry and wet seasons.

Plant indices	Malabar spinach vegetable				
	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5
	Dry season				
Final yield (ton ha^{-1})	17.7 ± 0.5^{c}	17.7 ± 0.6^{ab}	17.8 ± 0.7^{a}	17.7 ± 0.5^{bc}	17.5 ± 0.3^{d}
Final yield without roots (%)	68.9 ± 0.3^{ab}	68.7 ± 0.1^{ab}	69.0 ± 0.1^{a}	68.0 ± 0.1^{bc}	68.5 ± 0.2^{c}
Plant weight (g)	44.3 ± 0.1^{b}	44.4 ± 0.2^{a}	44.5 ± 0.1^{a}	44.2 ± 0.1^{b}	43.8 ± 0.1^{c}
Edible part of plant (%)	68.1 ± 0.2^{ab}	68.1 ± 0.1^{ab}	68.2 ± 0.1^{a}	68.1 ± 0.2^{ab}	68.0 ± 0.1^{b}
Plant indices	**Wet season**				
Final yield (ton ha^{-1})	17.7 ± 0.1^{b}	17.8 ± 0.6^{a}	18.0 ± 0.6^{a}	17.7 ± 0.5^{b}	17.6 ± 0.3^{c}
Final yield without roots (%)	69.1 ± 0.5^{ab}	69.5 ± 0.2^{a}	70.0 ± 0.2^{a}	69.3 ± 0.4^{ab}	68.8 ± 0.3^{c}
Plant weight (g $plant^{-1}$)	44.3 ± 0.1^{b}	44.5 ± 0.2^{ab}	44.6 ± 0.1^{a}	44.3 ± 0.1^{b}	43.9 ± 0.1^{c}
Edible part of plant (%)	68.3 ± 0.2^{a}	68.5 ± 0.3^{a}	68.8 ± 0.6^{a}	68.6 ± 0.4^{a}	68.3 ± 0.1^{b}
Plant indices	***Amaranthus cruentus* vegetable**				
	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5
	Dry season				
Final yield (ton ha^{-1})	9.9 ± 0.1^{b}	10 ± 0.1^{a}	10 ± 0.1^{a}	9.9 ± 0.1^{b}	9.7 ± 0.6^{c}
Final yield without roots (%)	68.0 ± 0.1^{b}	68.7 ± 0.6^{b}	68.8 ± 0.1^{a}	67.7 ± 0.1^{c}	66.7 ± 0.6^{d}
Plant weight (g $plant^{-1}$)	24.0 ± 0.1^{b}	25.0 ± 0.1^{a}	25.1 ± 0.1^{a}	24.4 ± 0.1^{b}	24.0 ± 0.1^{c}
Edible part of plant (%)	67.0 ± 0.1^{a}	67.0 ± 0.1^{ab}	67.1 ± 0.1^{a}	66.7 ± 0.6^{bc}	66.5 ± 0.1^{c}
Plant indices	**Wet season**				
Final yield (ton ha^{-1})	9.9 ± 0.2^{b}	10 ± 0.1^{a}	10 ± 0.1^{a}	9.9 ± 0.3^{b}	9.7 ± 0.1^{c}
Final yield without roots (%)	69.1 ± 0.5^{b}	69.7 ± 0.4^{b}	70.4 ± 0.3^{a}	69.0 ± 0.8^{c}	67.8 ± 1.0^{d}
Plant weight (g $plant^{-1}$)	24.4 ± 0.1^{b}	24.6 ± 0.1^{a}	25.3 ± 0.3^{a}	24.4 ± 0.1^{b}	24.0 ± 0.1^{c}
Edible part of plant (%)	67.3 ± 0.6^{a}	67.6 ± 1.2^{a}	67.2 ± 0.8^{a}	67.2 ± 1.3^{ab}	67.0 ± 0.6^{b}

Treatment 1 (Reference treatment): 100% inorganic fertilizer, Treatment 2: 75% inorganic fertilizer + 25% organic fertilizer, Treatment 3: 50% inorganic fertilizer + 50% organic fertilizer, Treatment 4: 25% inorganic fertilizer + 75% organic fertilizer, and Treatment 5: 100% organic fertilizer. The mean with different superscript t letters within rows is significantly different ($P < 0.05$).

results showed that there are significant differences between several treatments after 30 DAS planted in the dry and wet seasons, while there were fewer statistically significant differences after 10 and 20 DAS.

