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ORIGINAL ARTICLE

Is enrichment with inorganic and organic compounds feasible for improving the quality of vermicomposting using water hyacinth biomass?

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Abstract

In eutrophic environments, aquatic weeds reproduce rapidly, occupying extensive areas of the water body and preventing the multiple use of water resources. The use of the biomass of these plants in vermicomposting represents a sustainable alternative utilization of the excess biomass produced by eutrophication. The enrichment of macrophyte biomass during vermicomposting was tested using an inorganic solution (NPK 1.75 % and NPK 3.50 %) and an organic solution with glucose (0.25 g/L and 0.50 g/L) to improve the quality of the vermicompost. The consumption of biomass of the macrophytes by the *Eisenia fetida* increased as the vermicomposting progressed, reaching the highest values at the end of the experimental period. The control treatment, i.e., without earthworms, remained stable. The electrical conductivity tended to increase for the treatments NPK 1.75 %, Glucose 0.25 g/L and Glucose 0.50 g/L. The pH of the vermicomposting tended to be neutral in all treatments. The control and inorganic treatments showed a reduction in macrophyte biomass and the number of individuals of *Eisenia fetida*. The additions of NPK and glucose slightly improved vermicompost quality and biomass consumption by the earthworms. However, using vermicompost alone does not meet the requirements for its use as a fertilizer. Thus, we suggest the use of vermicompost in association with other fertilizers, adding moisture and structuring the soil.

Keywords: *Eichhornia crassipes*; *Eisenia fetida*; eutrophication; glucose; humification; mathematical modeling; nutrients.

1. Introduction

Macrophytes are aquatic plants that colonize both aquatic environments and terrestrial flooded environments [1]. These organisms present great plasticity and adaptability [2] and provide a variety of ecosystem services, such as refuge, food, and habitat [3]. The reproductive characteristics of these plants are higher in eutrophic environments, resulting in population explosions that promote the loss of multiple uses of water resources, causing several negative ecological and socioeconomic impacts [4, 5]. Among the floating macrophytes, typically present in eutrophic freshwater bodies, the water hyacinth *Eichhornia crassipes* (Martius) Solms-Laubach (Pontederiaceae) is usually found. This species is originally from South America and has widespread invasive potential [6, 7, 8].

Due to the high biomass production of *E. crassipes* in eutrophic systems, the utilization of this macrophyte biomass represents an ecological and sustainable alternative economic use. The main characteristic of vermicomposting is the possibility of using a great variety of organic materials to form a nutritious compound that can be used for fertilization. Water hyacinth is a source of macronutrients, such as nitrogen, phosphorus, and potassium, which can improve soil fertility [9]. Thus, using *E. crassipes* biomass as a raw material for composting can reduce an environmental problem by applying this biomass in sustainable techniques [2].

Composting is the treatment of waste regulated by aerobic microbial decomposition, resulting in the degradation and transformation of complex degradable materials into organic and inorganic compounds [10]. In the composting of agro-wastes, a decrease in aliphatic materials and an increase in aromatic groups occurs by the mediation of cellulose-degrading bacteria that break down the organic wastes [11, 12]. A process like composting is vermicomposting, which is distinguished by using mesofauna, especially *Eisenia fetida* (Oligochaeta, Lumbricidae). The success of vermicomposting depends upon the earthworm species that process organic materials. *Eisenia fetida* has been used as a reliable species for vermicomposting [13, 14]. The process of vermicomposting is accelerated by the combined action of earthworms with the flora present in the digestive tract of these organisms [15]. During composting, part of the organic matter is mineralized to carbon dioxide, ammonia, and water, while the other part is transformed into humic substances [16]. The priming effect is the process of stimulating the mineralization of organic matter in the soil. The positive effects of adding different organic substrates are often related to the mineralization of organic carbon in the soil [17]. The addition of carbon-rich compounds can strongly change the turnover of native organic matter, causing the priming effect [18].

Incorporating of inorganic and organic elements as an additional source of nutrients and carbon for a priming effect may improve the quality of the vermicompost generated by macrophyte biomass. It is common to add manure to vermicomposting of macrophytes, mainly from cattle [19, 20, 21, 22, 23]. The mixture of manure-macrophytes is favorable to the adaptation of earthworms and beneficial for improving the consumption of macrophyte biomass. Álvarez-Bernal et al. [24] vermicomposted *E. crassipes* and cattle manure in a combined treatment of both at the proportion of 50 %. The experiment achieved a total conversion of macrophyte biomass in 110 days. Ansari and Rajpersaud [25] used *E. crassipes* biomass in the vermicomposting with grass clippings and also, the combination of both substrates. Vermicompost with *E. crassipes* presented a conversion rate of 56.14 %, while in the combined treatment, the transformation was 76.19 %.

Production of nutrient-enriched vermicompost from macrophytes supplemented potentially enhances the growth of plants and can also contribute to the improvement in the physicochemical properties of the soil [26]. The production of enriched vermicompost from macrophytes by amending it with an easy to acquire and cheap substance is a viable alternative to spread the use of vermicomposting beyond and remove the macrophyte biomass excess in the eutrophic ecosystem. Thus, the use of the biomass of these plants in vermicomposting represents a sustainable alternative related to the excess biomass produced by eutrophication. Our study aimed to evaluate a vermicompost produced using the biomass of *Eichhornia crassipes* as a source of organic matter after adding organic and inorganic compounds (glucose and commercial fertilizer NPK) at two concentrations. The objectives were: (i) to evaluate the kinetics of macrophyte consumption by *E. fetida*; (ii) to estimate the quality of the humus formed from the vermicomposting; (iii) to identify whether the addition of priming (organic: glucose and inorganic: NPK) will increase the quality of the generated humus and (iv) calculate the consumption of macrophyte biomass by *E.*

fetida using mathematical modeling. We hypothesize that incorporating both substances, as an additional source of elements (i.e., N, P, K and C), may improve the quality of the vermicompost generated by the macrophyte biomass.

2. Materials and methods

2.1. Preparation of vermicomposting experiment

Samples of *E. crassipes* were collected manually at the Departmento de Botânica (DB) of the Universidade Federal de São Carlos (UFSCar). After being collected, the macrophytes were manually washed in running water to remove the adhered detritus. The plants were fractionated in 5 cm portions to facilitate consumption. A portion of the *E. crassipes* was dried (ca. 50 °C) to constant mass. This procedure ensured the maintenance of the dry and fresh proportions (3:1) of the *E. crassipes* biomass.

