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Chapter 10

THE USE OF VERMICOMPOST IN SUSTAINABLE AGRICULTURE: IMPACT ON PLANT GROWTH AND SOIL FERTILITY

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ABSTRACT

Vermicomposting is a low-technology, environmentally-friendly process used to treat organic waste. The resulting vermicompost has been shown to have several positive impacts on plant growth and health. This organic fertilizer is therefore increasingly considered in agriculture and horticulture as a promising alternative to inorganic fertilizers and/or peat in greenhouse potting media. However, the effects of vermicompost on plant-soil systems are not yet fully understood. In this chapter we summarize the research carried out during the last few decades, and the proposed mechanisms explaining the effects of vermicompost on soil quality and plant growth. Although much effort has been dedicated to the investigation of biologically mediated mechanisms of promoting plant growth, the conflicting results indicate the need to open up new lines of research, defining a clear and objective concept of vermicompost, and clarifying the conditions and sources of variability in the biological effects. A case study is presented in which the direct and indirect effects of vermicompost on plant growth, as well as variability in the plant responses, are examined in a field experiment with sweet corn.

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1. INTRODUCTION

1.1. The Use of Composted Materials in Sustainable Agriculture

In recent years, increasing consumer concern about issues such as food quality, environmental safety and soil conservation has lead to a substantial increase in the use of sustainable agricultural practices. Sustainable agriculture can be defined as a set of practices that conserve resources and the environment without compromising human needs, and the use of organic fertilizers such as animal manure has been indicated as one of its main pillars (Tilman et al., 2002). Animal manure is a valuable resource as a soil fertilizer because it provides large amounts of macro- and micronutrients for crop growth and is a low-cost, environmentally-friendly alternative to mineral fertilizers. However, the use of manure in agriculture is being abandoned because of increasing transportation costs and environmental problems associated with the indiscriminate and inappropriately-timed application to agricultural fields (Hutchison et al., 2005). Processing of this waste material through controlled bio-oxidation processes, such as composting, reduces the environmental risk by transforming the material into a safer and more stable product suitable for application to soil (Lazcano et al., 2008), and also reduces the transportation costs because of the significant reduction in the water content of the raw organic matter. Composted materials are therefore gaining acceptance as organic fertilizers in sustainable agriculture, and there has been a considerable increase in research dedicated to the study of the effects of compost-like materials on soil properties and plant growth.

The results of several long-term studies have shown that the addition of compost improves soil physical properties by decreasing bulk density and increasing the soil water holding capacity (Weber et al., 2007). Moreover, in comparison with mineral fertilizers, compost produces significantly greater increases in soil organic carbon and some plant nutrients (García-Gil et al., 2000, Bulluck et al, 2002, Nardi et al., 2004, Weber et al., 2007). Long-term beneficial effects of composted materials are also observed in soil humic substances (due to an increase in the complexity of their molecular structure, which increases the humic/fulvic acid ratio), as well as in soil sorption properties (with increased cation exchange capacity and base saturation) (Weber et al., 2007). In addition to the changes exerted on the chemical and physical properties, composted materials have a clear impact on soil biological properties, such as increases in microbial biomass and activity (Knapp et al. 2010), as well as changes in the activity of soil enzymes (Garcia-Gil et al., 2000, Ros et al., 2006) and in the structure of the soil microbial community (Ros et al., 2006).

1.2. Vermicomposting and Vermicompost Properties

Vermicompost is a nutrient-rich, microbiologically-active organic amendment that results from the interactions between earthworms and microorganisms during the breakdown of organic matter. It is a stabilized, finely divided peat-like material with a low C:N ratio, high porosity and high water-holding capacity, in which most nutrients are present in forms that are readily taken up by plants (Domínguez, 2004).

Unlike compost, vermicompost is produced under mesophilic conditions, and although microorganisms degrade the organic matter biochemically, earthworms are the crucial drivers of the process, as they aerate, condition and fragment the substrate, thus drastically altering the microbial activity. Earthworms act as mechanical blenders, and by fragmenting the organic matter they modify its physical and chemical status by gradually reducing the ratio of C:N and increasing the surface area exposed to microorganisms - thus making it much more favourable for microbial activity and further decomposition (Domínguez et al., 2010).

