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REVIEW

Benefits of Vermicompost in Agriculture and Factors Affecting its Nutrient Content

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Abstract
Vermicompost is an organic amendment rich in nutrients, humic substances, growth regulators, hormones and beneficial microorganisms. Vermicompost is produced by the bio-oxidation of various organic wastes through the combined action of earthworms and microorganisms. Because of its components, vermicompost helps maintain soil health, improve plant development and reduce environmental pollution. Compared to other organic fertilizers, vermicompost provides higher levels of macronutrients and micronutrients. However, it has been reported that the nutrient content of vermicompost depends on the proper management of some factors involved in the vermicomposting process. The main limitation to the widespread use of vermicompost in agriculture has been its low nutrient content compared to inorganic fertilizers. Research has been conducted to improve the nutrient content of vermicompost during the vermicomposting process; however, the available information on optimizing the factors involved in increasing the nutrient content of vermicompost is limited and scattered. This review, in addition to highlighting the effect of vermicompost on soil quality and crop development, has examined and concentrated the current literature on the progress of research aimed at improving the nutrient content of vermicompost by optimizing the factors involved in the vermicomposting process. It is expected that the information provided will encourage and guide new research aimed at improving the nutrient content of vermicompost.

Keywords Nutrient content · Earhtworms · Microorganisms · Black gold

1 Introduction

In recent decades, agriculture has relied heavily on inorganic nutrients to fertilize crops and achieve higher yields (Gómez-Brandón et al. 2020a). Despite the intention to increase production and feed a growing population, the overuse of chemical fertilizers leads to the loss of soil fertility and water pollution, reducing agricultural productivity and food quality (Kifle et al. 2017; Savci 2012). Understanding the negative impacts of inorganic fertilizers has sparket interest in the use of organic nutrient sources (Mahmud et al. 2018).

Waste from agricultural activities is considered an important source of pollution and has not been widely used to produce organic fertilizers through composting and vermicomposting (Hernández et al. 2010). Composting and vermicomposting are the biological processes commonly used to convert organic wastes into organic fertilizers (Nurhidayati et al. 2017). Composting is a method of aerobic and thermophilic (45–65 °C) decomposition of organic matter (OM) into a stable, nutrient-rich amendment (Ahmad et al. 2021; Finore et al. 2023; Sanasam and Talukdar 2017; Singh et al. 2022). This process involves mineralization and partial humification of OM by microorganisms and their associated enzymes (Mahapatra et al. 2022; Waqas et al. 2023). However, composting has the disadvantages of being a long-term process (≥ 5 months), often requiring mixing, presenting nutrient losses during the prolonged composting process, and providing heterogeneous material (Alidadi and Shamansouri 2005; Munnoli et al. 2010; Papadimitriou and

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Balis 1996). On the other hand, vermicomposting is the non-thermophilic biodegradation of OM by the combined action of earthworms and microorganisms (Fig. 1) (Sharma and Garg 2023; Thakur et al. 2021), which converts the unstable OM into a stabilized form called vermicompost (Saranraj and Stella 2012). Vermicompost is a product rich in humic acids, vitamins, antibiotics, enzymes, plant growth-promoting substances, beneficial microbes and nutrients (Arancon et al. 2006; Adhikary 2012; Banerjee et al. 2019).

Unlike composting, vermicomposting has a shorter processing time (<2 months), higher nutrient content, and provides a homogeneous product (Nurhidayati et al. 2017; Ramos et al. 2022; Thirunavukkarasu et al. 2022). The vermicomposting process consists of an initial and a final phase (Domínguez et al. 2017). The initial phase is characterized by the activity of the earthworm in aerating and fragmenting the OM, increasing the surface available for the adequate activity of the microorganisms (Domínguez et al. 2017), while in the final or maturation phase, the microorganisms, through enzymatic digestion, continue the transformation of the organic compounds digested by the earthworm, causing the maturation of the vermicompost, while the earthworms move to new layers of fresh substrate (Gómez-Brandon et al. 2020b). In the first phase of vermicomposting, earthworms and microorganisms preferentially use easily assimilated molecules, while in the final phase, microorganisms convert complex molecules (Gómez-Brandón et al. 2019; Gómez-Brandon et al. 2020b). During the vermicomposting process, a moisture content between 65 and 75%, a pH range between 5.5 and 8.5, and a temperature between 12 and 28 °C in the substrate must be guaranteed to favor the activity of earthworms and microorganisms in the biodegradation of OM (Singh et al. 2022). It is also necessary to ensure adequate aeration in the substrate to be vermicomposted by selecting porous waste and, most importantly, controlling the amount and frequency of irrigation (Kaur 2020). In addition, a high salt content in the substrate should be avoided when vermicomposting (Kaur 2020). Many types of manure have a high salt content, so it is necessary to perform heavy washing prior to starting the vermicomposting process to leach out excess salts.

This organic fertilizer has demonstrated its ability to restore soil fertility, improve overall plant growth and, most importantly, reduce environmental pollution (Bellitürk and Soyturk 2020; Hassan et al. 2022; Soobhany 2019). Despite its versatility, one of the limitations of the extensive use of vermicompost in crop production is the variation in its nutrient content and its low nutrient contribution compared to inorganic fertilizers (Gómez-Brandón et al. 2020a; Jafari et al. 2021). Vermicompost mainly provides N, P, K, Ca, Mg, S, and micronutrients; however, it has been shown that its nutrient content depends on the factors involved in the production process (Singh et al. 2008; Theunissen et al. 2010).

Although there is a large amount of research in which the suitability of different residues for the production of vermicompost has been evaluated and the ability of vermicompost to improve the development and production of different crops has been assessed, limited works have reported information on the proper management of the factors that improve the nutritional content of the final vermicompost, in addition to the fact that the little information available is scattered. In this review work, in addition to highlighting the effect of vermicompost on the improvement of soil fertility and plant development, the available information on the reported advances related to the optimization of the

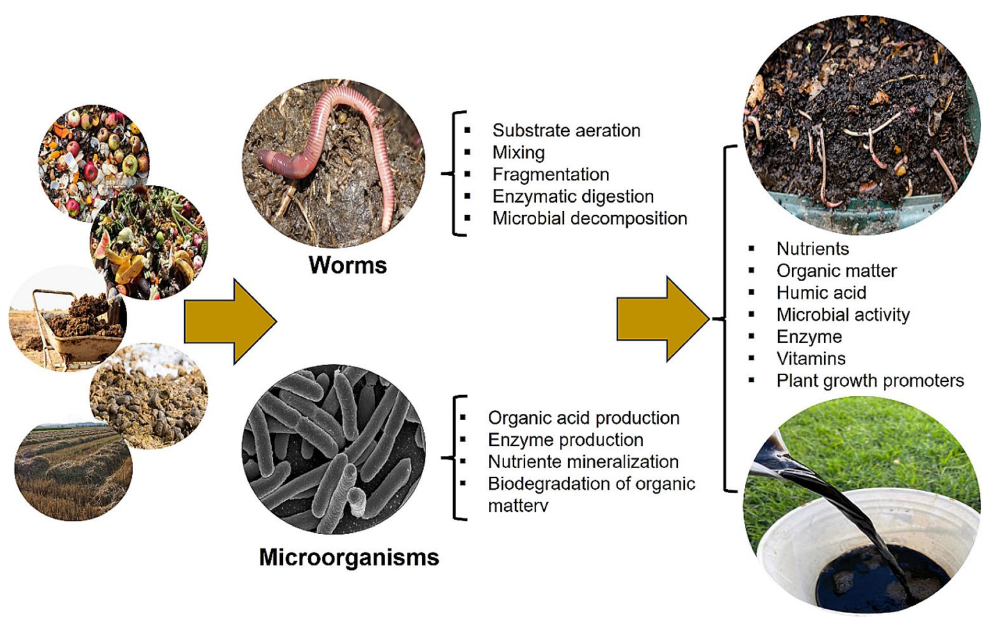

Fig. 1 Synergistic role of earthworms and microorganisms in the vermicomposting of organic waste

factors involved in improving the content has been concentrated nutritional value of vermicompost.