The vermicomposting experiment occurred in dark polypropylene boxes ($n = 3$), previously cleaned and dried (dimensions: 32 cm long, 16 cm wide, and 36 cm high). The vermicomposting system had two digester boxes (total volume: 8 L) and a collection box (volume: 4 L). In the digester boxes, a layer (ca. 2 cm) of an inert substrate was set. This substrate consisted of a mixture of vermiculite and sand (1:1). Above the substrate, a polypropylene mesh (mesh: 1 cm) was placed to separate the inert substrate and the water hyacinth biomass. This procedure aimed to facilitate the final separation of the remaining macrophyte biomass after the end of the vermicomposting and, therefore, to calculate the consumption efficiency of the water hyacinth biomass.

Thirty individuals of *E. fetida* with varying sizes and masses were selected, contemplating all stages of life of the earthworms. The individuals had their length (in cm) determined using a millimeter rule before and after the application of each treatment. The initial and final biomass of the *E. fetida* were determined on a precision scale (Bel Engineering, model M214Ai; precision 0.0001 g), and the number of individuals were counted at the beginning and after the end of the vermicomposting. Before the beginning of vermicomposting ($n = 3$ for each treatment), 30 individuals of *E. fetida* were maintained in the digestion boxes for 24 hours for adaptation. Some standards must be followed so the vermicomposting reaches its objectives and, at the same time, corresponds to the tolerance standard of the present macrofauna. Therefore, the earthworms were maintained at 25 °C and 75 % moisture [27]. The macrophytes were added in fresh and dry forms, in the proportion of 10:30 g of fresh and dry biomass, respectively.

At the same time, mini-systems ($n = 24$ for each treatment) were set up to monitor the consumption kinetics of macrophyte biomass by *E. fetida*. The mini-systems were prepared with *E. crassipes* biomass and *E. fetida* individuals in the same proportion, as previously described in the system (1 g of fresh biomass, 3 g of dry biomass, and 3 individuals of *E. fetida*). The mini-systems were deactivated weekly, and the consumption efficiency of *E. crassipes* biomass was calculated (Equation 1).

$$E = \frac{B_e - B_s}{B_e} \times 100 \qquad (1)$$

where E = consumption efficiency (%); B_e = input biomass; B_s = outgoing biomass.

For the evaluation of biomass consumption, a first-order model was used (Equation 2). The model parameters ($BC_{\max}$ and k) were obtained from nonlinear regressions using the iterative algorithm of Levemberg-Marquardt [28].

$$BC = BC_{\max} \times \left(1 - e^{-kt}\right) \tag{2}$$

where BC, accumulated biomass consumption (oxidized biomass + transferred biomass to *E. fetida*); $BC_{\max}$, maximum biomass consumption per condition (%); k, consumption coefficient (per wk); t, time (week).

Experiments without earthworms ($n = 24$) and without NPK or glucose were also set up to allow a comparison between the consumption of biomass by *E. fetida* and the microorganisms. This experiment was done in the same proportions as the mini-systems.

The treatments with the addition of compounds were conducted by the application of commercial inorganic fertilizer (used as foliar solution) containing nitrogen, phosphorus, and potassium (NPK) in the proportion 15-05-05 and the organic solution of glucose ($C_6H_{12}O_6$). The commercial fertilizer used was added as an aqueous solution in concentrations of 1.75 % and 3.50 %. The organic glucose solution was added in concentrations of 0.25 g/L and 0.50 g/L. Both solutions were used to maintain the moisture in the vermicomposting system during the experimental time of 60 days. To verify the priming effect on the vermicompost, three treatments (in replicas) were performed with *E. crassipes* biomass: (i) Control treatment - biomass without addition of inorganic compound; (ii) NPK 1.75 %; (iii) NPK 3.50 %: (iv) Glucose 0.25 g/L and (v) Glucose 0.50 g/L.

The first addition was made after the system assembly was finished. 100 mL of the solutions (NPK 1.75 and 3.50 % and Glucose 0.25 g/L and 0.50 g/L) were added to each system. To monitor the abiotic conditions in the system, fresh mass aliquots of the vermicompost weekly were analyzed in replica. The following variables were measured: temperature, moisture, pH, and electrical conductivity (EC). The temperature was obtained by measuring the mercury thermometer. The moisture was obtained by gravimetry [29, 30], using an oven and precision scale (Bel Engineering, model M214Ai). For the pH and EC analyses, an aliquot of vermicompost was separated from the systems to make the aqueous extract (2:8 ratio) with deionized water, where the pH and the EC were measured. The pH was obtained by a potentiometer (pHmeter DIGIMED, model DMPH-2), and the EC was obtained by a potentiometer (Condutivimeter DIGIMED, model DM3).

Weekly, an aliquot (ca. 50 mg of fresh mass) was separated and removed from the vermicompost system extract humic substances with alkaline extract (NaOH 0.5 mol/L). The extractions were performed until the extracting solution was no longer colored (i.e., transparent). After extraction, the alkaline solutions were measured at the wavelengths 250, 254, 365, 450, and 665 nm to quantify the concentrations of humic substances and calculate the humification indices E2/E3 and E4/E6. The E2/E3 ratio is an index related to the quality of the vermicompost. The value of this ratio decreases with the increase of light absorption by chromophore-dissolved organic matter with high molecular mass [31] and aromaticity [32, 31]. The E4/E6 ratio decreases with the increase in molecular mass and the condensation of aromatic constituents [33]. The E4/E6 ratio is inversely proportional to the degree of condensation of humic materials and the residence time of humic materials in the soil [34].

After the end of vermicomposting with all treatments (ca. 60 days), the remaining biomass (i.e., not consumed by the earthworms) of *E. crassipes* was removed from the system. The biomass was dried at 50 ºC and determined gravimetrically. To determine the global efficiency (Equation

1) of the vermicomposting, the quantification was obtained with the initial and final biomass of the *E. crassipes*. The time variation and boxplot graphics were plotted using the OriginPro 2023 software.

