Effect of Black Soldier Fly Larvae (BSFL) Dietary Inclusion on Ecosystem Services and NPK use efficiency of Aquaponics Systems with Tilapia and Spinach.

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Abstract

Aquaponics is a sustainable food production system that combines aquaculture and hydroponics in a symbiotic relationship. However, one of the challenges of aquaponics is to find a suitable and affordable feed source for the fish. Black soldier fly larvae (BSFL) are an alternative feed source that can be produced from organic waste and have high nutritional value for fish. BSFL can also provide ecosystem services such as waste reduction, nutrient recycling, and pest control. The aim of this study was to evaluate the effect of BSFL dietary inclusion on the ecosystem services and NPK use efficiency of aquaponics systems with Nile tilapia (*Oreochromis niloticus*) and spinach (*Spinacia oleracea*). Five experimental diets were formulated with different levels of BSFL inclusion: Control (0% BSFL), TA (10% BSFL), TB (20% BSFL), TC (30% BSFL), TD (40% BSFL), and TE (50% BSFL). The experiment was conducted for 35 days in a recirculating aquaponics system with six fish tanks and six plant beds. The fish growth performance, water quality parameters, plant biomass, NPK content, and waste reduction were measured and compared among the treatments. The results showed that TC had the best fish growth performance, with the highest weight gain, specific growth rate, feed conversion ratio, and protein efficiency ratio. The water quality parameters were within the acceptable ranges for both fish and plants in all treatments. The plant biomass and NPK content were highest in H, followed by Control, TC and TB. The waste reduction was also highest in TD, followed by TC and TE. The NPK use efficiency was calculated as the ratio of NPK uptake by plants to NPK input by fish feed. The results showed that TD had the highest NPK use efficiency, followed by TC and TB. The study concluded that BSFL dietary inclusion can improve the ecosystem services and NPK use efficiency of aquaponics systems with tilapia and spinach, with 40% BSFL being the optimal level.

Key word: Ecosystem service, NPK, Aquaponics, Nutrient dynamics, Black soldier fly, Nutrient use efficiency

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Introduction

Aquaponics is a sustainable food production system that combines aquaculture and hydroponics in a symbiotic relationship (Rakocy *et al*., 2006). In aquaponics, the fish waste provides nutrients for the plants, while the plants filter the water for the fish. Aquaponics can produce both fish and vegetables in a small area with minimal water use and environmental impact (Goddek *et al*., 2015). However, one of the challenges of aquaponics is to find a suitable and affordable feed source for the fish. Most commercial fish feeds are based on fish meal and fish oil, which are derived from wild-caught fish and have negative effects on the environment, such as overfishing, habitat degradation, and pollution (Tacon and Metian, 2008). Moreover, commercial fish feeds are expensive and may not be available or accessible in some regions (Love *et al*., 2015).

Black soldier fly larvae (BSFL) are an alternative feed source that can be produced from organic waste and have high nutritional value for fish (Makkar *et al*., 2014). BSFL are the juvenile stage of the black soldier fly (*Hermetia illucens*), which is a harmless insect that does not transmit diseases or annoy humans or animals (Tomberlin *et al*., 2002). BSFL can consume almost any kind of organic waste, such as food scraps, animal manure, or plant residues, and convert it into biomass rich in protein, fat, minerals, and vitamins (Diener *et al*., 2011). BSFL can also provide ecosystem services such as waste reduction, nutrient recycling, and pest control. Waste reduction is achieved by reducing the volume and weight of organic waste by up to 70% within 24 to 36 hours (Diener *et al*., 2009). Nutrient recycling is achieved by transforming organic waste into valuable products such as BSFL biomass for animal feed or biofertilizer for plants (Barragan-Fonseca *et al*., 2017). Pest control is achieved by repelling other flies from the organic waste due to an info-chemical emitted by BSFL (Holmes *et al*., 2012).

Several studies have evaluated the potential of BSFL as a feed source for different fish species, such as tilapia (*Oreochromis niloticus*), catfish (Clarias gariepinus), carp (Cyprinus carpio), and trout (Oncorhynchus mykiss) (St-Hilaire *et al*., 2007; Nguyen *et al*., 2015; Sealey *et al*., 2011; Stamer *et al*., 2014). The results showed that BSFL can partially or totally replace fish meal in fish diets without compromising the fish growth performance, feed utilization, or flesh quality. However, few studies have investigated the effect of BSFL dietary inclusion on the ecosystem services and nutrient use efficiency of aquaponics systems. Nutrient use efficiency is an important indicator of the sustainability and productivity of aquaponics systems, as it reflects how well the nutrients are utilized by the plants and how much nutrients are lost to the environment (Goddek *et al*., 2016). One way to measure nutrient use efficiency is to calculate the ratio of nutrient uptake by plants to nutrient input by fish feed, which is also known as NPK use efficiency (NUE) (Goddek *et al*., 2016). NPK stands for nitrogen (N), phosphorus (P), and potassium (K), which are the three main macronutrients required by plants.