As a result of the different processes involved in the production of compost and vermicompost, they exhibit different physical and chemical characteristics that affect soil properties and plant growth in diverse ways. Vermicomposting generally converts organic matter to a more uniform size, which gives the final substrate a characteristic earthy appearance, whereas the material resulting from composting usually has a more heterogeneous appearance (Ndegwa and Thompson, 2001; Tognetti et al., 2005).

The use of compost in horticulture has occasionally been shown to be limited by the high electrical conductivity and the excessively high amount of certain ions that cause phytotoxicity (García-Gómez et al., 2002), as a consequence of the chemical properties of the initial waste and /or inadequate composting procedures. These adverse effects, although possible, are less likely to occur when vermicompost is used as a potting amendment (Chaoui et al., 2003). Nevertheless, the most remarkable differences between compost and vermicompost are related to their biological properties. Composting and vermicomposting are two rather different biological processes, which condition the biological properties of the final substrate and result in important differences between compost and vermicompost, in both the bacterial community composition (Vivas et al., 2009) and fungal abundance (Lazcano et al., 2008), even when the same organic waste is used as a feedstock material. These differences may lead to rather different effects on plant growth and morphology that must be investigated. Although the composting process and the effects of compost on soil and plant growth have been fairly well studied, this is not the case for vermicompost and the vermicomposting process.

2. How Vermicompost Influences Plant Growth: Effects and Proposed Mechanisms

2.1. Effects of Vermicompost on Plant Growth

Vermicompost significantly stimulates the growth of a wide range of plant species including several horticultural crops such as tomato (Atiyeh et al., 1999; Atiyeh et al., 2000a, Atiyeh et al., 2000b; Atiyeh et al., 2001; Hashemimajd, et al., 2004; Gutiérrez-Miceli et al., 2007), pepper (Arancon et al., 2004a, Arancon et al., 2005), garlic (Argüello et al, 2006), aubergine (Gajalakshmi and Abbasi, 2004), strawberry (Arancon et al., 2004b), sweet corn (Lazcano et al, 2011) and green gram (Karmegam et al., 1999). Vermicompost has also been found to have positive effects on some aromatic and medicinal plants (Anwar et al., 2005;

Prabha et al., 2007), cereals such as sorghum and rice (Bhattacharjee et al., 2001; Reddy and Ohkura, 2004; Sunil et al., 2005), fruit crops such as banana and papaya (Cabanas-Echevarria, et al., 2005; Acevedo and Pire, 2004), and ornamentals such as geranium (Chand et al. 2007), marigolds (Atiyeh et al., 2002), petunia (Arancon et al., 2008), chrysanthemum (Hidalgo and Harkess 2002a) and poinsettia (Hidalgo y Harkess, 2002b). Positive effects of vermicompost have also been observed in forestry species such as acacia, eucalyptus and pine tree (Donald and Visser, 1989, Lazcano et al., 2010a, 2010b).

Vermicompost has been found to have beneficial effects when used as a total or partial substitute for mineral fertilizer in peat-based artificial greenhouse potting media and as soil amendments in field studies. Likewise, some studies show that vermicomposting leachates or vermicompost water-extracts, used as substrate amendments or foliar sprays, also promote the growth of tomato plants (Tejada et al. 2008), sorghum (Gutiérrez-Miceli et al. 2008), and strawberries (Singh et al. 2010).

Positive effects of vermicompost include stimulated seed germination in several plant species such as green gram (Karmegam et al. 1999), tomato plants (Atiyeh et al. 2000b; Zaller 2007), petunia (Arancon et al. 2008) and pine trees (Lazcano et al., 2010a). Vermicompost also has a positive effect on vegetative growth, stimulating shoot and root development (Edwards et al., 2004). The effects include alterations in seedling morphology such as increased leaf area and root branching (Lazcano et al., 2009). Vermicompost has also been shown to stimulate plant flowering, increasing the number and biomass of the flowers produced (Atiyeh et al., 2002; Arancon et al., 2008), as well as increasing fruit yield (Atiyeh, et al., 2000b; Arancon et al., 2004a, 2004b; Singh et al., 2008). In addition to increasing plant growth and productivity, vermicompost may also increase the nutritional quality of some vegetable crops such as tomatoes (Gutiérrez-Miceli et al., 2007), Chinese cabbage (Wang et al., 2010), spinach (Peyvast et al., 2008), strawberries (Singh et al., 2008), lettuce (Coria-Cayupán et al., 2009), and sweet corn (Lazcano et al., 2011).