To verify the fertility of the vermicompost in each treatment, analyses were performed indicating the quality of the compost in an accredited laboratory (Soil Fertility Laboratory - Soil Science Department of ESALQ/USP; Report nº 0017889.1-N-O.S.10668). Total organic matter (TOM) was obtained by ignition loss [35]. The organic carbon (OC) was extracted with dichromate and titulometry. The total nitrogen (TN) was measured by sulfuric digestion/Kjeldahl. Total phosphorous (TP) was evaluated by vanadium ammonium extraction and colorimetry. Total potassium (TK) was acquired by extraction with hydrochloric acid and flame photometry. Total sulfur (TS) was obtained by extraction with barium chloride and gravimetric method. Total calcium (TCa) and total magnesium (TMg) were assessed by extraction with hydrochloric acid and quantified by atomic absorption. The C/N ratio was evaluated according to MAPA [36].

2.2. Statistical analyses

Differences in the mean values of variables pH, EC, E2/E3, E4/E6, and humic substances between treatments and days of biomass consumption were compared using Two-way ANOVA without replications, and significant differences were considered with 95 % confidence intervals ($p < 0.05$). Changes in pH, EC, E2/E3, E4/E6 and humic substance values in the experiment were analyzed through multiple linear regression analysis. These variables were used as dependent variables and compared by analysis of variance (ANOVA), with significant differences considered at 95 % confidence intervals ($p < 0.05$). Spearman rank correlation analysis was used to analyze the associations between the significant variables in humic substance production. The significance of the associations between the variables was analyzed using the correlation coefficients, and the 95 % confidence intervals were considered ($p < 0.05$).

The initial biomass and abundances of *E. fetida* in each treatment were compared with the final values of the experiment using the Wilcoxon test. The values of water hyacinth composting efficiencies between treatments with the presence and absence *of E. fetida* were compared using Two-way ANOVA without replications. Significant differences were considered with 95 % confidence intervals ($p < 0.05$). The relationships of the vermicomposting efficiency of the different treatments with the total experimental period and with the presence and absence of *E. fetida* were analyzed through the analysis of linear multiple regression. The values of vermicomposting efficiency of the treatments, with the presence and absence of *E. fetida*, were considered dependent variables and, the values were compared by analysis of variance (ANOVA). Significant differences were considered with 95 % confidence intervals ($p < 0.05$). Statistical analyses were performed on Past - Palaeontological Statistics software, version 1.81 [37].

3. Results and Discussion

3.1. Monitoring abiotic variables during vermicomposting

Moisture and temperature are important variables for the maintenance of *E. fetida* individuals. The ideal temperature for the vermicomposting process is ca. 25 °C; however, earthworms can tolerate conditions at 30 °C [38]. The metabolic activity, i.e., breathing and growth of earthworms, are extremely influenced by temperature [15], in which vermicomposting remained below 30 °C and close to ideal: (24 ± 4) °C. The values of temperature during vermicomposting are presented

Table 1. Mean values and variances of the variables (electrical conductivity – EC: µS/cm; temperature: °C; Humic substances - HS: mg HS/g/humus) measured throughout the process of vermicomposting with E. crassipes from treatments enriched with different concentrations of inorganic (NPK) and organic (Glucose) compounds ± Standard Deviation.

Variables	Control treatment	NPK 1.75%	NPK 3.50%	Glucose 0.25 g/L	Glucose 0.50 g/L
EC	$(821.78 \pm 6.60) \times 10^4$	$(1041.993 \pm 0.085) \times 10^4$	$(770.58 \pm 0.24) \times 10^4$	$(1196.49 \pm 0.60) \times 10^4$	$(1108.63 \pm 0.99) \times 10^4$
Temperature	23.35 ± 1.00	23.38 ± 1.27	24.38 ± 0.84	21.08 ± 1.63	18.98 ± 1.09
pH	8.01 ± 0.13	7.87 ± 0.02	8.13 ± 0.29	7.87 ± 0.02	7.89 ± 0.03
E2/E3	3.66 ± 2.68	2.94 ± 1.10	3.25 ± 0.78	1.99 ± 16.48	2.32 ± 32.13
E4/E6	2.28 ± 7.64	9.67 ± 242.68	7.11 ± 303.71	1.76 ± 1.32	4.34 ± 21.40
HS	3.75 ± 9.26	68.90 ± 4365.86	13.41 ± 174.34	46.86 ± 2210.85	29.68 ± 1051.90

in **Table 1**. The temperature was not controlled during the vermicomposting once this process occurred at room temperature, subject to seasonal variation. The variation was 18.98 °C (Glucose 0.50 g/L) to 24.38 °C (NPK 3.50 %) and was not a limiting factor for earthworm activities.

E. fetida requires a substrate with relatively high moisture content, varying between 75 % and 90 % [15]. The values obtained were within the ideal range and the mean and standard deviation obtained for each treatment: (i) (56.65 ± 5.23) % (Control treatment); (ii) (69.24 ± 8.37) % (NPK 1.75 %); (iii) (44.41 ± 8.62) % (NPK 3.50 %), (iv) 61.73 ± 3.83 (Glucose 0.25 g/L) and (v) 57.48 ± 6.37 (Glucose 0.50 g/L). Moisture is directly related to temperature, and experiments on the life cycle of *E. fetida* are considered the ideal conditions for developing of this species: 25 °C and 75 % moisture [27].

The weekly EC variation of the vermicompost showed higher mean values in organic treatments (Table 1). High EC values contributed to the hypothesis of more fertile compost because of the greater availability of ions in the vermicompost and, subsequently, the higher potential as a fertilizer. The solubilization of the protoplasmic contents of aquatic macrophytes releases, into the soil, high amounts of ions, such as K [39, 40] and metals, e.g., Fe [41]. This increase, also, occurs from the increased availability of soluble salts resulting from the mineralization activity of earthworms and microorganisms that occurs in their tract [42].

The weekly EC variation displayed a significant increase in the treatments: NPK 1.75 %, Glucose 0.25 g/L, and Glucose 0.50 g/L, while, in the Control treatment and NPK 3.50 %, the ion concentration decreased (**Table 2**). The increase in EC values was related to releasing of ions from the macrophyte biomass, which were incorporated into the humus during the vermicomposting process.