The aim of this study was to evaluate the effect of BSFL dietary inclusion on the ecosystem services and NPK use efficiency of aquaponics systems with Nile tilapia and spinach. Nile tilapia is one of the most widely cultured fish species in the world, due to its fast growth, high adaptability, and good market value (El-Sayed, 2006). Spinach is a leafy green vegetable that has high nutritional and medicinal value, as it contains antioxidants, vitamins, minerals, and phytochemicals (Khan *et al*., 2014). Five experimental diets were formulated with different levels of BSFL inclusion: Control (0% BSFL), TA (10% BSFL), TB (20% BSFL), TC (30% BSFL), TD (40% BSFL), and TE (50% BSFL). The experiment was conducted for 35 days in a recirculating aquaponics system with six fish tanks and six plant beds. The fish growth performance, water quality parameters, plant biomass, NPK content, and waste reduction were measured and compared among the treatments. The NPK use efficiency was calculated as the ratio of NPK uptake by plants to NPK input by fish feed.

Materials and Methods

Experimental design

The experiment was conducted in a recirculating aquaponics system located at the Debre Berhan University, Biology department, Ethiopia. The system consisted of 12 fish tanks and 12 plant beds connected by pipes and pumps. Each fish tank had a volume of 100 L and was stocked with 50 kg/m^3 Nile tilapia fingerlings with an initial average weight of 10 g. Each plant bed had an area of 0.4 m^2 and was a floating raft type. Spinach seedlings with 5BBCH scale were transplanted with a density of 44 plants per m^2. The system was operated at a water flow rate of 1 L/min and a water exchange rate of 10% per day. The water temperature was maintained at 25 ± 2°C by using heaters. The photoperiod was set at 12 h light/12 h dark by using artificial lights.

Five experimental diets were formulated with different levels of BSFL inclusion: Control (0% BSFL), TA (10% BSFL), TB (20% BSFL), TC (30% BSFL), TD (40% BSFL), and TE (50% BSFL). The diets were prepared by mixing fish meal, soybean meal (SBM), wheat bran, wheat grain, vitamin-mineral premix, and BSFL meal in different proportions according to Table 1. The BSFL was obtained from Hawassa University and reared in Debre Berhan University BSFL rearing facility using organic waste from faculties' cafeteria as growing medium. The proximate composition and amino acid profile of the BSFL meal are shown in

Table 2. The diets were pelleted by using a pelletizer machine and air dried for 24 h. The diets were stored in sealed plastic bags at 4°C until use.

Table 1. Ingredient composition (%) of the experimental diets

Feed Ingredients	**Control**	**TA**	**TB**	**TC**	**TD**	**TE**
Wheat grain	8.88%	7.36%	2.00%	10.86%	15.90%	18.55%
Wheat Gluten	3.12%	0.10%	1.52%	3.08%	3.07%	3.06%
Wheat bran	5.00%	5.00%	5.00%	20.00%	11.51%	10.47%
Fish meal	50.00%	40.00%	30.00%	20.00%	10.00%	0.00%
SBM	5.21%	0.00%	1.61%	2.93%	10.49%	11.48%
BSF	0.00%	10.00%	20.00%	30.00%	40.00%	50.00%
DCP	0.05%	0.05%	0.05%	0.05%	0.05%	0.05%
Amino-vet	0.50%	0.50%	0.50%	0.50%	0.50%	0.50%
Mineral-premix	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%
fish-oil	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%
Ethoxyquin	0.005%	0.0050%	0.005%	0.005%	0.005%	0.005%
Taurine	0.005%	0.005%	0.005%	0.005%	0.005%	0.005%
Sodium aliginate	0.005%	0.005%	0.005%	0.005%	0.005%	0.005%

Table 2. Proximate composition (%) and amino acid profile (g/100 g protein) of the BSFL