Nevertheless, despite the large body of scientific evidence showing the positive effects of vermicompost on plant growth and yield, there is also strong evidence that these effects are not general or constant, and that there is great variability in the magnitude of the effects reported in different studies. In fact, some studies report that vermicompost may decrease growth and even cause plant death (Roberts et al., 2007; Lazcano et al., 2010c). The variability in the effects of vermicompost may depend on the cultivation system into which it is incorporated, as well as on the physical, chemical and biological characteristics of vermicompost, which vary widely depending on the original feedstock, the earthworm species used, the production process, and the age of vermicompost (Rodda et al., 2006, Roberts et al., 2007; Warman and AngLopez, 2010).

There is also a large variation in the effects of vermicompost depending on the plant species or even the variety considered. This was observed in tomato plants where the replacement of a fertilized commercial potting media with vermicompost had different effects on germination, seedling elongation, biomass allocation, fruit morphology and chemical properties of three tomato varieties (Zaller, 2007). Similar variation was observed in an experiment studying the effects of vermicompost and vermicompost extracts on the germination and early growth of six different progenies of maritime pine Lazcano et al. (2010a). In this experiment, the speed of maturation increased, relative to the control without vermicompost, in three out of the six pine progenies, decreased in two of the progenies and was unaffected in the other. It may be expected that different hybrids or plant genotypes will respond differently to vermicompost, considering that plant genotype determines important differences in nutrient uptake capacity, nutrient use efficiency and resource allocation within the plant. Different genotypes may therefore enhance root growth or modify root exudation patterns in order to increase nutrient uptake (Kabir et al. 1998; Cavani and Mimmo 2007), and all of these strategies will determine the establishment of different interactions with the microbial communities at the rhizosphere level. In fact, after the application of vermicompost to sweet corn crops, the different genotypes showed important differences in their rhizosphere microbial community (Aira et al. 2010).

In light of this evidence, it is clear that vermicompost constitutes a promising alternative to inorganic fertilizers in promoting plant growth. However, further research into the exact mechanisms and circumstances that stimulate plant growth by this organic substrate is necessary in order to maintain consumer confidence in this type of fertilizer.

2.2. Plant Growth Regulating Mechanisms

Vermicompost is a microbiologically-active, nutrient-rich, peat-like material, which when added to plant growing media may influence plant growth directly or indirectly through different chemical, physical and biological mechanisms (Figure 1).

2.2.1. Direct Mechanisms

As regards the direct effects on plant growth, vermicompost constitutes a source of plant macro- and micronutrients. Although some of these nutrients are present in inorganic forms and are readily available to plants, most are released gradually through mineralization of the organic matter, thus constituting a slow-release fertilizer that supplies the plant with a gradual and constant source of nutrients (Chaoui et al., 2003). However, in contrast to chemical fertilizers, the amount of nutrients provided may vary greatly depending on the original feedstock, processing time and maturity of the vermicompost (Campitelli and Ceppi, 2008).