2 Agricultural Implications of Vermicomposting

2.1 Effects on the Soil

Vermicompost has demonstrated a high capacity to improve various physical, chemical and biological properties of soil. The physical properties of the soil that are modified by the addition of vermicompost inclide structure, porosity, water retention, bulk density, and resistance to soil erosion (Gómez-Brandón et al. 2020a; Parthasarathi et al. 2008; Piya et al. 2018) (Table 1). The increase in aeration, water retention and soil structure is naturally related to the stability of soil aggregates (Gómez-Brandón et al. 2020a). Therefore, the incorporation of vermicompost increases the stability of the aggregates due to the presence of humic substances and the polysaccharides present in the OM, which act as cementing agents between the soil particles (Demir 2019; Lim et al. 2015; Mupambwa and Wakindiki 2012). In addition, by improving soil aggregation, vermicompost can reduce soil erosion caused by water or air (Piya et al. 2018). Meanwhile, the reduction in soil bulk density is due to the increase in OM in the soil (Ahmad et al. 2022a; Uz et al. 2016), increase in aggregate formation and increase in soil porosity (Manivannan et al. 2009).

As a result of vermicompost incorporation, it is possible to increase the availability of nutrients in the soil (Bellitürk et al. 2022; Wang et al. 2023) (Table 2). The increase in soil nutrient content is due to: (1) the nutrient content of the vermicompost; (2) the activity of microorganisms responsible for fixation, mineralization and/or solubilization of nutrients present in the vermicompost which increase the availability of nutrients in the soil during mineralization of OM (Yatoo et al. 2020); (3) the high molecular weight acids present in the vermicompost components that help to solubilize some nutrients in the soil (Wang et al. 2023); and (4) the reduction of nutrient leaching due to the increase of the negative charges of the soil by the OH^- present in the vermicompost (Ernani et al. 2012).

Other chemical parameters that are improved by the addition of vermicompost are electrical conductivity, cation exchange capacity, and pH of the amended soil (Piya et al. 2018; Sinha et al. 2011) (Table 2). It has been reported that the incorporation of vermicompost into the soil, increases the electrical conductivity of the soil due to the high nutrient content (Bagheri et al. 2021; Demir 2019), with increasing values of electrical conductivity as the dose of vermicompost (Atiyeh et al. 2001). Similary, vermicompost increases the cation exchange capacity of the soil due to the high content of humic acids in the OM (Adhikary 2012; Aktaş and Yüksel 2020), thus keeping most of the cations in the exchange sites available for uptake by plants. Studies such as Wei et al. (2018) have shown that humic acids act as weak acid polyelectrolytes in compost retaining cations through cationic bonding.

On the other hand, soil pH controls plant nutrient availability and microbial activity (Demir 2019; Vuković et al. 2021). Demir (2019) and Manivannan et al. (2009) showed that vermicompost application causes a decrease in soil pH. The release of organic acids during microbial metabolism in vermicompost and/or increased permeability and leaching of salts may contribute to the decrease in pH of the amended soil (Manivannan et al. 2009; Vuković et al. 2021). On the contrary, vermicompost has also been shown to increase soil pH (Gopinath et al. 2008). The increase in pH of vermicomposted-treated soils was reported to be the result of an increase in the availability of nutrients in the soil (Gómez-Brandon et al. 2020a; Sinha et al. 2011). However, the direction of the change in soil pH as a result of vermicompost application depends on the initial pH, the application rate and the duration of vermicompost application, since the higher the value of these parameters, the greater the increase in soil pH value (Angelova et al. 2013; Manyuchi et al. 2013). Likewise, it has been pointed out that the effect of vermicompost on soil pH may vary depending on the initial pH of the soil (Zhang et al. 2020). For example, Fernández-Bayo et al. (2009) showed that the addition of vermicompost to acidic soils increased soil pH, whereas the addition of vermicompost to alkaline soils decreased soil pH.

The OM, nutrient content, growth promoters, and microbial communities present in vermicompost not only improve soil physicochemical properties, but also increase soil microbial diversity and activity (Gómez-Brandón et al. 2020a; Kaur 2020; Vuković et al. 2021; Yatoo et al. 2021) (Table 3). Indeed, in a two-year study, Koskey et al. (2023) showed that the addition of liquid vermicompost extract increased soil microbial diversity, including N-fixing, P-solubilizing, C-degrading bacteria, and arbuscular mycorrhizal fungi. Similary, Zhao et al. (2020) reported that by adding vermicompost to the soil they observed an increase in the population, activity and diversity of microorganisms, the abundance of which was attributed to the increase in OM and organic carbon in the soil. For their partWang et al. (2021a); Zhao et al. (2017) showed that the application of vermicompost increased the microbial population in the soil, attributing this effect to indirect changes in the soil environment and to the improvement of its chemical properties (pH, organic carbon, electrical conductivity, P, NH_4^+, and NO_3^-).

Table 1 Effect of vermicompost on soil physical properties

Application rate	Macroaggregates	Porosity	Apparent density	Water retention capacity	References
	(%)	(%)	(g cm^{-3})	(%)	
%					
0	-	44.29	1.33	30.83	(Nada et al. 2011)
3	-	44.34	1.31	32.70	
12.5	-	48.17	1.18	58.22	
25	-	52.59	1.04	72.60	
%					
0	-	50.4	1.32	-	(Aksakal et al. 2016)
0.5	-	52.7	1.26	-	
1	-	53.5	1.24	-	
2	-	55.2	1.19	-	
4	-	56.9	1.15	-	
t ha^{-1}					(Liu et al. 2019a)
0	39.23	-	-	-	
3.75	63.61	-	-	-	
%					(Usmani et al. 2019)
0		46.24	1.32	43.75	
3		47.66	1.34	45.78	
6		46.54	1.28	45.42	
9		46.28	0.96	47.76	
12		45.27	0.94	46.84	
15		44.89	0.89	48.32	
t ha^{-1}					
10	-	-	0.92	63.7	(Sahariah et al. 2020)
20	-	-	0.90	65.9	
30	-	-	0.92	63.4	
t ha^{-1}					
0	-	-	1.30	-	(Hafez et al. 2021)
10	-	-	1.25	-	
t ha^{-1}					
0	52.32	8.77	-	-	(Liu et al. 2020)
3.75	54.85	9.14	-	-	
t ha^{-1}					
0	-	-	1.14	-	(Pasha et al. 2020)
9.8	-	-	1.09	-	
t ha^{-1}					
0	-	52.8	1.25	-	(Emamu and Wakgari 2021)
10	-	56.5	1.15	-	
t ha^{-1}					
0	-	-	1.40	-	(Shen et al. 2022)
25	-	-	1.37	-	
50	-	-	1.34	-	
125	-	-	1.23	-	
250	-	-	1.00	-	

In addition to increasing the population of beneficial microorganisms in the soil, vermicompost application has been shown to suppress the growth of pathogenic fungi through volatile organic compounds produced by bacteria and actinomycetes present in the vermicompost and bioactive compounds present in the coelomic fluid, mucus and skin secretions of earthworms (Gudeta et al. 2022; Mu et al. 2017; Yatoo et al. 2021; Zhao et al. 2019). Liu et al. (2021) isolated 374 bacterial strains from fresh cow dung vermicompost, of which 28 strains showed antagonistic activity against *Fusarium oxysporum f. sp. cucumerinum*. Similary, Zhao et al. (2019) revealed that the bacteria of the genus *Nocardioides*, *Ilumatobacter* and *Gaiella*, present in vermicompost played an important role in inhibiting *Fusarium*