Nutrient composition	**Control**	**TA**	**TB**	**TC**	**TD**	**TE**
Crude protein	39.425	37.000	36.836	36.700	36.400	36.362
Crude fiber	7.068	6.863	6.911	8.879	8.559	8.663
NDF	11.650	13.608	15.929	26.984	27.481	30.322
ADF	13.382	13.392	13.723	16.563	16.447	16.869
Lignin	1.363	1.306	1.248	1.915	1.669	1.652
Ether extract	3.000	2.548	2.275	2.829	2.462	2.233
Ash	3.724	3.365	3.643	4.994	5.490	5.768
Starch (polarimetry)	31.000	27.761	22.722	31.000	31.000	31.000
Total sugars	6.722	7.156	8.226	10.800	12.226	13.403
Gross energy	16.958	14.868	14.447	19.427	20.136	20.523

Calcium	1.822	2.025	2.267	2.540	2.799	3.039
Phosphorus	1.537	1.270	1.216	1.383	1.259	1.161
Potassium	0.854	0.708	0.666	0.892	0.835	0.794
Sodium	0.633	0.505	0.423	0.343	0.258	0.163
Magnesium	0.315	0.213	0.251	0.368	0.479	0.503
Manganese	0.282	0.013	0.142	0.288	0.288	0.290
Zinc	1.192	0.045	0.584	1.181	1.177	1.173
Copper	0.410	0.016	0.200	0.403	0.401	0.399
Iron	3.500	0.132	1.731	3.500	3.500	3.500
Alanine	4.410	4.019	4.180	5.543	5.841	6.093
Arginine	4.442	3.859	3.754	5.319	5.540	5.650
Aspartic acid	6.092	5.746	5.885	7.790	8.150	8.503
Cystine	0.870	0.639	0.499	0.986	0.954	0.934
Glutamic acid	11.133	9.777	8.449	13.947	13.789	14.185
Glycine	4.199	3.777	3.660	4.866	5.000	5.083
Histidine	2.060	1.596	1.720	2.554	3.170	3.368
Isoleucine	3.212	2.859	2.894	3.884	4.241	4.427
Leucine	5.463	4.735	4.775	6.651	6.905	7.149
Lysine	4.834	4.450	4.290	5.134	5.137	5.120
Methionine	1.909	1.669	1.570	1.923	1.912	1.882
Phenylalanine	3.057	2.762	2.804	4.070	4.369	4.622
Proline	3.779	3.401	3.366	5.642	6.232	6.748
Serine	2.968	2.661	2.399	3.430	3.201	3.185
Threonine	2.776	2.592	2.443	3.192	3.026	3.029
Tryptophan	0.797	0.704	0.587	0.851	0.732	0.689
Tyrosine	2.122	2.336	2.659	3.779	4.085	4.528
Valine	3.447	3.576	3.739	5.211	5.366	5.762

The experiment was conducted for 35 days with two replicates per treatment in a completely randomized design. Each fish tank and plant bed was randomly assigned to one of the six treatments. The fish were fed twice a day at 9:00 and 17:00 h at a feeding rate of 5% of their body weight, which was adjusted weekly according to the fish biomass. The uneaten feed and feces were collected daily from the bottom of the fish tanks by using a siphon and weighed to calculate the feed intake and waste production. The spinach plants were watered continuously using a timer-controlled pump that delivered the water from the fish tanks to the plant beds. The water was drained back to the fish tanks by gravity through a standpipe.

Data collection and analysis

The fish growth performance was evaluated by measuring the weight and length of each fish at the beginning and end of the experiment. The weight gain (WG), specific growth rate (SGR), feed conversion ratio (FCR), and protein efficiency ratio (PER) were calculated as follows:

WG (%) = [(final weight - initial weight) / initial weight] x 100

SGR (%/day) = [(ln final weight - ln initial weight) / days] x 100

FCR = feed intake / weight gain

PER = weight gain / protein intake

The water quality parameters were monitored weekly by measuring the temperature, pH, dissolved oxygen (DO), ammonia (NH_3-N), nitrite (NO_2-N), nitrate (NO_3-N), and orthophosphate (PO_4-P) in each fish tank by using a multiparameter probe (Hanna Instruments, USA) and colorimetric method by a spectrophotometer (AOAC, 2000). The water quality parameters were compared with the recommended ranges for tilapia and spinach culture (Rakocy *et al*., 2006).

The plant biomass was evaluated by harvesting all the spinach plants from each plant bed at the end of the experiment. The fresh weight and dry weight of the plants were measured after washing and drying in an oven at 70°C for 48 h. The NPK content of the plants was determined by using a Kjeldahl apparatus for N, a spectrophotometer for P, and a flame photometer for K (AOAC, 2000).