The pH temporal analysis of the vermicompost for the different treatments showed variations in the treatments tending to neutrality (Table 1 and Table 2). Experiments using *Eichhornia crassipes* as a substrate in vermicomposting [14] also showed a neutral pH range (average value = 7.3). However, the EC was much lower (mean value = 180 µS/cm) than that obtained in our study, which used an inorganic substrate as an amendment and increased the ionic concentration of the vermicompost. Pramanik et al. [43] pointed out that the decomposition of organic matter involves the formation of ammonium and humic acids, these two substances responsible for antagonistic effects on the soil. While the presence of humic compounds propitiates the decrease of the pH, the ammonium ions induce its increase and the concomitant presence of the two substances makes the pH tend to neutrality. The formation of humic substances is characterized by the mineralization of organic matter [16]. As for the humification indexes, De Haan [44] points out that values of E2/E3 close to 4 indicate high humification. The results showed that the Control treatment and

Table 2. Changes in vermicomposting variables (electrical conductivity – EC: µS/cm; temperature: ^{o}C; Humic substances - HS: mg HS/g/humus) of *E. crassipes* over the decomposition period in treatments enriched with different concentrations of inorganic and organic compounds. Where: coefficient (Coeff.), Standard error (Std. err.) and * (significant differences).

Variable	Treatment	Coeff.	Std. err.	T	P	R^2
EC	Control	-4.80	1.29	-3.75	< 0.001	0.08*
	NPK 1.75	2.68	1.51	1.78	0.08	0.02
	NPK 3.50	-3.10	0.78	-3.99	< 0.001	0.10*
	Glucose 0.25	3.67	1.24	2.94	0.03	0.05*
	Glucose 0.50	9.50	1.44	6.59	< 0.001	0.23*
pH	Control	-0.01	0.00	-8.26	< 0.001	0.32*
	NPK 1.75	0.001	0.00	2.69	0.01	0.04*
	NPK 3.50	-0.00	0.00	-1.14	0.25	0.00
	Glucose 0.25	0.00	0.00	2.69	0.01	0.04*
	Glucose 0.50	0.00	0.00	5.28	< 0.001	0.16*
E2/E3	Control	-0.00	0.02	-0.42	0.067	0.00
	NPK 1.75	0.01	0.01	0.73	0.47	0.02
	NPK 3.50	-0.00	0.01	-0.75	0.46	0.02
	Glucose 0.25	0.04	0.05	0.85	0.40	0.03
	Glucose 0.50	-0.03	0.07	-0.52	0.60	0.01
E4/E6	Control	-0.03	0.03	-1.01	0.32	0.04
	NPK 1.75	-0.15	0.20	-0.76	0.45	0.02
	NPK 3.50	0.25	0.22	1.15	0.26	0.05
	Glucose 0.25	0.00	0.01	0.44	0.65	0.00
	Glucose 0.50	-0.12	0.05	-2.15	0.04	0.17*
HS	Control	-0.05	0.03	-1.30	0.20	0.07
	NPK 1.75	-1.08	0.82	-1.30	0.20	0.07
	NPK 3.50	0.14	0.16	0.87	0.39	0.03
	Glucose 0.25	1.33	0.54	2.46	0.02	0.22*
	Glucose 0.50	1.07	0.36	3.02	0.01	0.29*

NPK 3.50 % had mean values closer to the stated value (Table 1). However, these values did not change along the vermicomposting experiment days. Low values of the E4/E6 ratio (less than 5) show high-quality compounds [45]. Values between 2 and 5 indicate higher humification [46]. The Control treatment, the Glucose 0.25 g/L and Glucose 0.50 g/L treatments showed means within this range, although the humic substance in the compound enriched with NPK 1.75 % was much higher than the other treatments (Table 1). The glucose-enriched treatments presented significant increases compared to the other treatments (Table 2). Humic substances represent the main component of stabilized organic matter and are essential for plant growth [47], highlighting the possibility of using the compound as fertilizer.

3.2. Biomass consumption efficiency

The efficiency of biomass consumption in vermicomposting was not an important indication of the feasibility of using macrophyte biomass; however, it showed the effectiveness of its use as a sustainable alternative. The kinetics consumption observed in the mini-systems showed similar patterns in all treatments, i.e., an efficiency of less than 50 % in the initial weeks. Up to the fourth week of the experiment, the efficiency values remained between 50 % and 75 %. It was also possible to observe a sharp increase in biomass consumption from all treatments throughout the experiment, especially at the end, reaching values around 80 % (**Figure 1**). The treatment without earthworms showed a more stable efficiency through the experiment, varying between 30 % and 50 %. Therefore, we consider that the variation obtained in efficiency was related especially to extrinsic variables (e.g., temperature, moisture, pH) that influence the rates of consumption of *E. fetida* for the organic treatments. Dominguez and Edwards [48] highlight that the earthworms used in vermicomposting have well-defined limits for these variables, with the organic matter being processed more efficiently within a restricted range of favorable chemical and environmental conditions. The degradation resulting from the bioconversion by earthworms accelerates the mineralization of organic matter, favoring the breakage of structural polysaccharides (such as fibers), and increasing the humification rate [49]. The increase in humic acid content and increases in mineral nutrients (e.g., S, N, P, and K) is related to the degradative processes (decomposition/mineralization) of the organic compounds by earthworms [50, 51].