Table 2 Effect of vermicompost on soil chemical properties

Dose	pH	EC[α]	OM	OC[β]	N	P	K	References
%		dS m^{-1}	%		mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	(Abdeen 2020)
0	7.7	1.73	0.45	–	44.5	10.0	78.5	
1	7.4	1.78	0.55	-	58.5	11.8	83.6	
2	7.2	1.90	0.65	-	64.5	12.5	88.4	
t ha^{-1}		dS m^{-1}					meq L^{-1}	(Hafez et al. 2021)
0	8.0	3.70	-	-	-	-	0.40	
10	8.0	3.45	-	-	-	-	0.42	
t ha^{-1}		dS m^{-1}	g kg^{-1}		µg g^{-1}			(Liu et al. 2020)
0	8.2	5.54	16.9	-	129.2	-	-	
3.75	8.1	5.26	18.97	-	140.0	-	-	
t ha^{-1}					%	%	%	(Mahmud et al. 2020)
0	3.6	-	-	-	0.10	0.02	0.04	
10	4.9	-	-	-	0.18	0.04	0.05	
t ha^{-1}		dS m^{-1}		%	%			(Pasha et al. 2020)
0	6.2	0.43	-	1.22	0.18	-	-	
9.8	6.7	0.56	-	1.71	0.25	-	-	
%					%	%	%	(Adiloglu et al. 2021)
0	-	-	-	-	0.13	0.25	1.14	
8	-	-	-	-	0.27	1.13	4.29	
t ha^{-1}				%	%	mg kg^{-1}		(Baghbani-Arani et al. 2021)
0	-	-	-	0.64	0.065	15.33	-	
2.7	-	-	-	0.82	0.084	19.70	-	
t ha^{-1}				%	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	(Salma and Hossain 2021)
0	5.7	-	-	0.89	60	38.3	409.8	
5	5.6	-	-	1.14	100	61.8	412.5	
%		dS m^{-1}			%	mg kg^{-1}	mg kg^{-1}	(Przemieniecki et al. 2021)
0	6.8	2.08	-	-	0.21	92.2	142	
10	7.0	2.42	-	-	0.15	358	1199	
20	0.7	2.66			0.19	521	1912	
t ha^{-1}		dS m^{-1}	mg g^{-1}		g kg^{-1}	mg kg^{-1}	mg kg^{-1}	(Benaffari et al. 2022)
0	8.2	0.71	196.1		0.9	29.2	5983	
5	7.9	0.87	234.3		1.4	135.9	5835	
10	8.2	0.69	259.8		1.9	91.0	5428	
t ha^{-1}		dS m^{-1}			g kg^{-1}	g kg^{-1}		(Shen et al. 2022)
0	8.6	6,92	-	-	0.305	0.521	-	
25	8.6	6,42	-	-	0.470	0.652	-	
50	8.4	5,62	-	-	0.768	0.874	-	
125	8.1	4,94	-	-	1.100	0.792	-	
250	7,8	3,96	-	-	1.530	0.879	-	

[α]EC = electrical conductivity; [β]OC = organic carbon

oxysporum f. sp. Lycopersici in the soil by acting as antagonistic microorganisms. Przemieniecki et al. (2021) showed that the addition of vermicompost to the soil reduced the presence of pathogens such as *Fusarium spp.* and *Penicillium spp.* and increased *Bacillus* spp., Clostridium *spp.* and Actinomycetes. These authors attributed the reduction in soil to the increase in *Bacillus* spp. because of this bacterium's ability to produce antifungal metabolites.

2.2 Effects on Plants

The use of vermicompost as an alternative to synthetic fertilizers stimulates plant production. The effects of vermicompost and its derivatives on plant growth and yield have been reported in several studies, such as the one carried out by Esmaielpour et al. (2020), who reported that by replacing the base medium with 20% vermicompost, greater plant height, leaf area, stem dry weight, root dry weight and fruit yield of cucumber plants were obtained, exceeding the control by 15.0, 23.5, 53.5, 53.4 and 64.3%, respectively. For their part, Feizabadi et al. (2021), by adding 5 t ha^{-1} of vermicompost

Table 3 Effect of vermicompost on soil biological properties

Microorganisms	Vermicompost dose						References
CFU g^{-1}	**0 t ha^{-1}**	**2.5 t ha^{-1}**					(Mahanta et al. 2012)
Bacterial population (x10^6)	5.3	16.6					
Fungal population (x10^5)	4.3	9.0					
CFU g^{-1}	**0%**	**3%**	**6%**	**9%**	**12%**	**15%**	(Usmani et al. 2019)
Phosphate solubilizing bacteria (x10^4*)*	14	74	85	97	106	116	
*Azotobacter (*x10^3)	10	65	73	84	92	101	
*Potash mobilizing bacteria (*x10^2)	7	15	19	21	23	31	
CFU g^{-1}	**0%**	**1.3%**					(Zhao et al. 2020)
Bacteria (x10^6)	2.98	6.88					
Fungi (x10^3)	5.70	6.34					
Actinomycetes (x10^5)	1.78	3.38					
CFU g^{-1}	**0 t ha^{-1}**	**10 t ha^{-1}**	**20 t ha^{-1}**				(Przemieniecki et al. 2021)
Total bacteria (x10^7)	8.61	14.20	37.93				
Total fungi (x10^4)	0.61	1.56	4.42				
Penicillium spp. (x10^3)	3.96	5.31	0.10				
Fusarium spp.	12.0	0.00	2.00				
Pseudomonadaceae (x10^6)	2.03	3.50	3.01				
Bacillus spp. (x10^6)	0.003	2.86	10.40				
Clostridium spp. (x10^5)	1.05	9.11	7.38				
Actinomycetes (x10^6)	4.67	14.8	8.53				
lg copies g^{-1}	**0%**	**3%**	**5%**				(Wu et al. 2023)
Proteobacteria	56.63	50.34	46.43				
Acidobacteria	10.11	14.72	12.99				
Actinobacteria	8.21	10.71	7.74				
Ascomycota	47.58	70.98	62.70				
Anthophyta	41.43	14.72	29.28				
Mortierellomycota	0.32	0.68	3.10				

to the soil, obtained an increase in plant height, biomass and grain yield of rapeseed, exceeding the control by 5.5, 8.1 and 7.8%, respectively. The results obtained by Ahmadpour and Armand (2020) showed that by adding 30% vermicompost to the growth medium, they achieved an increase in leaf area, number of leaves and root dry weight of tomato plants, exceeding by 14.0, 22.7 and 21.0% compared to the control. Esringü et al. (2022) showed that an application of 60% vermicompost in the growth medium is an effective growth medium for the production of ornamental plants (*Vinca rosea valiant rosea*, *P. patio rose*, and *P. peltatum*), since they achieved an improvement in the number of flowers, plant height, stem diameter, and fresh flower weight, exceeding the control by 264, 71, 58, and 255% for *Vinca rosea valiant rosea*, 138, 12, 160, and 55% for *P. patio rose*, and 50, 14, 23, and 61% for *P. peltatum*, respectively.