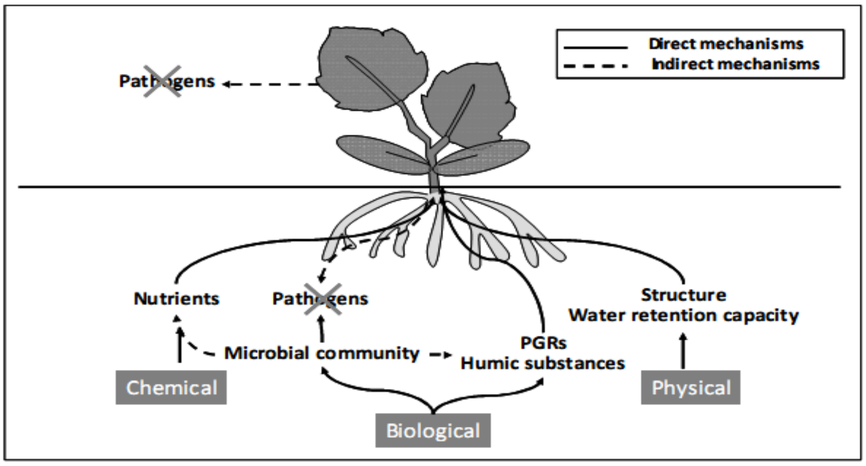

Figure 1. Some of the proposed chemical, biological and physical mechanisms by which vermicompost may directly or indirectly influence plant growth and development.

Vermicompost is a finely-divided peat-like material and because of this fine structure, the addition of vermicompost to plant potting media causes significant changes in the physical properties, altering water and air availability in the substrates and conditioning root growth. Nonetheless, the type and magnitude of these effects depends on the physical characteristics of the original growing medium. For example, the bulk density of vermicompost is usually higher and the particle size lower than in some of the most commonly used peat-based substrates (Atiyeh et al. 2001); mixing of these two substrates produces a significant increase in the bulk density and water holding capacity, while decreasing particle size and total porosity (Atiyeh et al. 2001; Bachmann and Metzger, 2007). Hidalgo and Harkess (2002a) and Hidalgo et al. (2006) reported a significant increase in total porosity and water holding capacity after addition of vermicompost to a greenhouse potting medium comprising a mixture of sand, pine bark and peat. Vermicompost may also have significant effects on soil physical properties. Ferreras et al. (2006) observed that addition of 20 tn ha^{-1} of vermicompost to an agricultural soil in two consecutive years significantly improved soil porosity and aggregate stability. The number of large, elongated soil macropores increased significantly after a single application of a dose of vermicompost equivalent to 200 kg ha^{-1} of N to a corn field (Marinari et al., 2000). Similarly, Gopinath et al. (2008) reported a significant decrease in soil bulk density and a significant increase in soil pH and total organic carbon after application of vermicompost in two consecutive growing seasons, at a rate equivalent to 60 kg ha^{-1} of N. Together these changes in soil properties improve the availability of air and water, thus encouraging seedling emergence and root growth.

Despite the above-mentioned physical and chemical mechanisms, there is much experimental evidence showing that vermicompost enhances plant growth further than expected because of nutrient supply and improvements in the physical condition of substrates. This was first suggested by Scott (1988) and Edwards and Burrows (1988), who observed that small doses of vermicompost added to the potting media of several ornamental species, produced a much larger increase in plant growth than the equivalent dose of nutrients. These effects were maintained even when vermicompost was diluted 1:20 with other potting media, resulting in a dose of vermicompost would be expected to have negligible physical effects (Edwards and Burrows, 1988). This was also observed more recently in field experiments carried out by Arancon et al. (2004b) and Singh et al. (2008). Both studies indicated a significant increase in the growth and productivity of strawberries cultivated with 5 and 7.5 t ha^{-1} of vermicompost respectively, in comparison with strawberries cultivated with equivalent doses of mineral fertilizers. Furthermore, many studies have shown that increases in growth and yield often involve changes in plant development and/or plant morphology such as increased leaf area, root volume and root branching (Singh et al., 2008; Lazcano et al., 2009). It has been postulated that such enhancement of plant growth may be attributed to the existence of biologically-mediated plant growth promoting mechanisms.