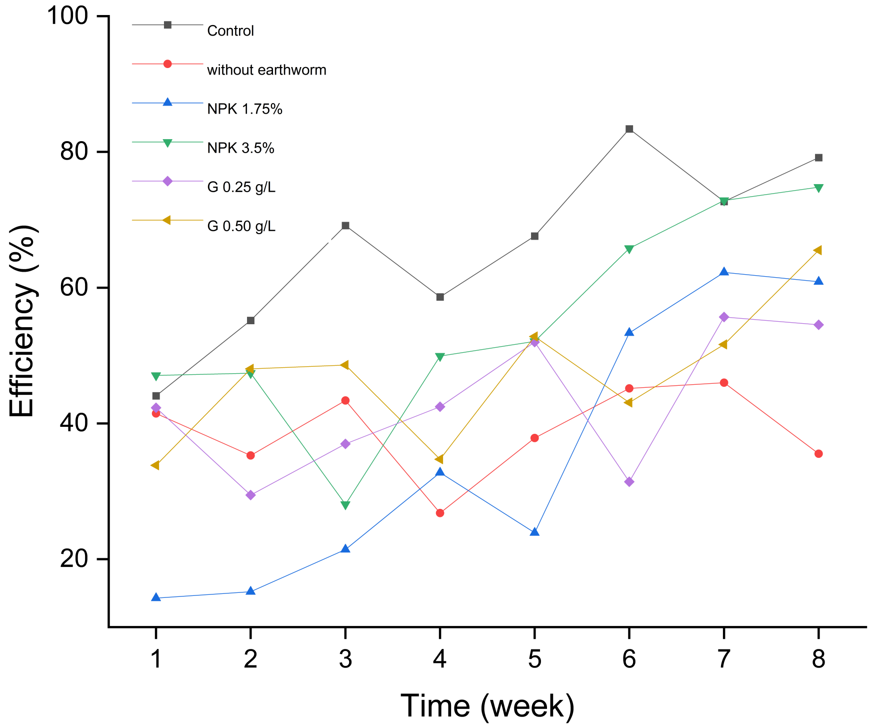

Figure 1. Weekly variation in consumption efficiency of macrophytes biomass in the treatments (Control treatment; NPK 1.75 %; NPK 3.50 %; Glucose 0.25 g/L and Glucose 0.50 g/L).

The comparative analyses of initial and final biomass and abundance of *E. fetida* showed that the Control treatment, NPK 1.75 % and 3.50 % treatments concentrations showed a significant reduction of biomass at the end of the experiment. The same result was observed for the number of individuals only in the inorganic nutrient treatments (**Table 3**). The comparative analysis between the vermicomposting efficiency treatments with the presence and absence of the earthworms showed that the Control treatment followed by NPK 3.50 % presented significantly higher average efficiencies than the other treatments ($F = 16.31$, $p < 0.001$, **Figure 2**). The treatments with added organic compounds showed less variation in average efficiency values.

Table 3. Results of Wilcox's test analysis between initial and final biomass and number of *E. fetida* individuals in the decomposition process of *E. crassipes* from treatments enriched with different concentrations of inorganic and organic compounds.

	Treatment	**Initial**	**Final**	*W*	*z*	*p*
Biomass	Without earthworms	3.11 ±0.01	1.96 ±0.10	300	4.28	< 0.0001*
	Control	2.38 ± 0.33	1.43 ± 0.45	300	4.28	< 0.0001*
	NPK 1.75%	2.51 ± 0.52	0.44 ± 0.22	300	4.28	< 0.0001*
	NPK 3.50%	2.74 ± 0.83	1.16 ± 0.70	295	4.14	< 0.0001*
	Glucose 0.25 g/L	1.21 ± 0.12	1.12 ± 0.24	164	0.41	0.68
	Glucose 0.50 g/L	2.50 ± 18.29	1.51 ± 0.27	141	0.47	0.64
Number of individuals	Control	2.70 ± 0.22	2.20 ± 1.65	101	1.78	0.07
	NPK 1.75%	3.00 ± 0.00	1.37 ± 1.81	168	3.68	< 0.0001*
	NPK 3.50%	3.00 ± 0.00	1.70 ± 0.91	205	3.85	< 0.0001*
	Glucose 0.25 g/L	3.00 ± 0.00	2.67 ± 1.27	40	1.35	0.17
	Glucose 0.50 g/L	3.00 ± 0.00	2.70 ± 0.56	10	1.84	0.07

The treatments also differed significantly over the total vermicomposting period ($F = 3.40$, $p < 0.0001$). The influence analysis of the variables showed that the efficiency of vermicomposting was significantly positive over the long period (**Figure 3**), contradicting the final number of *E. fetida* (**Figure 4**). The control and inorganic nutrient treatments showed the highest values of determination coefficients, positively influencing the efficiency of water hyacinth composting. We concluded that the influence of *E. fetida* individuals on the vermicomposting process of water hyacinth will depend on the compound type (i.e., organic × inorganic).

We observed that the inorganic treatments decreased biomass and number of earthworms, presenting the strongest efficiency. The rate of biomass consumption in vermicomposting is linked to the processing of organic matter by earthworms. Najar and Khan [20] indicated that low biomass consumption at the beginning of the experiment may be related to the acclimatization time of the earthworms to a new supply of organic resources. The change in biomass structure (i.e., decrease in the physical resistance of the biomass) during vermicomposting may have contributed to an increase in the consumption, as observed in the final weeks of the experiment, especially for the Glucose 0.50 g/L (Figure 1). Najar and Khan [20] point out that the chemical composition of organic resources influences the palatability of earthworms, which affects biomass consumption. In a review of earthworm nutritional ecology, the organic matter consumption can be very variable, depending on factors such as ideal environmental conditions for earthworm metabolic activity, nutritional quality of food, and palatability. Also, the exclusive use of water hyacinth biomass of vermicomposting results in increased mortality of *E. fetida* individuals due to the amounts of phenols in these plants, which are unpleasant to earthworms.

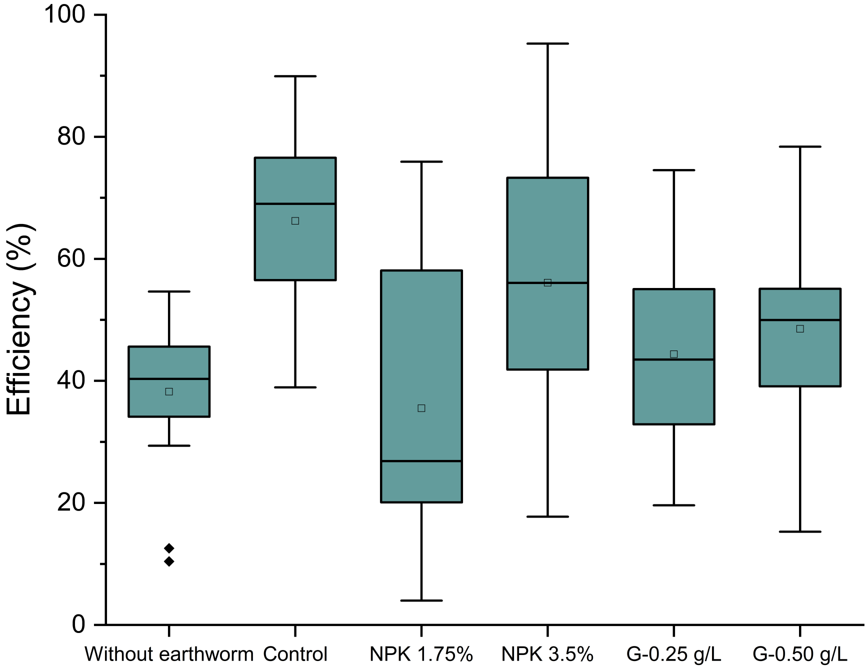

Figure 2. The average efficiency of vermicomposting of water hyacinth in mini-systems with different treatments enriched with different concentrations of inorganic and organic compounds (NPK 1.75 %; NPK 3.50 %; Glucose 0.25 g/L and Glucose 0.50 g/L) and absence of earthworms. Where: Box: 25 ≈ 75 %; bar: range within; line: median line; square: mean; diamond: outliers.