The waste reduction was evaluated by measuring the weight of the organic waste before and after being consumed by BSFL in each treatment. The waste reduction (%) was calculated as follows:

Waste reduction (%) = [(initial waste weight - final waste weight) / initial waste weight] x 100

The NPK use efficiency (NUE) was calculated as the ratio of NPK uptake by plants to NPK input by fish feed. The NPK uptake by plants was calculated as the product of plant dry weight and NPK content. The NPK input by fish feed was calculated as the product of feed intake and NPK content.

The data were subjected to one-way analysis of variance (ANOVA) followed by Tukey's test to compare the means among the treatments. The level of significance was set at $p < 0.05$. The data were analyzed by using SPSS software version 25.

Results

Fish growth performance

The fish growth performance is presented in Table 3. There were differences among the treatments in terms of WG, SGR, FCR, and PER ($p < 0.05$). Despite the lack of significant difference, Control had the highest WG, SGR, FCR, and PER, followed by TC, TB, TA, TD and TE whereas TE had the lowest WG, SGR, FCR, and PER.

Table 3. Fish growth performance of Nile tilapia fed with different levels of BSFL inclusion

Treatment	AGR	SGR	FCR	PPV	CP	FAT	Fiber	Ash	Moisture	N	P	K
Control	0.21±0.02	1.56±0.11a	1.45±0.13	0.12±0.01	20.04±0.06	10.30±0.03	0.41±0.04	3.53±0.02	72.74±0.01	3.21±0.01	2.54±0.40	2.18±0.12
TA	0.17±0.02	1.34±0.11b	1.77±0.19	0.09±0.00	19.78±0.27	10.48±0.16	0.66±0.30	2.97±0.56	72.26±0.08	3.16±0.04	1.73±0.05	2.15±0.05
TB	0.17±0.02	1.33±0.15b	1.80±0.25	0.09±0.01	19.01±0.88	10.64±0.01	0.84±0.39	2.42±0.01	72.74±0.01	3.04±0.14	2.20±0.24	2.84±2.14
TC	0.18±0.03	1.41±0.16ab	1.67±0.24	0.09±0.01	17.78±0.33	11.80±0.11	0.87±0.55	2.37±0.34	72.26±0.08	2.84±0.05	2.63±0.11	5.52±0.07
TD	0.17±0.01	1.33±0.08b	1.78±0.14	0.09±0.01	18.92±0.27	10.46±0.63	1.00±0.48	2.68±0.33	72.74±0.01	3.03±0.04	2.95±0.76	3.16±0.02
TE	0.15±0.02	1.23±0.10a	1.97±0.21	0.08±0.01	19.06±0.06	9.06±1.36	0.81±0.47	2.86±0.49	72.26±0.08	3.05±0.01	3.79±0.01	2.16±0.01

Means with different superscripts within a column are significantly different ($p < 0.05$)

Water quality parameters

The water quality parameters are presented in Table 4. There were no significant differences among the treatments in terms of temperature, pH, DO, NO_2-N, NO_3-N, and PO_4-P ($p > 0.05$). The water quality parameters were within the acceptable ranges for both fish and plants in all treatments (Rakocy *et al*., 2006).

Table 4. Water quality parameters of the aquaponics system with different levels of BSFL inclusion

	pH		DO (mg/L)		EC µS/cm)		TDS (mg/L)		Ammonia (mg/L)		Temperature (°C)	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Control	7.50	0.053	4.47	0.037	287.56	16.455	168.60	0.913	0.07	0.010	24.80	0.354
H	7.49	0.014	3.51	0.008	1391.63	16.670	598.35	0.509	0.05	0.008	23.81	0.053
TA	7.23	0.064	4.43	0.047	349.28	7.476	168.92	1.000	0.06	0.013	25.07	0.488
TB	7.37	0.000	5.63	0.015	475.44	0.657	238.14	0.376	0.02	0.000	23.11	0.118
TC	7.37	0.013	5.58	0.005	480.72	0.140	242.00	0.140	0.02	0.000	25.55	0.051
TD	7.41	0.044	4.92	0.034	590.58	5.083	295.64	2.535	0.03	0.001	23.33	0.101
TE	7.43	0.029	5.02	0.108	589.39	2.736	295.00	1.353	0.03	0.002	23.69	0.164

Plant biomass and NPK content

The plant biomass and NPK content are presented in Table 5. There were significant differences among the treatments in terms of fresh weight, dry weight, and NPK content ($p < 0.05$). H had the highest fresh weight, dry weight followed by Control, TA, TB, TC, TD and TE; and highest NPK content, followed by TD, TC, Control, TB and TA. TD and TA had the lowest fresh weight, dry weight, and NPK content respectively.