Vermicompost may influence plant growth directly via the supply of plant growth regulating substances (PGRs). This was first proposed by Tomati et al. (1983, 1987, 1988), Tomati et al. (1990); Grapelli et al. (1987) and Tomati and Galli (1995). In these experiments the authors compared the effects of different vermicompost extracts on the growth of Begonia, Petunia and Coleus with the effects produced by auxins, gibberellins and cytokinins, and concluded that there was a strong evidence of hormonal activity caused by the earthworms. Hormonal activity has also been associated with the humic substances present in vermicompost. Canellas et al. (2002) and Zandonadi et al. (2006) reported that the humic substances extracted from earthworm compost were capable of inducing lateral root growth in maize plants by stimulation of the plasma membrane H^+-ATPase activity, thus producing similar effects such as the exogenous application of indole-3-acetic acid (IAA). Furthermore, the induction of lateral root initiation by vermicompost-derived humic substances in arabidopsis has been related to the activation of the transcription of some auxin responsive genes (Trevisan et al., 2010). The hypothesis of the auxin activity of vermicompost humic substances is reinforced by the presence of exchangeable auxin groups in their macrostructure (Canellas et al., 2002).

It has been suggested that earthworms may be important agents capable of influencing the production of PGRs by microorganisms through the stimulation and promotion of microbial activity in organic substrates (Nielson, 1965; Springett and Syers, 1979; Grappelli et al., 1987; Tomati et al., 1983, 1987, 1988; Tomati et al., 1990; Tomati and Galli, 1995, Nardi et al., 1988; Graf and Makeschin, 1980; Dell'Agnola and Nardi, 1987). Nevertheless, some authors suggest that earthworms, and not microorganisms, are responsible for the production of PGRs. Nielson (1965) reported the first evidence of the presence of indole compounds in the tissues of *Aporrectodea caliginosa*, *Lumbricus rubellus*, and *Eisenia fetida*. More recently, El Harti et al. (2001a, 2001b) showed that a crude extract of the earthworm *Lumbricus terrestris* was able to stimulate rooting in bean seeds due to the presence of indole compounds of endogenous origin.

2.2.2. Indirect Mechanisms

Vermicompost has also been found to have a wide range of indirect effects on plant growth such as the mitigation or suppression of plant diseases (Figure 1). Suppression of plant diseases has been extensively investigated in other organic amendments such as manure and compost (Noble and Coventry, 2005; Termorshuizen et al., 2006; Trillas et al., 2006). Likewise, some studies have shown that vermicompost can suppress a wide range of microbial diseases, insect pests and plant parasitic nematodes.

As regards the suppression of fungal diseases, Orlikowski (1999) observed that the addition of vermicompost extracts to three ornamental plant species significantly reduced sporulation of the pathogen *Phytophthora cryptogea*. Similarly Nakasone et al. (1999) observed that aqueous extracts of vermicompost were capable of reducing the growth of pathogenic fungi such as *Botrytis cinerea, Sclerotinia sclerotiorum, Corticium rolfsii, Rhizoctonia solani* and *Fusarium oxysporum*. The addition of solid vermicompost to tomato seeds significantly reduced infection caused by *Fusarium lycopersici* (Szczech, 1999) and *Phytophthora nicotianae* (Szczech and Smolinska, 2001). Nevertheless, Szczech and Smolinska (2001) did not find any significant suppressive effects of a sewage sludge vermicompost on *Phytophthora nicotianae*, in comparison with peat. Edwards et al (2006) observed that the suppressive effect exerted by several types of vermicompost on several plant pathogens such as *Pythium*, *Rhizoctonia, Verticillium,* and *Plectosporium*, disappeared after sterilization of the vermicompost, and concluded that disease suppression may be related to the presence of biological suppressive agents in vermicompost.

As regards the effects of vermicompost on insect pests and mites, field studies have shown that the addition of vermicompost to soil significantly reduces the incidence of the psyllid *Heteropsylla cubana* (Biradar et al., 1998), the sucking insect *Aproaerema modicella* (Ramesh, 2000), jassids, aphids, beetles, and spider mites (Rao, 2002).

Furthermore, some studies show that vermicompost reduces not only the degree of plant infestation, but also the populations of plant parasitic insects in soils. This has been reported by Arancon et al., (2005b), who showed that vermicompost produced from food waste significantly reduced the populations of two species of beetles in soil (*Acalymma vittatum*, *Diabotrica undecimpunctata*), in comparison with inorganic fertilization. Similarly Yardim et al., (2006) observed a significant decrease in the larvae of the worm *Manduca quinquemaculata* after addition of vermicompost to a cucumber crop. Arancon et al. (2007) observed a significant reduction in the populations of spider mites (*Tetranychus urticae*), mealy bugs (*Pseudococcus* sp.) and aphids (*Myzus persicae*) after the addition of food waste vermicompost to several vegetable crops (tomatoes, cucumber, cabbage, bush beans and eggplants).