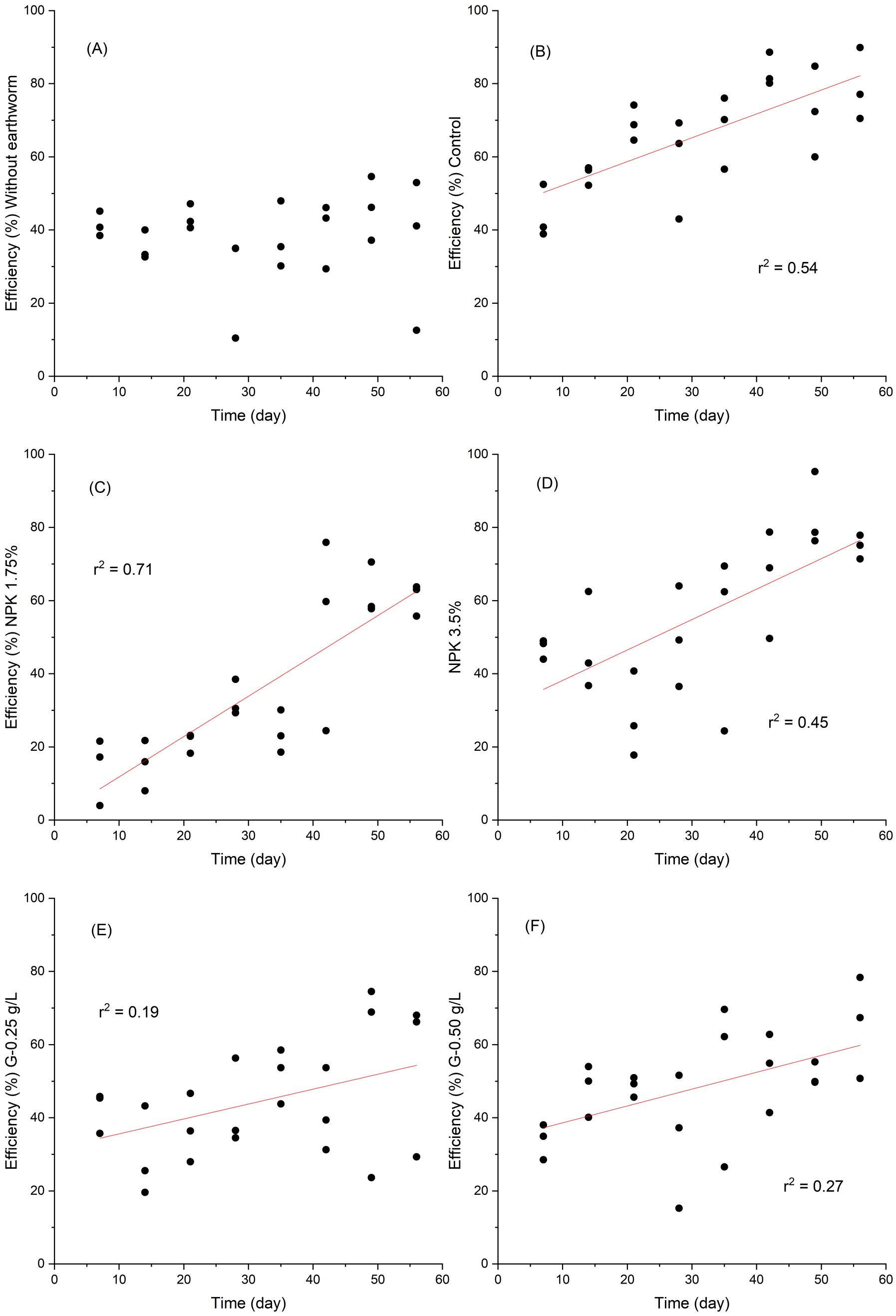

Figure 3. Influence of the days on the formation of humic substances in the vermicomposting process with different treatments enriched with different concentrations of inorganic and organic compounds (Control treatment; NPK 1.75 %; NPK 3.50 %; Glucose 0.25 g/L and Glucose 0.50 g/L).