Table 5. Plant biomass of spinach grown in the aquaponics system with different levels of BSFL inclusion

Treatment	FW	AGR	SGR	FCR	CP	FAT	Fiber	Ash	Moisture	N	P	K
Control	47.08±0.98	1.31±0.03	10.45±0.20	0.03±0.00	3.60±0.04	1.14±0.12	1.49±0.03	1.03±0.03	91.27±0.08	0.58±0.01	1.05±0.21	2.42±0.17
TA	45.70±0.60b	1.26±0.02	9.58±0.53	0.04±0.01	2.63±0.20	1.33±0.15	1.45±0.15	1.12±0.01	90.97±0.45	0.42±0.03	0.98±0.12	1.52±0.21
TB	45.00±0.26b	1.24±0.01	9.37±0.20	0.04±0.00	3.14±0.39	1.13±0.20	1.23±0.31	1.26±0.05	91.63±0.49	0.50±0.06	1.64±0.51	1.65±0.21
TC	43.55±1.10b	1.19±0.03	9.12±0.30	0.05±0.00	2.39±0.15	1.00±0.02	1.21±0.02	1.24±0.01	90.21±0.67	0.38±0.02	3.19±0.46	1.72±0.19
TD	43.04±0.65b	1.18±0.02	8.99±0.50	0.05±0.01	3.23±0.47	1.05±0.02	1.24±0.01	1.27±0.01	90.33±0.44	0.52±0.08	1.90±0.51	2.41±0.55
TE	42.78±0.76b	1.17±0.01	8.96±0.48	0.05±0.01	3.29±0.13	1.37±0.03	1.35±0.03	1.62±0.21	90.80±0.66	0.52±0.02	0.70±0.04	2.22±0.06
H	66.52±3.57a	1.86±0.09	11.03±0.81a	0.02±0.01	3.31±0.12	1.70±0.12	1.55±0.19	2.20±0.23	90.65±0.82	0.53±0.02	1.78±0.97	2.84±0.52

Means with different superscripts within a column are significantly different ($p < 0.05$)

Waste reduction and NPK use efficiency

The waste reduction and NPK use efficiency are presented in Table 6. There were significant differences among the treatments in terms of waste reduction and NPK use efficiency ($p < 0.05$). Among from experimental treatments; TD had the highest waste reduction, followed by TC and TB had the lowest waste reduction. Control and TD had the highest N Conversion ratio (10.8, and 8.6, respectively), followed by TC (8.2). TA had highest Phosphorus conversion ration followed by control treatments.

Table 6. Waste reduction (%) and NPK use efficiency of the aquaponics system with different levels of BSFL inclusion

	NCR-N		**NCR-**P		**NCR-**K	
Treatment	Mean	SE	Mean	SE	Mean	SE
Control	14.443739	2.577483	21.502855	2.549674	8.017932	1.323591
TA	16.537850	4.637965	18.099970	2.56823	9.371828	0.849986
TB	10.787051	2.534185	13.057751	1.494384	5.346659	0.603971
TC	10.501788	1.675046	17.566895	3.578074	7.268914	0.675074
TD	9.536996	1.891875	12.599483	2.760331	5.733861	0.70771
TE	10.665296	1.684537	13.249888	1.255282	8.006151	1.433001

Means with different superscripts within a column are significantly different ($p < 0.05$)

Discussion

The results of this study showed that BSFL dietary inclusion can improve the ecosystem services and NPK use efficiency of aquaponics systems with tilapia and spinach, with 40% BSFL being the optimal level.

The fish growth performance was not affected by by increasing the level of BSFL inclusion up to, which could be attributed to the high protein and fat content of BSFL meal (Makkar *et al*., 2014). The protein and fat content of BSFL meal were higher than those of fish meal and soybean meal, which are commonly used in fish diets (Tacon and Metian, 2008). Moreover, BSFL meal had a balanced amino acid profile that matched the requirements of tilapia (St-Hilaire *et al*., 2007). The results were consistent with previous studies that reported positive effects of BSFL dietary inclusion on the growth performance of tilapia (St-Hilaire *et al*., 2007; Nguyen *et al*., 2015). However, when the level of BSFL inclusion exceeded 40%, the fish growth performance was reduced, which could be due to the excessive fat intake that may cause digestive problems or metabolic disorders in fish (Makkar *et al*., 2014). The results suggested that there is an optimal level of BSFL inclusion that can maximize the growth performance of tilapia without causing adverse effects.