Vermicompost may also have significant effects on both the incidence and abundance of plant-parasitic nematodes in soil. This was first reported by Swathi et al. (1998), who found that addition of vermicompost to soil at a rate of 1kg m^{-2} significantly inhibited the incidence of the parasite nematode *Meloidogyne incognita* in tobacco plants. Similar reductions in the degree of plant infestation by *Meloidogyne incognita* were observed by Morra et al. (1998), while Ribeiro et al. (1998) reported a significant decrease in the egg mass of *Meloidogyne javanica* after the application vermicompost to the growth medium. Arancon et al. (2003) indicated significant reductions in the abundance of plant-parasitic nematodes in soil plots amended with different doses of two types of vermicompost, in comparison with the effects of inorganic fertilizers.

According to the mechanisms proposed for compost (Hointink and Bohem, 1999; Noble and Coventry, 2005), disease suppression by vermicompost may be attributed to either direct suppression of pathogens or to the induction of systemic resistance in the plant (Figure 1). Direct suppression of the pathogen by the vermicompost-associated microflora and/or microfauna may be general or specific, depending on the existence of a single suppressive agent or the joint action of several agents. In both cases, the proposed mechanisms are competition, antibiosis and parasitism. The mechanisms responsible for disease suppression by vermicompost are not yet well known, and the effects of biopesticides are usually attributed to general suppressive effects. Vermicompost increases microbial biomass in soil and changes the diversity and abundance of soil fauna (Gunadi et al., 2002; Arancon et al., 2006), and thus a broader range of organisms may act as biocontrol agents. Furthermore, there is recent evidence showing that the use of vermicompost extracts as foliar sprays in different crop plants effectively reduces the incidence of fungal diseases such as *Phytophthora infestans* (Zaller, 2006), *Erysiphe pisi* and *Erysiphe cichoracearum* (Singh et al., 2003). Reductions in disease incidence are sometimes accompanied by an increase in the production of defence substances by the plant (Singh et al. 2003), thus suggesting the induction of plant systemic resistance by vermicompost.

Some of the indirect effects of vermicompost have been related to the change in the microbiological properties of the soil or the potting media. Processing by earthworms during vermicomposting has a strong effect on the microbial community of the initial waste (Dominguez et al., 2010). Vermicompost therefore has a rather different microbial community structure than the parent waste, with lower biomass and activity but enhanced metabolic diversity (Lores et al., 2006; Aira et al., 2007, Gómez-Brandón et al., 2010). Application of such a microbiologically active organic substrate may have important effects on the microbial properties of soil or greenhouse potting media thereby influencing plant growth. However, information regarding the impacts of vermicompost on soil microbial properties is still limited. A single application of vermicompost to a strawberry crop has been shown to produce a significantly higher increase in soil microbial biomass than application of an inorganic fertilizer, independently of the dose used (Arancon et al., 2006). As well as increasing microbial biomass, vermicompost increases microbial activity (Ferreras et al., 2006) promotes the establishment of a specific microbial community in the rhizosphere different from that of plants supplemented with mineral fertilizers or other type of organic fertilizers such as manure (Aira et al., 2010). Kale et al., (1992) observed that the application of vermicompost may produce significantly greater increases in the abundance of N-fixers, actinomycetes and spore formers than in soil supplemented with inorganic fertilizers. Soil enzyme activity is also significantly increased by vermicompost addition as compared to equivalent rates of mineral fertilizers (Marinari et al., 2000; Arancon et al., 2006, Saha et al., 2008).