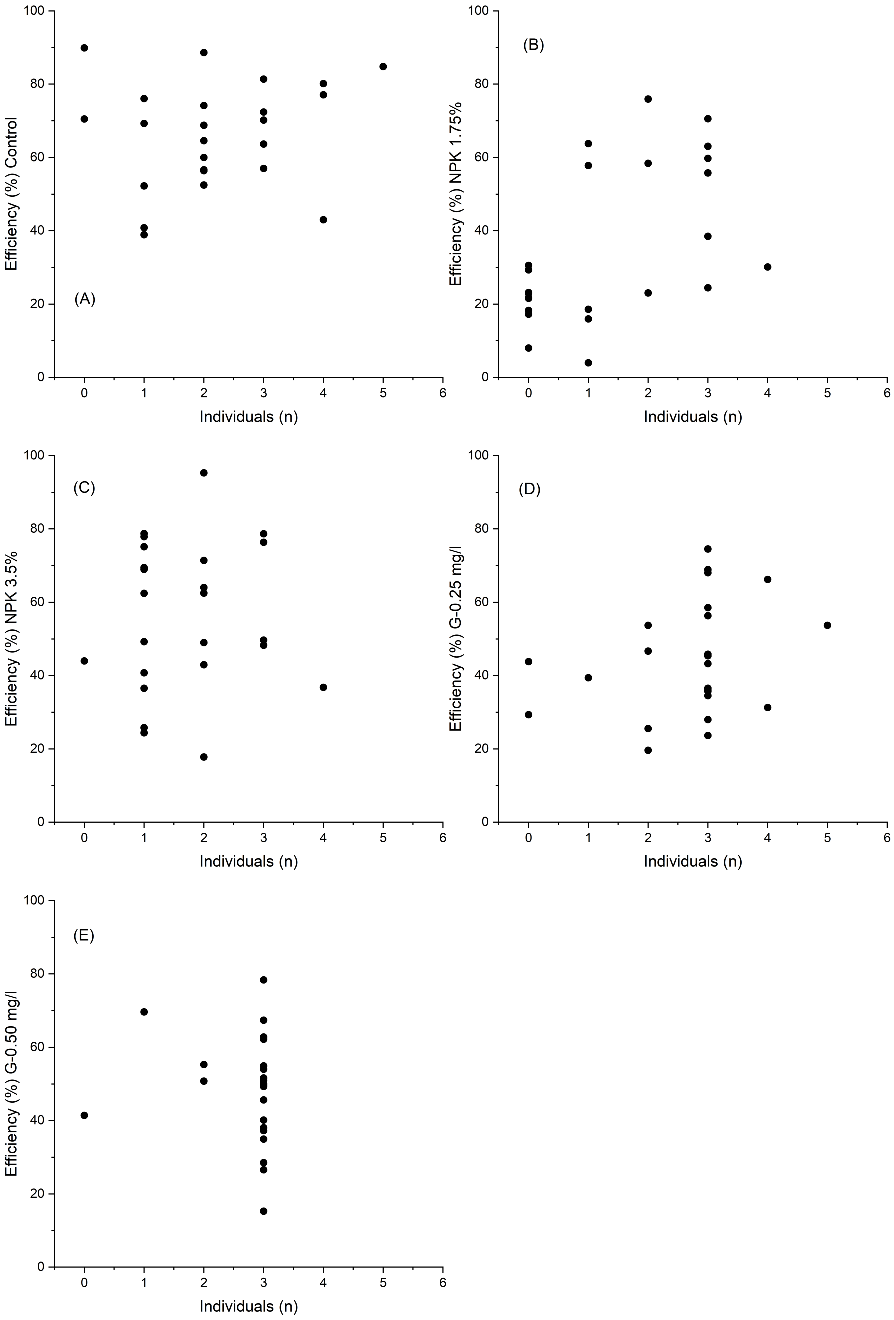

Figure 4. Influence of the final number of individuals on the formation of humic substances in the vermicomposting process with different treatments enriched with different concentrations of inorganic and organic compounds (Control treatment; NPK 1.75 %; NPK 3.50 %; Glucose 0.25 g/L and Glucose 0.50 g/L).

Considering the possibility of *E. fetida* mortality, pre-composting using cattle manure is a more favorable environment for earthworms [52]. Plant biomass appears less nutritive and attractive to the earthworms, whereas animal product waste results in high biomass and is favorable to *E. fetida* life cycle [53]. Concerning this, we can infer that the efficiency of water hyacinth consumption was due to the activity of microbiota in vermicomposting. The vermicomposts were usually microbiologically active with the presence of bacteria, fungi and actinomycetes [54].

Table 4 indicated the temporal variations of accumulated consumption and the parameters of the mathematical model (Eq. 2) used to describe the kinetics of biomass consumption of *E. crassipes* by *E. fetida*. A higher biomass consumption in the high inorganic enriched treatment (NPK 3.50 %), with a maximum consumption of 79.7 %, was observed. However, this condition presented a consumption coefficient (0.31 per wk) lower than the control treatment (0.74 per wk). The intermediate enrichment condition (NPK 1.75 %) showed the lowest consumption yield (65.0 %) and the lowest consumption coefficient (0.20 per wk). The coefficient of determination (r^2) obtained for the Control treatment was higher (0.94) when compared to the other treatments. Also, for the Control treatment, the accumulated biomass consumption ($BC_{\max}$) was the second highest (Table 4). Glucose 0.50 g/L presented the highest consumption coefficient (0.99 per wk) despite having the lowest accumulated consumption among the observed treatments (47.5 %). The consumption coefficient for the organic treatments was much higher than the others, reaching maximum values (0.95 and 0.99 per wk).

Table 4. Parameters of the model of biomass consumption of water hyacinth by *E. fetida* in the tested treatments (Control treatment; NPK 1.75 %; NPK 3.50 %; Glucose 0.25 g/L and Glucose 0.50 g/L).

Treatment	$BC_{\max}$ (%)	k (per wk)	r^2
Control	74.50	0.74	0.94
NPK 1.75%	65.00	0.20	0.83
NPK 3.50%	79.70	0.31	0.72
Glucose 0.25 g/L	52.50	0.95	0.83
Glucose 0.50 g/L	47.50	0.99	0.76

3.3. Vermicompost fertility

The results of the fertility tests for the vermicompost obtained in the treatments are described in **Table 5**. The treatments NPK 3.50 % and with glucose addition displayed higher values of TOM, but the amount of organic matter is still below the recommended value. Phosphorus is an essential element for photosynthesis and respiration, besides acting in storing and transferring energy and plant growth [55]. All treatments showed values within the lower limit of this range (0.11 % and 0.12 %). The concentrations of calcium and magnesium are correlated since both form basic cations, which are widely used in the correction of soil pH [56, 57]. The values of TMg in the vermicompost were significant, with higher values obtained for the treatments enriched with glucose (1.61 % and 1.92 %), followed by the Control treatment (1.75 %) and the systems enriched with NPK (1.34 % and 1.05 %).

The concentration of macronutrients below the recommended limit showed that the formation of a fertile vermicompost, although feasible, lacks some of the attributes necessary for adequate plant nutrition. Other experiments conducted with the association of macrophytes and animal manure [25, 58, 59] showed much higher values than those obtained for the concentration of macronutrients. The addition of manure also has disadvantages due to the possibility of the

Table 5. Results of fertility evaluation (in %) parameters (total organic matter: TOM; organic carbon: OC; total nitrogen: TN; total phosphorus: TP; total potassium: TK; total calcium: TCa; total magnesium: TMg and total sulfur: TS) for vermicompost using *E. crassipes* biomass (Control treatment; NPK 1.75 %; NPK 3.50 %; Glucose 0.25 g/L and Glucose 0.50 g/L). A: recommended values according to Mendes [55] and B: recommended values according to Prezotti and Guarçoni [56].