The improvement in plant development with the addition of vermicompost has been attributed, in part, to its potential to retain water and its physicochemical properties, which correct soil fertility and consequently improve plant development (Gómez-Brandón et al. 2020a; Houshmandfar et al. 2019; Joshi et al. 2015). Likewise, it has been reported that humic acids and plant growth hormones (cytokinins, auxins and gibberellins) present in vermicompost are responsible for increasing the growth of plants treated with this amendment (Ahmad et al. 2022a; Arancon et al. 2020). The effect of humic acid on the positive responses of plants begins with the association of the humic fraction with the membrane of the root cells, which induces a positive stress effect and causes the regulation of the hormonal signaling pathways, followed by an improvement in the metabolism of plants (Mora et al. 2010; Van Tol de Castro et al. 2021). In this regard, Van Tol de Castro et al. (2021) reported that the addition of humic acids extracted from vermicompost to rice plants resulted in changes in the performance of the photochemical step of photosynthesis and in soluble nitrogen and carbon metabolites. These changes stimulated the growth and development of the plants. It has also been suggested that the positive effects of humic acids on plant growth are due to the fact that they stimulate the supply of nutrients to the plant through changes in the activity of enzymes, such as nitrate reductase, glutamine synthetase and H^+-ATPase (Mora et al. 2010; Zanin et al. 2018, 2019).

Regarding the growth hormones present in vermicompost, Aremu et al. (2015), when analyzing vermicompost leachate, found the presence of cytokinins, indole-3-acetic acid, gibberellins and brassinosteroids, suggested that these substances may be responsible for favorable physiological responses of plants after vermicompost application. For their part, Rekha et al. (2018), when comparing the effect of vermicompost application to soil (50%) and foliar application of synthetic plant growth regulators (100 μg ml^{-1} of auxin or gibberellin) on the growth of sweet pepper plants, reported that plants treated with vermicompost showed better growth (shoot length, internode length, number of leaves, and number of branches) than plants treated with gibberellin and synthetic auxin. Likewise, Arancon et al. (2020) evaluated the development of cuttings of sugarcane, mint and begonia cuttings treated with vermicompost tea and a commercial rooting hormone, which showed that the rooting of the cuttings obtained with the addition of vermicompost behaved in a similar way to that of the commercial hormone. The increase in root development of the cuttings was attributed to the presence of auxin, cytokinin, gibberellin and humic acid in vermicompost tea.

Vermicompost also improves plant growth by increasing plant tolerance to certain types of biotic and abiotic stresses (Kiran 2019; Vuković et al. 2021). Several studies have shown that vermicompost helps to prevent diseases caused by pathogens (Amooaghaie and Golmohammadi 2017; Domínguez et al. 2019; Öztürkci and Akköprü 2021; Szczech et al. 2002), reduce pest populations (Jangra and Gulati 2019; Liu et al. 2019b; Mondal et al. 2021), and alleviate stress caused by salinity and drought (Abdel-Magied et al. 2023; Benazzouk et al. 2020; Beyk-Khormizi et al. 2023; El-Dakak et al. 2021). The mechanisms by which vermicompost and its derivatives suppress pests and diseases are diverse. Among the most important mechanisms are (1) the release of phenolic compounds such as anthocyanins and flavonoids, which are repellent compounds and deterrents to pests and diseases (Rehman et al. 2023; Theunissen et al. 2010); (2) increasing the availability of nutrients in the growth medium, thereby improving the nutritional status and resistance of plants (Arancon et al. 2007); (3) improvement of the physical properties of the soil, promoted by the humic substances, which reduces soil-borne diseases (Adhikary 2012); (4) increase in the population of predatory nematodes in the amended soil, which negatively affects the pest population by directly attacking it (Rehman et al. 2023); (5) release of coelomic fluid by earthworms, which contains bioactive molecules (lumbricin PG, bioactive amino acid residues, and lysenin) that negatively affect the physiological functions of pests and combat pathogens (Gudeta et al. 2022; Rehman et al. 2023); and (6) improvement of the microbial population in the growth medium, which reduces the availability of nutrients, space, and energy for pathogens (Mazzola and Freilich 2017; Rehman et al. 2023).

While the positive response of plants to salt stress treated with vermicompost has been attributed to the increase in the activity of antioxidant enzymes (SOD, CAT, and APX), which play an important role in eliminating the concentrations of reactive oxygen species, increasing the stability of membranes, reducing the penetration of Na ions, and reducing the leakage of electrolytes (El-Dakak et al. 2021; Juleel et al. 2023). The increase in the synthesis of antioxidant enzymes in plants treated with vermicompost under stress is favored by the contribution of microelements (Fe, Cu, Mn, and Zn) by the vermicompost, which act as prosthetic groups and serve for the synthesis of these enzymes (Hosseinzadeh et al. 2018). El-Dakak et al. (2021) have indicated that vermicompost improves the salt tolerance of plants because this organic amendment increases the expression of the SOS1 signaling gene, which acts in the export of Na from the cytoplasm to the external environment when this ion is present in high concentrations, inducing a lower Na content along with a higher K content in the plant. For their part, Ahmadi and Akbari (2021) indicated that the preventive mechanism of plants treated with vermicompost under salt stress conditions is the activation of osmotic adjustment through the production of proline and the accumulation of K in the leaves and a higher concentration of sugars in the root to allow water absorption by the plant and thus maintain its growth.

As a mechanism of action of vermicompost that allows plants to tolerate stress caused by drought, it has been reported that vermicompost increases the activity of enzymes SOD, POD, and CAT, which reduce the level of reactive oxygen species in the cell, thus increasing the stability of membranes and reducing lipid peroxidation of the biological structure of the cell membrane (Ahmad et al. 2022b; Kiran 2019). In other works, it has been pointed out that the improvement of water potential, balanced absorption of nutrients, leaf area of plants, and the decrease of chlorophyll photooxidation activity in plants treated with vermicompost through the positive regulation of antioxidant system causes the increase of soluble sugars and proline in plants, which is a mechanism to tolerate drought stress because they help osmotic regulation (Ghaffari et al. 2022; Hosseinzadeh et al. 2017).

In addition, there is evidence that the supply of vermicompost to soils or growth substrates leads to an improvement in the yield and quality of fruits of various crops such as eggplant (Ebrahimi et al. 2021), jalapeño pepper (Espinosa et al. 2020), tomato (Boyacı et al. 2024), pepper (Alam et al. 2023), and beans (Mahmoud and Gad 2020), among others of commercial interest. In addition to the mechanisms of action of vermicompost that improve plant growth, the effect of which is reflected in crop yield, some researchers have suggested that the increase in fruit yield can be attributed to the hormone gibberellin present in vermicompost (Kist Steffen et al. 2019; Kilic et al. 2023). The influence of gibberellin on fruit growth occurs mainly in the first phase of fruit development (Kilic et al. 2023). In this phase, gibberellin facilitates the transition from cell division to cell enlargement and also facilitates the mobilization, transport, and accumulation of nutrients within the fruit (Kist Steffen et al. 2019). For their part, Ghimire et al. (2023) indicate that the better development of plants treated with vermicompost is the result of better root development, which leads to better absorption of water and nutrients in the pre-fruiting stage and greater availability of nitrogen during the fruiting stage. These factors contribute to accelerated plant growth, earlier onset of flowering and fruiting, and improved crop yield (Sahu et al. 2020).