The Malabar spinach growth indices differed slightly between the dry and wet seasons. Plant length at 10 DAS ranged between 5.9–6.3 cm and 6.1–6.4 cm in the dry season and wet season, respectively ($P < 0.05$). The plant length of *Amaranthus cruentus* at 10 DAS ranged between 6.1 cm and 6.4 cm and was similar between the seasons. Plant length, leaf length, and leaf width of Malabar spinach at 30 DAS in the dry and wet seasons ranged between 30.2–33.8 cm, 5.8–13.5, and 4.2–8.8 cm, respectively. The plant length, leaf length, and leaf width of *Amaranthus cruentus* at 30 DAS in the dry and wet seasons ranged between 29.1–32.7 cm, 5.2–6.6 cm, and 39–4.9 cm, respectively ($P < 0.05$). During the first 10 days of the experiment, the leaf number of each plant was approximately 5 leaves, and after 30 days it had reached 13–15 leaves in both seasons. The highest growth performance indices in both Malabar spinach and *Amaranthus cruentus* vegetables in the dry and wet seasons were found in Treatment 3 (50% inorganic fertilizer + 50% organic fertilizer), followed in descending order by Treatment 2 (75% inorganic fertilizer + 25% organic fertilizer), Treatment 1 (reference treatment) (100% chemical fertilizer), Treatment 4 (25% inorganic fertilizer + 75% organic fertilizer), and Treatment 5 (100% organic fertilizer) ($P < 0.05$) (Table 4).

Final yield and edible weight of malabar spinach vegetables

The results in Table 5 show that the final yield, individual plant weight, and edible part of Malabar spinach in the dry and wet seasons ranged between 17.5–18.0 t ha^{-1}, 43.8–44.6 g $plant^{-1}$, and 68.0–68.8%, respectively ($P < 0.05$). Malabar spinach had overall high adjusted-R^2 values (0.939–0.960) for the final yield (t ha^{-1}) (Figure 5a) and (0.945–0.964) and the edible weight (g $plant^{-1}$) (Figure 5b) from the different treatments.

The edible weight of Malabar spinach was higher in the wet season compared with the dry season in Treatment 3, Treatment 2, and Treatment 4, but there was no difference in Treatment 1 (reference treatment) and Treatment 5. The highest edible weight was found in Treatment 3 in the dry season (30.4 g) and wet season (30.7 g) (Figure 5b). Moreover, the lowest edible weight was identified in Treatment 5 in the dry season (29.8 g) and wet season (29.9 g). In terms of yield and edible weight, a mixture of inorganic and organic