3. Effects of Vermicompost on Plant Growth and Soil Fertility in a Sweet Corn Stand: A Case Study

As mentioned earlier in this chapter, vermicompost has been shown to increase the growth and yield of a wide range of species due to several direct and indirect beneficial effects. Furthermore, the use of organic fertilizers such as vermicompost helps maintain soil fertility, and has evident environmental benefits as it enables on-farm recycling of organic waste. However, agricultural producers often claim that crop yields are much lower with this type of fertilizer than with inorganic fertilizers. This is generally attributed to the fact that the amount of nutrients provided by organic fertilizers is very unreliable in comparison with those supplied by inorganic fertilizers (Trewavas, 2001). Furthermore, most of the benefits of organic fertilizers on soil fertility have mainly been reported to be long-term effects, so that repeated applications over several years are necessary to achieve the desired steady state that will guarantee crop productivity.

We carried out a field experiment in which we tested whether the replacement of 25% of the applied inorganic NPK fertilizers with rabbit manure vermicompost could maintain the yield of a sweet corn crop at the same levels. Crop yield was assessed three months after vermicompost application to soil. We hypothesized that for the same amounts of nutrients supplied, vermicompost would produce similar or higher plant growth yields than inorganic fertilizers. The effects of vermicompost were compared with those of the equivalent unprocessed organic matter (rabbit manure). Thus, three types of fertilization regimes were applied: (i) a conventional fertilization regime with inorganic fertilizer, and integrated fertilization regimes in which 75% of the nutrients were supplied by the inorganic fertilizer and 25% of the nutrients were supplied by either (ii) rabbit manure, or (iii) vermicompost. All three fertilizers were supplied at two different doses, a *normal* dose (80:24:20 kg ha^{-1} of N:P:K) for an expected final crop yield of 4 t ha^{-1} of dry weight grain, and a *high* dose of 120:36:30 kg ha^{-1} of N:P:K for an expected final yield of 6 t dry grain ha^{-1}, according to the dry grain yield reported for sweet corn (Ordás et al., 2007). The amounts of each fertilizer required to supply these nutrient requirements were calculated taking into account the nutrient content of each and the nutrient content of the soil at the experimental site. Thus, the normal doses were 5.4 and 4.2 t substrate per ha for manure and vermicompost, respectively, and the high doses were 8.2 and 6.3 t substrate ha^{-1} for manure and vermicompost, respectively. The field trial was repeated over two consecutive years. In both years, fertilizers were applied manually to the plots one week before sowing, and incorporated by mixing into the upper 20 cm of the soil.

As already explained, much of the observed variability in the effects of vermicompost can be attributed to the different plant species and genotypes used. Therefore in this experiment, four different sweet corn hybrids (H1, H2, H3 and H4) were included, in order to explore the interactions between the type of fertilizer and plant genotype. Experimental units consisted of 10 m^2 plots each with one combination of hybrid, fertilizer and dose. Each plot contained two central and two border rows spaced 0.80 m apart, with 25 two-plant hills spaced 0.21 m apart; plots were overplanted and thinned to a final density of approximately 60000 plants ha^{-1}. Plots were arranged in the field following a randomized complete block design with two replications per year.

At harvest, three months after sowing, five plants were selected at random from the two central rows of each plot, and their heights were measured. Plants were subsequently cut to soil level and transported to the laboratory for determination of total yield (total ear biomass per plant), quality of the marketable ear (grain percentage, NPK content), leaf NPK nutrient content and total plant biomass. In order to evaluate the effects of the fertilizers on soil biochemical and microbiological properties, one composite soil sample, consisting of 3 randomly selected sub-samples, was collected in each plot. The structure of the soil microbial community was assessed by PLFA analysis; certain PLFAs were used as biomarkers to determine the presence and abundance of specific microbial groups. Microbial community function was determined by measuring bacterial and fungal growth rates, by incorporating radioactively labelled leucine into proteins and radioactively labelled acetate into the fungal-specific lipid ergosterol, respectively (Bååth et al., 2001). The activities of some of the main soil enzymes (β-Glucosidase, protease and alkaline phosphomonoesterase) were also assessed, as were the available N (NH_4^+ and NO_3^-) and P (PO_4^-) contents. Data were analyzed on a plot mean basis, by linear mixed models. Post hoc comparisons of means were performed with the LSMEAN statement in the SAS 9.1. software program.