2.3 Adverse Effects of Vermicompost on Plants

Although vermicompost has been shown to significantly improve plant growth when used as a component of horticultural soils or growing media, the proper concentration of vermicompost to be added for optimal plant growth and production should be considered, as applying vermicompost at high concentrations may inhibit plant growth (Lim et al. 2015; Piya et al. 2018). Seed germination and the early stages of seedling growth are more sensitive to the negative effects of vermicompost, but this detrimental effect may decrease over time (Ievinsh 2020). Furthermore, it has been shown that the reduction in plant growth is linear to the increase in the addition of vermicompost as reported by Esmaielpour et al. (2020) who replaced the base medium with 0, 10, 20, 30, 40, 50 and 60% by volume of vermicompost and observed plant height, leaf area, stem dry weight and yield of cucumber plants it was reduced when more than 30% vermicompost was applied to the growth medium. Yuvaraj et al. (2018b) evaluated the development of *T. foenum graecum* plants in different concentrations of vermicompost (25, 50, 75, and 100%) and reported that plant height, leaf area, leaf number, root length, shoot, root dry weight, and total plant dry weight were reduced when a high dose (100%) of vermicompost was added to the growth medium. In the study conducted by Amooaghaie and Golmohammadi (2017), they reported that adding 75% vermicompost to the growth medium negatively affected the growth of roots and shoots of *Thymus vulgaris* plants, which was associated with lower chlorophyll content and carotenoids in the plants.

It has been suggested that the reduction in plant growth when vermicompost is used as a growing medium is due to the reduction in pore space of the growing medium, especially when the concentration of vermicompost in the potting medium approaches 100% (Atiyeh et al. 2001). Similarly, it has been pointed out that the negative effect of vermicompost on plant growth is due to toxicity caused by phenolic compounds, mainly when immature vermicompost is used, high concentration of soluble salts (Na, Cl, and SO_4^{2-}), and high EC (Amooaghaie and Golmohammadi 2017; Erşahin et al. 2017; Lim et al. 2015). The above conditions lead to osmotic and oxidative effects, resulting in cell death, root destruction, and inhibition of plant growth (Wang et al. 2021b).

Despite all the above, it is evident that vermicompost continues to have a beneficial role for plants, depending on the amount added to the soil. However, as reported by Ievinsh (2020), the negative response of plants to vermicompost application depends on the sensitivity, diversity of nutrient availability and variability of vermicompost characteristics. While, Lazcano et al. (2011) reported that the effect of vermicompost on plants will depend on the species and genotype of the plant and the dose used. Therefore, when using vermicompost as an organic fertilizer or as a substrate component, it is necessary to ensure the appropriate level of vermicompost for each plant species to obtain an adequate crop (Lim et al. 2015).

3 Nutrient Content of Vermicompost

Vermicompost is the best option for farmers to replace chemical fertilizers because it contains high levels of essential nutrients necessary for proper plant development compared to other organic fertilizers (Gómez-Brandón et al. 2020a). The main nutrients present in vermicompost are C, H, O, N, P, K, Ca, Mg, S and micronutrients (Na, Fe, Mn, Zn, Cu and B) (Adhikary 2012; Singh et al. 2008, 2020b; Theunissen et al. 2010). The nutrients in vermicompost are in a form that is readily available to plants (Gómez-Brandón et al. 2020a). In addition, vermicompost contains nutrients for a longer period of time compared to inorganic fertilizers, which generally deliver a large amount of nutrients to the soil in a relatively short period of time, resulting in environmental pollution (Hoque et al. 2022). According to Adhikary (2012), vermicompost contains an average of 1.5–2.2% N, 1.8–2.2% P, and 1.0–1.5% K. On the other hand, Singh et al. (2020b) reported that vermicompost contains between 2 and 3% N, 1.55–2.25% P and 1.85–2.25% K. Similary, Kale (1995) states that vermicompost contains on average of 05-1.5% N, 0.1–0.30% P, 0.15–0.56% K, 0.06–0.30% Na, 22.67–47.60 meq 100 g^{-1} Ca and Mg, 128–548 mg kg^{-1} S, 2-9.50 mg kg $^{-1}$ of Cu, 2-9.30 mg kg^{-1} of Fe and 5.70–11.50 mg kg^{-1} of Zn.

The increase in the N content in the substrate during vermicomposting is the result of the degradation of protein-containing OM and the conversion of the released N (NH_4^+, NO_2^-, NH_3) to NO_3^- by microorganisms and enzymes (Garg and Gupta 2011; Gusain and Suthar 2020; Kumar et al. 2017); the activity of N_{2-} fixing bacteria in the intestinal microflora of the earthworm; the excretion of mucus, body fluids, growth-stimulating hormones, and enzymes by earthworms (Soobhany 2019); and the decomposition of N- rich dead worm tissues (containing 60–70% protein) (Gusain and Suthar 2020; Mahanta and Jha 2009). While the increase in P content in the substrate during the vermicomposting process is due to the mineralization of OM by earthworms and microorganisms, the action of organic acids released by P-solubilizing microorganisms, and to the action of phosphatase enzymes and phytase (Deepthi et al. 2021; Singh et al. 2020a). The increase in K content in the substrate during the vermicomposting is caused by the physical decomposition of the OM of the waste by biological grinding during its passage through the intestine of the earthworms and the production of acids (carbonic acid and sulfuric acid) that promote the dissolution of insoluble K (Das et al. 2016; Kaviraj and Sharma 2003). Similary, it has been suggested that the increase in the Ca content during vermicomposting is due to enzymatic solubilization in the worm gut and the release of $CaCO_3$ by the worm calcareous glands (Domínguez 2004; Gusain and Suthar 2020), while the subsequent release of the Ca after vermicomposting is carried out by fungi and actinomycetes that invade the worm excreta (Domínguez 2004; Pramanik and Chung 2011). While the degradation of OM, the mineralization and volume the reduction of the matter by the bacteria and fungi in the gut of the worm result in a higher content of micronutrients in the vermicompost (Kızılkaya 2004).

4 Factors Affecting the Nutrient Content of Vermicompost

The main limitation for its commercial adoption is the wide variation in the quality of vermicompost, which may depend mainly on the characteristics and proportions of the organic substrates used, the species and density of the earthworms, the maturity of the vermicompost, the microbial population involved, and the interaction between these factors (Durán and Henríquez 2007; Gómez-Brandón et al. 2020a; Kumar et al. 2011; Soobhany 2019; Sarker and Kashem 2021).

4.1 Types and Proportions of Vermicompostable Wastes

Plant, animal, urban and industrial wastes, although heterogeneous in nature, their biodegradable nature provides an opportunity for their transformation into organic fertilizers rich in nutrients and beneficial to the environment through vermicomposting (Sharma and Garg 2023). Earthworms and microorganisms are responsible for the biodegradation of wastes during vermicomposting; however, earthworms have shown a preference for consuming wastes rich in mineral nutrients (Chang and Chen 2010; Manna et al. 2003). Likewise, it has been reported that the development of the microbial community in vermicomposting also depends on the organic waste used, whose behavior is related to changes in the quantity and quality of nutrient supply during the course of the vermicomposting process (Gómez-Brandón et al. 2020a). Therefore, the selection of wastes and the proportion in which they are used is an important step in vermicomposting, since the type of waste or mixture of wastes affects the activity of earthworms, microorganisms and, consequently, the nutrient content in vermicompost (Tables 4 and 5) (Gómez-Brandón et al. 2020a; Vuković et al. 2021; Wei et al. 2012).

In addition to considering the initial nutrient content of the organic waste for adequate activity of earthworms and microorganisms, it is necessary to consider the nutrient content of the waste to be vermicomposted, since the nutritional value of the produced vermicompost depends largely on the initial value of content of the waste used (A'ali et al. 2017; Gusain and Suthar 2020). In this regard, Askari et al. (2020) when evaluating wastes of plant and animal origin, indicated that the nutrient content in the vermicompost improved when wastes with higher N content were incorporated, i.e., animal origin wastes, due to the higher protein content of animal tissues compared to plant tissues. Likewise, Mahanta and Jha (2009) reported that the nutrient content in vermicompost prepared from different wastes (rice straw, *Ipomoea carnea*, *Eichhornia crassipes*) increased significantly compared to the initial level in the respective waste, since initially *Ipomoea carnea* presented the highest content of N, P and K, followed by *Eichhornia crassipes* and rice straw, observing the same behavior in the nutrient content at the end of vermicomposting.