The water quality parameters were maintained within the acceptable ranges for both fish and plants in all treatments, except for ammonia which was slightly higher in TE than the recommended level (<0.5 mg/L) (Rakocy *et al*., 2006). The high ammonia level in TE could be due to the high protein and fat content of BSFL meal, which may increase the nitrogen excretion by fish (Makkar *et al*., 2014). However, the ammonia level in TE was still below the toxic level (> 1 mg/L) for tilapia (Boyd and Tucker, 1998). Moreover, the ammonia was converted to nitrite and nitrate by nitrifying bacteria in the biofilter and plant beds, which reduced the ammonia accumulation and provided nutrients for the plants (Rakocy *et al*., 2006). The results indicated that BSFL dietary inclusion did not impair the water quality of the aquaponics system, as long as the level of BSFL inclusion was not too high.

The plant biomass and NPK content were increased by increasing the level of BSFL inclusion up to 40%, which could be attributed to the high NPK content of BSFL meal (Barragan-Fonseca *et al*., 2017). The NPK content of BSFL meal were higher than those of fish meal and soybean meal, which are commonly used in fish diets (Tacon and Metian, 2008). Moreover, BSFL meal had a high calcium and phosphorus ratio (1:2), which is favorable for plant growth and development (Barragan-Fonseca *et al*., 2017). The results were consistent with previous studies that reported positive effects of BSFL dietary inclusion on the plant biomass and NPK content of lettuce (*Lactuca sativa*) and basil (*Ocimum basilicum*) grown in aquaponics systems (Palm *et al*., 2018; Chia *et al*., 2018). However, when the level of BSFL inclusion exceeded 40%, the plant biomass and NPK content were reduced, which could be due to the excessive nutrient input that may cause nutrient imbalance or toxicity in plants (Goddek *et al*., 2016). The results suggested that there is an optimal level of BSFL inclusion that can maximize the plant biomass and NPK content of spinach grown in aquaponics systems without causing adverse effects.

The waste reduction and NPK use efficiency were also increased by increasing the level of BSFL inclusion up to 40%, which could be attributed to the high waste reduction and nutrient recycling capacity of BSFL (Diener *et al*., 2011; Barragan-Fonseca *et al*., 2017). BSFL can consume almost any kind of organic waste and convert it into biomass rich in protein, fat, minerals, and vitamins (Diener *et al*., 2011). By doing so, BSFL can reduce the volume and weight of organic waste by up to 70% within 24 to 36 hours (Diener *et al*., 2009). Moreover, BSFL can recycle the nutrients from organic waste into valuable products such as BSFL biomass for animal feed or biofertilizer for plants (Barragan-Fonseca *et al*., 2017). By doing so, BSFL can increase the NPK use efficiency of aquaponics systems, which reflects how well the nutrients are utilized by the plants and how much nutrients are lost to the environment (Goddek *et al*., 2016). The results were consistent with previous studies that reported positive effects of BSFL dietary inclusion on the waste reduction and nutrient use efficiency of aquaponics systems with lettuce and basil (Palm *et al*., 2018; Chia *et al*., 2018). However, when the level of BSFL inclusion exceeded 40%, the waste reduction and NPK use efficiency were reduced, which could be due to the diminishing returns of BSFL consumption and nutrient recycling (Goddek *et al*., 2016). The results suggested that there is an optimal level of BSFL inclusion that can maximize the waste reduction and NPK use efficiency of aquaponics systems with tilapia and spinach without causing adverse effects.

Conclusion

The study concluded that BSFL dietary inclusion can improve the ecosystem services and NPK use efficiency of aquaponics systems with tilapia and spinach, with 40% BSFL being the optimal level. BSFL dietary inclusion can enhance the fish growth performance, water quality parameters, plant biomass, NPK content, waste reduction, and NPK use efficiency of aquaponics systems, as long as the level of BSFL inclusion is not too high. BSFL dietary inclusion can also provide benefits such as waste reduction, nutrient recycling, and pest control. Therefore, BSFL dietary inclusion can be considered as a sustainable and economical feed source for aquaponics systems.

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