	Control treatment	NPK 1.75%	NPK 3.50 %	Glucose 0.25 g/L	Glucose 0.50 g/L	A	B
TOM	0.95	1.88	3.11	3.30	5.16	5.00	-
OC	0.30	0.31	0.30	0.29	0.60	-	-
TN	0.17	0.14	0.19	0.24	0.24	-	-
TP	0.09	0.11	0.12	0.13	0.13	0.10 - 1.0	1.60
TK	0.16	0.17	0.19	0.19	0.27	1 - 3.50	1.50
TCa	0.30	0.32	0.36	0.36	0.36	0.60	0.50 - 3.00
TMg	1.75	1.34	1.05	1.61	1.92	6.00	0.15 - 1.00
TS	0.03	0.05	0.07	0.05	0.05	0.10 - 0.40	-

presence of fecal coliforms and pathogens, making further use as fertilizer not viable. The enrichment with both inorganic (NPK) and organic (glucose) compounds caused a slight increase in the quality of the vermicompost formed. The vermicompost, however, can work as an aggregator for the soil, promoting the increase of moisture and providing greater soil structuring, and in association with another fertilizer. The vermicompost enriched with glucose was superior in terms of biomass consumption efficiency, which was 51.5 % and 40.5 % higher than the average of the treatments with NPK. The addition of glucose has the benefits of being easy to obtain and low cost, being a viable alternative for improving production through a sustainable alternative for the use of surplus biomass and transformation into a fertilizer applicable in other local productions. We suggest that future studies test the application of this technique on a large scale.

4. Conclusion

Vermicomposting using macrophytes represents a sustainable alternative for using this biomass. The priming effect tested is appropriate as it increases a possible limitation of nutrient availability from fresh organic matter.

The addition of organic (glucose) and inorganic (NPK) compounds was adequate for this process, contributing to an increase in the efficiency consumption of biomass and a subtle improvement in the fertility of the vermicompost formed. The addition of glucose is low-cost, easily obtained, and applicable. Although the addition of glucose and NPK showed an increase in compost quality, in the tested concentrations, it does not meet the requirements for its use as a sole source of fertilizer. However, we suggest the use of vermicompost in association with other fertilizers, adding moisture and structuring to the soil.

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6. Conflict of interest

The authors declare no conflict of interest with the research presented.

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¿Puede el enriquecimiento con compuestos inorgánicos y orgánicos mejorar la calidad del vermicompost a partir malas hiervas acuáticas?

Resumen: En ambientes eutróficos, las malas hierbas acuáticas se reproducen rápidamente, cubriendo grandes porciones de los cuerpos de agua. Este crecimiento extensivo impide el uso múltiple de los recursos hídricos. El uso de la biomasa de estas plantas para el vermicompostaje representaría una alternativa sostenible para gestionar el exceso de biomasa generado por la eutrofización. Realizamos experimentos enriqueciendo biomasa de macrófitos durante el vermicompostaje con dos tipos de soluciones: una inorgánica que contenía 1,75% y 3,50% de NPK, y una orgánica que contenía 0,25 g/L y 0,50 g/L de glucosa, para evaluar si esta adición mejoraba la calidad del vermicompost. El consumo de biomasa macrófita por *Eisenia fetida* aumentó a medida que avanzaba el vermicompostaje, alcanzando su punto máximo al final del período experimental. Las condiciones del tratamiento control sin lombrices, se mantuvieron estables. La conductividad eléctrica tendió a aumentar para tres tratamientos: NPK 1,75%, Glucosa 0,25 g/L y Glucosa 0,50 g/L. El pH del vermicompostaje tendió a ser neutro en todos los tratamientos. Los tratamientos control y enriquecidos con una solución inorgánica mostraron una reducción en la biomasa de macrófitos y en el número de individuos de *E. fetida*. La adición de NPK y glucosa mejoraron ligeramente la calidad del vermicompost y el consumo de la biomasa. Sin embargo, el vermicompost obtenido no cumplió por sí solo con los requisitos para el uso como fertilizante. Por lo tanto, recomendamos combinar el vermicompost obtenido a partir de biomasa macrófita con otros fertilizantes para mejorar la humedad y la estructura del suelo.

Palabras Clave: *Eisenia fetida*; *Eichhornia crassipes*; eutrofización; glucosa; humificación; modelo matemático; nutrientes.

O Enriquecimento com Compostos Inorgânicos e Orgânicos Pode Melhorar a Qualidade do Vermicomposto de Plantas Daninhas Aquáticas?

Resumo: Em ambientes eutróficos, as plantas daninhas aquáticas se reproduzem rapidamente, ocupando extensas áreas do corpo hídrico. Esse crescimento extensivo impede o uso múltiplo dos recursos hídricos. A utilização da biomassa dessas plantas para vermicompostagem representaria uma alternativa sustentável para o manejo do excesso de biomassa gerado pela eutrofização. Foram conduzidos experimentos enriquecendo biomassa de macrófitas durante a vermicompostagem com dois tipos de soluções: uma inorgânica contendo 1,75% e 3,50% de NPK e uma orgânica contendo 0,25 g/L e 0,50 g/L de glicose, para avaliar se essa adição melhorava a qualidade do vermicomposto. O consumo de biomassa de macrófitas por *Eisenia fetida* aumentou à medida que a vermicompostagem evoluiu, atingindo os maiores valores ao final do período experimental. As condições do tratamento controle, sem vermes, mantiveram-se estáveis. A condutividade elétrica tendeu a aumentar para em tratamentos: NPK 1,75%, Glicose 0,25 g/L e Glicose 0,50 g/L. O pH da vermicompostagem tendeu a ser neutro em todos os tratamentos. Os tratamentos controle e os enriquecidos com solução inorgânica mostraram redução na biomassa de macrófitas e no número de indivíduos de *E. fetida*. A adição de NPK e glicose melhorou ligeiramente a qualidade do vermicomposto e o consumo de biomassa. No entanto, o vermicomposto obtido por si só não cumpriu os requisitos para utilização como fertilizante. Portanto, recomenda-se combinar o vermicomposto obtido da biomassa de macrófitas com outros fertilizantes para melhorar a umidade e a estrutura do solo.

Palavras-chave: *Eisenia fetida*; eutrofização; humificação; *Eichhornia crassipes*; modelagem matemática; glicose; nutrientes.

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