Another characteristic to consider when selecting the waste, combination, or ratio for vermicomposting is the C/N and C/P ratio, as the adequate degradation and mineralization of nutrients present in organic waste is correlated with the C/N and C/P ratio of the waste (Li et al. 2019). This is because C, N, and P are the main elements required for protein formation, energy production, and microbial growth (Mupambwa and Mnkeni 2018). Some researchers have indicated that organic wastes with high initial C/N (>20) and C/P (≥ 200) ratios result in net N and P immobilization, while amendments with low initial C/N (<20) and C/P (≤ 200) ratios result in mineralization of these nutrients (Alamgir et al. 2012; Truong and Marschner 2018). In the work of Shrimal and Khwairakpam (2010), they evaluated the best C/N ratio (16.4, 20.39, 31.85 and 40.18) for vermicomposting of vegetable waste mixed with cow dung and sawdust for 42 days. They concluded that the C/N ratio of 30:1 was the best ratio for vermicomposting based on the quality of vermicompost finally obtained.

Table 4 Effect of the type of organic waste vermicompost on the nutritional quality of the final product

Vermicompost waste	Relation	Observation	Reference
Lantana camara: CM[§]	2:1	*Lantana camara*: CM had a higher N content (2.53%). The P content was higher in the mushroom culture residues: CM (1.46%). While the K content was highest in *Ageratum conyzoides*: CM (3.29%).	(Bajal et al. 2019)
Ageratum conyzoides: CM			
Banana pseudostem: CM			
Garden waste: CM			
Vegetable wastes: CM			
Mushroom culture residue: CM			
CM	-	Mixed paper mill sludge: CM: *Tephrosia purpurea* presented a higher content of N (31.26 g kg^{-1}) and P (23.15 g kg^{-1}), while the highest K content (27.48 g kg^{-1}) was obtained by vermicomposting paper mill sludge: CM: *Gliricidia sepium.*	(Karmegam et al. 2019)
Paper factory sludge: CM	1:1		
Paper factory sludge: *Tephrosia purpurea*: *Gliricidia sepium*	2:1:1		
CM: *Tephrosia purpurea*: *Gliricidia sepium*	2:1:1		
Paper factory sludge: CM: *Tephrosia purpurea*	2:1:1		
Paper factory sludge: CM: *Gliricidia sepium*	2:1:1		
Bean residue: CM	1:2.5	The highest content of N (4.26%) and available P (1227.62 mg kg^{-1}) was obtained by vermicomposting grass residues, while the highest content of available K (7327.7 mg kg^{-1}) and Fe (54.24 mg kg^{-1}) was obtained by vermicomposting teff residues. The Mn content was higher when bean residues were used and the Cu (6.67 mg kg^{-1}) and Zn (58.72 mg kg^{-1}) contents were higher when sorghum residues were vermicomposted.	(Geremu et al. 2020)
Grass residue: CM			
Teff residue: CM			
Corn residue: CM			
Sorghum residue: CM			
Mixture of all residues: CM			
Potato crop residue	-	The highest content of N, P, K, Ca, and Mg was observed in the potato crop residue substrate: EV (18.2 g kg^{-1}, 8402.4 mg kg^{-1}, 278.9 mg kg^{-1}, 8.27 mg kg^{-1} and 998.6 mg kg^{-1}, respectively).	(Das and Deka 2021)
Potato crop residue: CM	5:1		
Aquatic plants: CM	1:1	The highest contents of N (2.87%), P (0.86%) and K (3.74%) were obtained by vermicomposting the mixture of aquatic plants: CM: kitchen waste.	(Yatoo et al. 2022)
Aquatic plants: CM: Kitchen waste	1:1:2		

[§]CM = cow manure

4.2 Earthworm Species and Density

Earthworms perform the function of aeration, mixing, fragmentation, and enzymatic digestion of the substrate during vermicomposting, which improves the population and activity of OM-degrading microorganisms (Domínguez et al. 2019; Lazcano et al. 2008; Maji et al. 2017). For the degradation of organic and inorganic debris in soils, three groups of earthworms have been used, including epigeal, anecic, and endogeal (Ratnasari et al. 2023). However, epigeal earthworms are considered the most suitable for vermicomposting due to their high feeding rate, high reproductive rate, short life cycle, and high tolerance to different environmental conditions (Bhat et al. 2017; Gajalakshmi and Abbasi 2004). Among the epigeal earthworms, the species *Eisenia fetida*, *Eisenia andrei*, *Perionyx excavates*, and *Eudrilus eugeniae* have been extensively used in vermicomposting (Dominguez and Edwards 2010; Vuković et al. 2021).

The species and population density of earthworms used in the vermicomposting process determine the final quality of the vermicompost (Mupambwa and Mnkeni 2016; Unuofin and Mnkeni 2014). This effect has been reported in the work of Kumar et al. (2021) who by vermicomposting groundnut shells mixed with cow dung (1:1) under the action of two species of epigeal earthworms (*Eisenia fetida* and *Perionyx sansibaricus*) observed that *Eisenia fetida* presented better decomposition of agricultural residues and production of vermicompost rich in N, P and K. Likewise, Pattnaik and Reddy (2009), when evaluating three species of epigeal earthworms (*Eudrilus eugeniae*, *Eisenia fetida*, and *Perionyx excavates*) in vermicomposting of urban green waste (vegetable and floral waste), reported that the vermicompost where *Eudrilus eugeniae* was used had higher concentrations of nutrients (N, P, K, Ca, and Mg) followed by *Eisenia fetida* and *P. excavates*. For their part, Usmani et al. (2017), when evaluating the vermicomposting of fly ash amended with cow dung under the action of three epigean species (*Eisenia fetida*, *Eudrilus eugeniae*, and *Lumbricus rubellus*), reported that the maximum content of N, P, and K was observed with *Eudrilus eugeniae*.

Table 5 Effect of the ratio of different organic residues used on the nutritional quality of vermicompost

Vermicompost substrate	Relation	Observation	Reference
Paper factory sludge: CM[§]	1:1 1:2 2:1	The highest N (5.97 g kg^{-1}), P (11 g kg^{-1}) and K (2.99 g kg^{-1}) contents were obtained at the 1:1 ratio.	(Yuvaraj et al. 2018a)
Walnut shell: CM	9:1 3:1 1:1 1:3 1:9	The highest contents of N (1.75%), P (0.38%), K (1.12%), Ca (1.7%) and Mg (0.38%) were obtained in the 1:9 ratio.	(Bellitürk and Soyturk 2020)
Urban green waste: sugar-cane bagasse	1:3 1:1 3:1 1:0	The contents of N (0.73 g kg^{-1}), P (0.60 g kg^{-1}) and K (1.8 g kg^{-1}) tended to be higher in the 1:0 ratio.	(Cai et al. 2020)
Household waste: CM	3.5:6.5 1:1 6.5:3.5	The vermicompost obtained from the 1:1 ratio registered the highest amount of N (2.40%), P (1.34%) and K (1.79%).	(Chiranjeeb and Prasad 2020)
Ageratum conyzoides: CM	1:3 1:1 3:1	Total N (34.87 g kg^{-1}) was higher in the 3:1 ratio, while available P (20.49 g kg^{-1}) was higher in the 1:1 ratio and total K (105.69 g kg^{-1}) was higher in the 1:3 ratio.	(Gusain and Suthar 2020)
Buffalo manure: lawn waste: kitchen waste	2:1:2 6:1:3 3:1:6 1:0:1	The highest N content (1.89%) was observed in the 2:1:2 ratio, while the highest content of K (1.06%), P (0.44%) and Ca (0.99%) was observed in the 6:1:3 ratio.	(Karwal and Kaushik 2021)
Biochar (0, 2, 4, and 6%) + banana leaf waste: CM	1:1 2:1 3:1	The highest contents of N (1.82%), P (1.18%) and K (1.67%) were observed in the vermicompost obtained from the 1:1 ratio (with 4% biochar).	(Kumar et al. 2023)