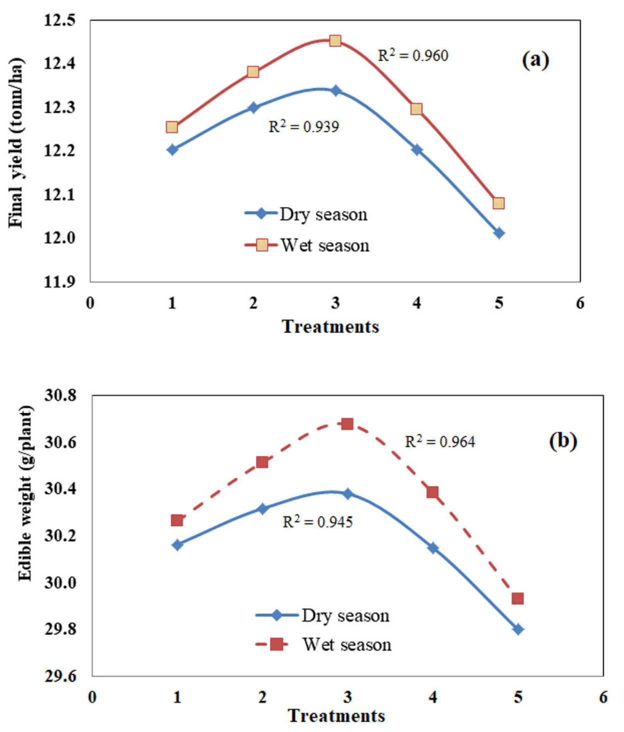

FIGURE 5
Final yield (ton ha^{-1}) **(a)** and edible weight (g $plant^{-1}$) **(b)** of Malabar spinach (*Basella alba* L.) vegetable fertilized with five different treatments for the two seasons.

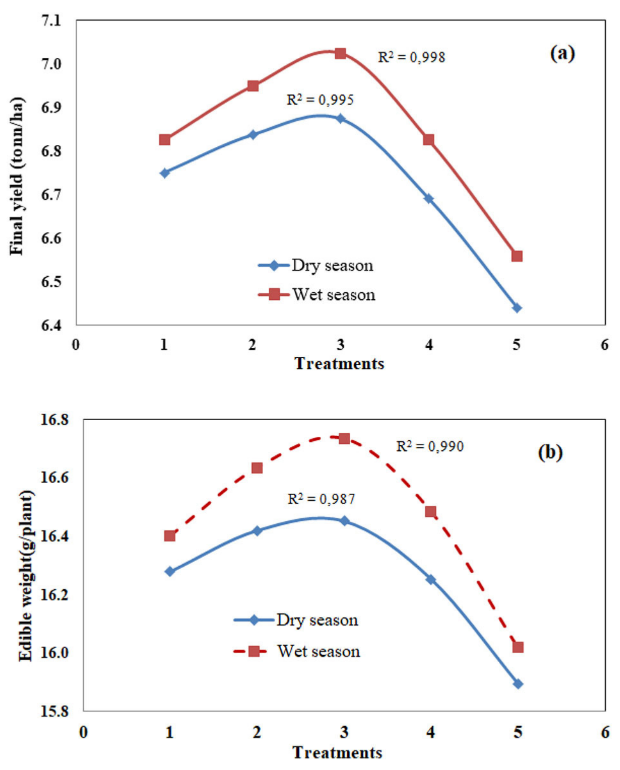

FIGURE 6
Final yield (ton ha^{-1}) **(a)** and edible weight (g $plant^{-}$) **(b)** of *Amaranthus cruentus* (*Amaranthus* L.) fertilized with five different treatments for the two seasons.

fertilizers resulted in a higher production than the treatments with only inorganic or organic fertilizers.

Final yield and edible weight of *Amaranthus cruentus* vegetable

The highest final yield, yield without roots, individual plant weight, and edible weight in the dry and wet seasons were found in Treatment 3 (50% inorganic fertilizer + 50% organic fertilizer) followed by Treatment 2 (75% inorganic fertilizer + 25% organic fertilizer) ($P < 0.05$) (Table 5). A mixture of inorganic and organic fertilizers resulted in a higher production than treatments with only inorganic fertilizer or organic fertilizer. There were a slightly higher final yield and edible weight in the wet season (adjusted-R^2 values ranged from 0.990 to 0.998) (Figure 6a) compared with the dry season (adjusted-R^2 values ranged from 0.987 to 0.995) (Figure 6b) for all treatments. The inorganic fertilizer and organic fertilizer proportion used for *Amaranthus cruentus* vegetable cultivation had a significant impact on the yield and edible weight. Therefore, applying appropriate proportions of inorganic and organic fertilizer to *Amaranthus cruentus* can improve the yield and the edible weight as well as minimize costs for fertilizers and the environmental impact.

Economic efficiency of organic fertilizers for vegetable cultivation

In Treatment 1 (reference treatment), without organic fertilizer, the use of N, P, and K were 55, 75, and 60 kg ha^{-1}, respectively. This resulted in the highest cost of US\$170 ha^{-1} compared with the other treatments, but the yield of vegetables was not higher but often lower than in the other treatments (Table 6). While in Treatment 2, Treatment 3, and Treatment 4, a reduction in N, P, and K and an increase in organic fertilizer lead not only to reduced costs but also to increased vegetable yields. The present study found that Treatment 3 can be considered the optimal option when comparing the cost, vegetable yield, and edible weight with the other treatments. Treatment 3, which used 50% inorganic and 50% organic fertilizers required at 28 kg N:38 kg P:30 kg K ha^{-1} with an estimated cost of US\$87 ha^{-1} and resulted in the highest yield and edible weight of Malabar spinach and *Amaranthus cruentus* vegetables in both the dry and wet seasons. Using 100% organic fertilizer, however, in Treatment 5 resulted in the lowest yield of vegetables in both the dry and wet seasons and reduced financial benefits. Thus, an optimized combination of inorganic and organic fertilizers can improve the financial and environmental performance of vegetable farming.

Discussion

Nutrient content of sludge/sediment of snakehead fish pond and organic amendments

Our results show that the carbon (OC%), nitrogen (TN), phosphorous (TP), and potassium (TK) contents of sludge/sediment from snakehead fish ponds were in the same range and in good agreement with the values measured in sludge/sediment from

TABLE 6 Economic efficiency of Malabar spinach (*Basella alba* L.) and *Amaranthus cruentus* (*Amaranthus* L.) vegetables production by reducing inorganic fertilizers.

Items	Unit	Treatment				
		Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5
Amount of inorganic fertilizers used (N: P: K)	Kg ha^{-1}	55: 75: 60	41: 56: 45	28: 38: 30	14: 19: 15	0: 0: 0
Estimated cost	US$	174.0	130.43	86.95	43.48	0.0
Comparative cost for inorganic fertilizer	%	100%	75%	50%	25%	0

Treatment 1 (Reference treatment): 100% inorganic fertilizer, Treatment 2: 75% inorganic fertilizer + 25% organic fertilizer, Treatment 3: 50% inorganic fertilizer + 50% organic fertilizer, Treatment 4: 25% inorganic fertilizer + 75% organic fertilizer, and Treatment 5: 100% organic fertilizer. Market price: 1 kg N = US$0.65; 1 kg P = US$0.87; 1 kg K = US$1.22.

Pangasius catfish ponds in Vietnam (Phu and Tinh, 2012; Da et al., 2020, 2021), Bangladesh (Haque et al., 2016), and rainbow trout ponds in Poland (Dróżdz et al., 2020). However, it was lower compared with the levels reported for manures from cattle, chicken, and horses (Rahman et al., 2004; Boyd et al., 2011; Karak et al., 2013). The sludge/sediment from the studied snakehead fish ponds had a good nutrient content, and our study shows that it can be used as a potential organic fertilizer, which not only could help to enhance the quality of soil for vegetable cultivation but also to reduce environmental pollution from aquaculture production through increased recycling of nutrients.

To make the sludge more suitable as organic fertilizer, it was complemented with peanut shell and coconut fiber, which contained higher contents of TN, TP, and TK than many other organic amendments that have been used in previous studies, such as rice straw, water hyacinth (Thanh et al., 2015; Da et al., 2020, 2021), wheat straw, potato plant residues, mustard stover, and freshly cut grass (Karak et al., 2013; Dróżdz et al., 2020). Overall, the results show that organic composting is an effective way to reuse fish pond sediments and local agricultural waste in a mixture that can be converted into relatively valuable organic fertilizers for vegetable farming and other agricultural production (Karak et al., 2013; Thanh et al., 2015; Saldarriaga et al., 2019).

The nutrient quality of produced organic fertilizers

The physicochemical properties of the composting products varied between treatments (Table 3) because they were influenced by the initial material used, the duration of the decomposition step, and the conditions during the process (e.g., moisture content, temperature, pH, degree of aeration, the ratios of C/N, and the physical structure of the raw materials) (Zhu, 2007; Cofie et al., 2009; Saldarriaga et al., 2019). The nutrient content of the organic fertilizer produced in our study was in good agreement and within the range of the nutrient content found in green waste composts (Sun et al., 2012); organic fertilizers produced from combinations of fish pond sediments, water hyacinth, and rice straw (Thanh et al., 2015; Da et al., 2021); fish pond sediment composted with fresh grass and wheat straw (Dróżdz et al., 2020); and agricultural wastes composted with FPS (Cofie et al., 2009; Karak et al., 2013).