[§]CM = cow manure

The optimal population density of earthworms for organic waste vermicomposting depends on the worm species which are widely used (Malińska et al. 2017). In this regards, Unuofin and Mnkeni (2014) evaluated the vermicomposting of a mixture of organic waste (cow dung and waste paper amended with 2% phosphorus as phosphate rock) with different population densities of *Eisenia fetida* (0, 7.5, 12.5, 17.5, and 22.5 g of earthworms per kg of waste), where they observed that a population density of 12.5 g of earthworms resulted in better P mineralization. Similary, Mupambwa and Mnkeni (2016) evaluated the vermicomposting of a mixture of waste paper and dung (CD) with incorporation of fly ash (FA) in a PC: FA ratio of 2:1 under different population densities of *Eisenia fetida* (0, 12.5, 25, and 37.5 g of earthworms per kg of waste). The nutrient mineralization was better at higher worm population densities (25 to 37.5 g of earthworms per kg of waste).

4.3 Aging of Vermicompost

Vermicomposting time plays an important role in modifying the physical, chemical, and biological properties of organic wastes and thus stabilizing vermicompost for use as organic fertilizer (Ramos et al. 2022). Maturity is one of the most important criteria commonly used to evaluate the quality of vermicompost (Tippawan et al. 2022). C/N ratio, NO_3^-/NH_4^+ ratio, and humification index are reliable indicators to provide information on the maturity and stability of the composted material (Lim et al. 2015; Wang et al. 2021b); however, C/N ratio is the criterion traditionally used to evaluate the decomposition and maturity of vermicompost (Wang et al. 2021b).

Mature vermicompost tends to be characterized by a low C/N ratio, which is associated whit a higher rate of organic waste decomposition and higher nutrient content (Das et al. 2016; Wang et al. 2021b). According to Lim et al. (2015); Wang et al. (2021b), a ratio below 20 reflects an advanced level of OM stabilization and an acceptable level of maturity of the vermicomposted material. The decrease in the C/N ratio of the vermicomposted substrate is due to the increase in mineralized N, the loss of C in the form of CO_2 caused by the respiration of earthworms and microorganisms during the degradation and conversion of the initial feed mixtures, the use of organic C as an energy source for microorganisms or earthworms, and the conversion of part of the organic fraction of the substrates to earthworm biomass (Ajibade et al. 2020; Li et al. 2020; Wang et al. 2021b).

Vermicompost is usually harvested after a production period of only 40 to 60 days (Che et al. 2020; Rini et al. 2020), without considering the final C/N ratio. In a study conducted by Sharma and Garg (2019), when evaluating the vermicomposting of different proportions of lignocellulosic waste: cattle manure in different proportions (10:90, 20:80, 30:70, 40:60 and 50:50) for 105 days, they found that the 10:90 ratio reached maturity 60 days after vermicomposting (C/N ratio around 20) and at the end of vermicomposting it presented the lowest C/N ratio (12.26) than the rest of the treatments, while the other ratios reached maturity after 75 days of vermicomposting. In addition, the authors indicated that the 10:90 ratio presented the highest content of N, P and K. Likewise, Ramos et al. (2022) reported that in the vermicomposting bovine of cattle manure, due to the high activity of earthworms and microorganisms at the beginning of the process, it was, it was possible to use the vermicompost as an organic fertilizer after 30 days of vermicomposting; however, they observed that the highest earthworms population, the lowest C/N ratio, and the most pronounced increase in P, K, Ca, Mg, Cu, and Zn occurred between 45 and 120 days, with a higher nutrient value after 120 days of vermicomposting. Biruntha et al. (2020) when vermicomposting algae, sugarcane, coconut and vegetable residues for 50 days, observed that the vermicompost obtained a lower C/N ratio (11.03 for algae residues and 19.12 for sugarcane residues) at the end of the process presented higher content of N, P and K, comparated to the waste that obtained a higher C/N ratio (27.12 for coconut residues and 28.05 for vegetable residues). Therefore, the vermicomposting time and the C/N ratio in which the best nutrient content will be presented depend on the vermicomposted waste.

4.4 Microbial Activity

Earthworms are key players in the vermicomposting process; however, microorganisms perform the actual biochemical decomposition of OM (Vuković et al. 2021). The microorganisms present in the worm gut and vermicompost produce enzymes and organic acids that are responsible for accelerating the biodegradation and mineralization of nutrients (Aira et al. 2007; Alshehrei and Ameen 2021; Lores et al. 2006). In the initial phase of vermicomposting, the first microbial colonizers are characterized by consuming substrates rich in nutrients and easily assimilable molecules (simple carbohydrates, peptides, proteins, vitamins, etc.) (Gómez-Brandón et al. 2019; Ho et al. 2017). In the final phase of vermicomposting, late decomposers take control, with a low growth rate and better efficiency in metabolizing complex (recalcitrant) carbon compounds (Gómez-Brandón et al. 2019; Ho et al. 2017). Likewise, it has been shown that the increase in population and microbial diversity, time of appearance, and microbial dominance during vermicomposting are influenced by worm species, vermicomposting procedure, and substrate characteristics (Domínguez et al. 2019; Gómez-Brandón et al. 2020a; Lores et al. 2006; Vuković et al. 2021). In this context, Domínguez et al. (2019) evaluated the microbial community present in the vermicomposting of scotch broom (*Cytisus scoparius*), and observed that the microbial community during this process was mainly divided into *Proteobacteria*, *Bacteroidetes*, *Actinobacteria*, and *Firmicutes*, but mainly dominated by *Proteobacteria* (99.8%). While Miao et al. (2023) indicated that in the process of vermicomposting of kitchen waste, the phyla that promote OM degradation (*Actinobacteria*, *Firmicutes*, and *Acidobacteria*) increased, the bacterial genera that favor compost maturity and quality (*Cellvibrio* and *Pseudomonas*) increased, and pathogenic *Enterobacter* decreased. On their part, Chitrapriya et al. (2013) showed that vermicompost made from cow manure and sawdust contained *Bacillus*, *Streptomyces*, and *Pseudomonas* sp. as phosphate solubilizers and Azotobacter as N_2-fixing bacteria.

It has been found that the biological mechanisms involved in vermicomposting, such as the activity and type of microorganisms, determine the dynamics of the process and the properties of the final product (Gómez-Brandón et al. 2020a). While Pramanik et al. (2007) evaluated the development of the microbial population in the vermicomposting of cow manure, grass, aquatic weeds and municipal solid waste residues, they found that cow manure allowed the highest microbial population, as well as a higher enzymatic status and nutrient content. With the above information, it is evident that the population and microbial activity present in the gut of the worm and the processed material influence the nutrient content of the vermicompost. However, despite having research in which the microbial population present during the vermicomposting process has been evaluated, little is known about the effect of the population and microbial diversity during the vermicomposting process on the nutrient content of the final vermicompost.