The total nitrogen content and pH of the compost mixtures increased over time. According to Dróżdz et al. (2020), the increase in pH in the initial stages of composting is associated with the release of ammonia. The pH of the produced organic fertilizer was approximately 6.5–7.5, which is a suitable pH for vegetables and plant growth (Agricultural Extension Center of Ho Chi Minh city, 2009; Zhang et al., 2016). The final C/N ratios (12.1–15.6) of the compost products were within the range of C/N ratios of compost products from fish pond sediment mixed with rice straw and water hyacinth (Zhu, 2007; Cofie et al., 2009; Thanh et al., 2015; Da et al., 2020), and it is in good agreement with the C/N ratios (12–26) of salmon trout fish pond sediment composted with fresh grass or wheat straw (Dróżdz et al., 2020). A C/N ratio of 15–16:1 is recommended for composts used in agriculture (Emeterio and Victor, 1992; Hien, 2003; Cofie et al., 2009). Thanh et al. (2015) showed that the highest growth of vegetables was achieved at a C/N ratio of 30 for sediment–straw composts and a C/N ratio of 25 for sediment–hyacinth composts.

Benefits of organic fertilizers for vegetables and soil quality

Similar to several earlier studies, this study shows that the reuse and recycling of nutrients in integrated aquaculture and agricultural systems help to improve the efficiency of food production and help to reduce pollution by excessive nutrients, thereby contributing to improved living conditions for farmers through increased income and environmental health (Berg, 2002; Dróżdz et al., 2020; Pueppke et al., 2020; Ahmed and Turchini, 2021; Farrant et al., 2021). We found that chemical fertilizer supplemented with 25 and 50% of organic fertilizers applied to the soil had a significant positive impact on the growth performance indices of Malabar spinach and *Amaranthus cruentus* and resulted in the highest final yield of these vegetables. The results of the present study are in good agreement with a study using *Pangasius* catfish pond sediments as organic fertilizer for vegetables (water spinach, cucumber fruit, and mustard greens) and fodder grass reported by Thanh et al. (2015), Haque et al. (2016), and Da et al. (2015).

The nutrient quality of the experimental soils in Table 2 shows that the OC and effective N–P–K contents in the soils at the end of the experiment in the last crop during the wet season are slightly higher than in the soils before the first experiment in the dry season. Similar soil quality improvements were found when fish pond sediment was used to fertilize soils for fodder grass, vegetables, and rice production in Bangladesh, China, and Palestine (Rahman et al., 2004; Karak et al., 2013; Haque et al., 2016).

Conclusion

This study found that the highest content of nutrients in the organic fertilizer was produced from a mixture of 30% sludge from snakehead fish ponds and 70% organic amendments (50% peanut shell and 50% coir fiber). The result shows that the organic fertilizers produced from snakehead fish sludge composted with organic amendment had a positive effect on growth performance and final yields of Malabar spinach and *Amaranthus cruentus* vegetables in both the dry and wet seasons. The study revealed that organic fertilizers can replace 25 to 50%, or even up to 75% of the chemical fertilizers used for vegetables. The use of organic fertilizers resulted in higher yields and was able to meet the nutritional demands of the tested vegetables. The present study confirmed that the recycling of fish pond sediments and local agricultural by-products can be used in integrated aquaculture–agriculture systems for enhanced and more efficient food production. This also has the potential to provide environmental benefits and improve the income of the farmers.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

DT, NT, CD, and NH: conceptualization and design of research methodology. DT, NT, and CD: performed statistical data analyses. DT, NT, CD, and TN: completed writing—original draft preparation and compilation. HB, PV, and VM: contributed to editing and finalizing the manuscript. All authors read and contributed to the manuscript and approved the submitted final version.

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Conflict of interest

TN is employed by Mekolink Co. Ltd., Vietnam.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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