Undoubtedly, the improvement of the nutrient content in vermicompost as a result of the adequate control of the factors that determine the nutritional quality of the final vermicompost, already mentioned above, will allow vermicompost to be an efficient organic fertilizer to improve crop production, improve soil fertility and, above all, reduce the use of inorganic fertilizers. Currently, some reports emphasize the importance of proper management of factors such as type of waste, proportion of each waste used, type of worm used in the process, and vermicomposting time to improve the nutrient content of vermicompost. However, most studies focus only on evaluating the physicochemical and biological characteristics of the final vermicompost. Currently, there is a limited number of complete studies that include the evaluation of the optimization of the factors that determine the nutritional quality of vermicompost and the effect of these vermicomposts on the growth and yield of crops. Considering that the quality of vermicompost is determined by its high nutrient content and its beneficial effect on plant development, it is important to promote more comprehensive research, such as that carried out by Rath et al. (2020) and Chatterjee et al. (2021). These researchers evaluated the efficiency of different residues and different proportions of residues to obtain vermicompost with high nutrient content; likewise, the researchers evaluated the effect of each vermicompost obtained on the development of the crop, observing that each vermicompost obtained affected the morphological characteristics of the plants differently, obtaining greater development when the plants were grown with vermicompost with higher nutrient content.

5 What else has been done to Increase the Nutrient Content of Vermicompost?

In addition to vermicomposting different substrates, different proportions of the substrate, and using different earthworms to obtain nutrient-rich vermicompost, incorporating of microbial inoculants, minerals, and inorganic fertilizers into the vermicomposting process is one technique used to increase the nutrient content of the final vermicompost. Several researchers have explored the possibility of using microbial inoculants to increase biological activity, optimize the biodegradation of organic waste, and improve the nutrient content of soil vermicompost (Ajibade et al. 2020; Lukashe et al. 2019). The microorganisms inoculated in the vermicomposting process are mainly P-solubilizing and N_2-fixing microorganisms. Mal et al. (2021) studied the feasibility of inoculating with N_2-fixing and P-solubilizing bacteria (*Azotobacter chroococcum* and *Pseudomonas fluorescens*) in the vermicomposting process of cow dung and vegetable waste (1:1) to improve the availability of N and P in the product, they observed a significant increase in the amount of mineralized N and P solubilized in the vermicompost when the microorganisms were added. Singh and Sharma (2002) incorporated P-solubilizing and N_2-fixing microorganisms (*Pleurotus sajor-caju*, *Trichoderma harzianum*, *Aspergillus niger*, and *Azotobacter chroococcum*) in the vermicomposting of wheat straw and showed that the inoculation reduced the time required for vermicompost production and increased the content of N, P, and K. Das et al. (2016) evaluated the effect of the type of vermicomposted substrate (water hyacinth, rice straw, and sawdust, each mixed with cow dung at a ratio of 70:30%) and the inoculated microorganism (*Trichoderma viride*, *Azotobacter chroococcum*, *Bacillus polymixa*, *Bacillus firmus*, and a mixture of the four microorganisms) on the content of N, P and K in the vermicompost. These researchers found that the highest levels of N, P and K were obtained by inoculating the vermicompost material with the mixture of microorganisms; however, the highest levels of N and K were obtained by vermicomposting water hyacinth and the highest levels of P were obtained by vermicomposting rice straw.

Similary, to improve the nutrient content of vermicompost, nutrient-rich inorganic materials have been added to the vermicomposting process (Mupambwa and Mnkeni 2018). Among the inorganic materials that have shown the potential to increase the content of bioavailable nutrients in vermicompost are phosphate rock and fly ash (Gómez-Brandón et al. 2020a). Although the concentration of nutrients in phosphate rock and fly ash is high, they have low solubility when applied directly to the soil (Mupambwa and Mnkeni 2018; Wei et al. 2012); however, by adding these inorganic materials in the organic waste vermicomposting process, the solubility of nutrients is improved (Bhattacharya and Chattopadhyay 2006). A study conducted by Wei et al. (2012) indicated that by adding phosphate rock in the vermicomposting process of rice straw and cow dung (4:1), 17% more extractable P was obtained in the vermicompost compared to vermicompost without adding phosphate rock; similarly, the availability of N, P and Ca was improved by adding phosphate rock in the process. Mupondi et al. (2018) reported that the application of 2, 4, and 8% P as phosphate rock in the vermicomposting process of cow manure and waste paper resulted in 19, 28, and 33% more available P, respectively, compared to the control.

In addition to the aforementioned minerals, studies have also been conducted on the enrichment of vermicompost with K-containing minerals including Zhu et al. (2013), who evaluated the addition of K-rich mineral dust in the vermicomposting of cow manure, and found that the amount of available K increased significantly. In other works, inorganic fertilizers have been incorporated into the vermicomposting process to enrich the vermicompost, as in the case of Sengupta et al. (2020), who applied Fe and Zn in vermicomposting of cow manure and plant residues (6:4) with *E. fetida*, based on the hypothesis that vermicompost enriched with Fe and Zn will result in a better mediated slow release by complexation to utilize the nutrients without causing them to precipitate. These researchers reported an increase in total and available Fe and Zn in vermicompost and plant tissue.

Likewise, other studies have evaluated the combined effect of microbial inoculation and the incorporation of inorganic minerals during the vermicomposting process to obtain increases in the nutrient content of the final product. Among the works carried out, the one reported by Rahbar et al. (2020) stands out, who tried to improve the content of P and Fe in the vermicompost by adding phosphoric rock, mineral sulfur (as source of energy for the metabolism of the bacteria) and steel dust (as a source of Fe) with the help of *Halothiobacillus neapolitanus*, a sulfur-oxidizing bacterium. The *Halothiobacillus neapolitanus* bacteria converted inorganic sulfur into sulfuric acid, thereby lowering the pH of the vermicompost, and the resulting acidic condition improved the availability of P and Fe during the enrichment process. Similary, Busato et al. (2012) evaluated the effect of incorporating phosphate rock and inoculating N_2-fixing and P-solubilizing bacteria (*Burkholderia silvatlantica*, *Burkholderia spp*, and *Herbaspirillum seropedicae*) during vermicomposting of cow mature and sunflower residue

(3:1) on N and P content. At the end of the process (120 days), N and P content had increased by 18% and 106% in the inoculated vermicompost compared to the uninoculated vermicompost. Busato et al. (2021), when incorporating phosphate rock and inoculating *T. asperellum* and *T. virens* in the vermicomposting process, observed that the combined inoculation of *T. asperellum* and *T. virens* efficiently accelerated vermicompost stabilization due to the high production of degrading enzymes; while inoculation with *T. asperellum* increased soluble P in the final product. On the other hand, Lukashe et al. (2019) added fly ash and P-solubilizing bacteria (*P. fluorescens*) to vermicomposting to improve waste degradation, nutrient mineralization, and biological activity, and observed that the biodegradation process was accelerated and P in the vermicompost increased by 48.3%.

6 Conclusions

Vermicompost improves the physical, chemical and biological properties of the soil and increases the growth and yield of crops. This is due to its high nutrient content and the presence of bioactive substances. Among the most important nutrients provided by vermicompost are N, P, K, Ca, Mg, S and micronutrients, as well as humates and plant growth regulators. Research that has focused on evaluating the factors involved in the vermicomposting process to improve the nutrient content of this amendment has shown that the nutrient content of the final vermicompost depends on the residue used, the proportion of each residue used, the type and density of worms, vermicompost maturity, and microbial activity during vermicomposting. However, research on how to adequately control these factors during the vermicomposting process is very limited. Therefore, the concentration of existing information on this subject will help to emphasize the importance of an adequate management of these factors to increase the nutritional content of vermicompost and, above all, to promote new research aimed at improving the nutritional quality of vermicompost and that in the short term this organic fertilizer is valued as a real alternative for its use in the restoration of degraded agricultural soils and as an important source of nutrient supply for crops.

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Declarations

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