3.1. Effects of Vermicompost on Sweet Corn Growth and Yield

In the present study vermicompost produced significant improvements in the growth and yield of sweet corn, as also reported by Atiyeh et al. (2000b), Arancon et al. (2004b) and Singh et al. (2008). Replacement of 25% of the nutrients provided to the plants by vermicompost produced significant greater increases in plant height and marketable crop yield than those produced by 100% inorganic fertilization (Figure 2). Nevertheless the magnitude of such effects was relatively small and not general, with a large degree of variability between the different hybrids assayed. Furthermore, there was little or no difference from the effects produced by manure on plant height and crop yield. Interestingly, increases in sweet corn growth and marketable yield were produced by both the normal and the high doses of vermicompost and manure, indicating that these effects were independent of the amount of N, P and K provided.

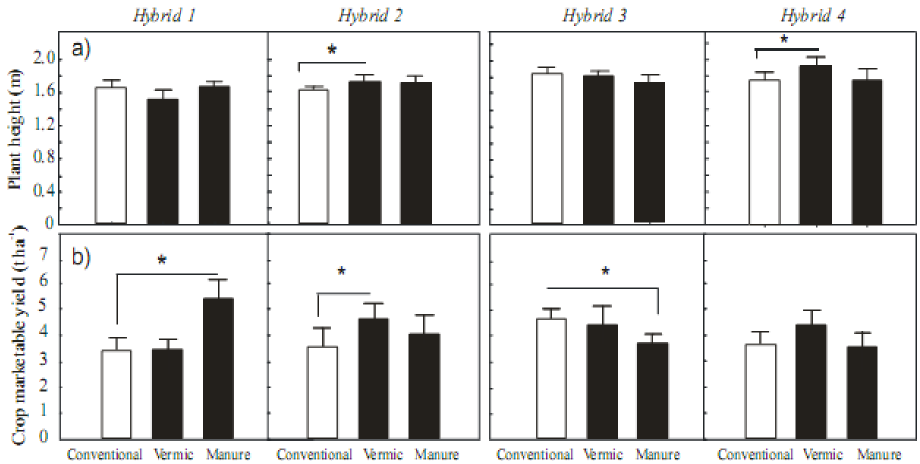

Figure 2. Plant height, crop yield, N content in grain and grain yield of the marketable ear of the four sweet corn hybrids grown under the different fertilization treatments evaluated: conventional (100% inorganic NPK), vermicompost (75% inorganic + 25% organic NPK), and manure (75% inorganic + 25% organic NPK). Asterisks and bars indicate significant differences at P< 0.05. Values are means ± SE (Modified from Lazcano et al. 2011).

Table 1. Leaf nutrient content of the sweet corn hybrids subjected to normal and high doses of the different fertilization regimes. Values are means ± standard error. Different letters within the same row indicate significant differences at P<0.05

Nutrient	Normal			High		
	Conventional	Vermicompost	Manure	Conventional	Vermicompost	Manure
N (mg kg-1dw)	30751 ± 1206	30931 ± 1222	29950 ± 1206	31394 ± 1206	31574 ± 1206	29545 ± 1212
P (mg kg-1dw)	2625 ±167 b	3044 ±171 a	2908 ± 167 ab	2546 ± 168 b	2766 ± 168 a	2737 ± 168 ab
K (mg kg-1dw)	13875 ± 3809	14634 ± 3816	13976 ± 3810	12987 ± 3809	13960 ± 3809	14262 ± 3813

Foliar analysis revealed that the differences in macronutrient content between the plants cultivated with the three types of fertilizers were minor (Table 1). However, plants cultivated with vermicompost showed a slightly higher foliar P content. The same amounts of nutrients (NPK) were supplied with each dose of the three fertilizers and therefore the higher foliar phosphorus content in plants amended with vermicompost presumably corresponds to greater availability of this nutrient in the soil.

3.2. Effects of Vermicompost on the Quality of the Marketable Ears

The fertilizers applied had a significant effect on the quality of the marketable ears in the sweet corn plants. Grain content of the marketable ear was higher in response to vermicompost and manure amendment than in response to 100% inorganic fertilization (Figure 3).

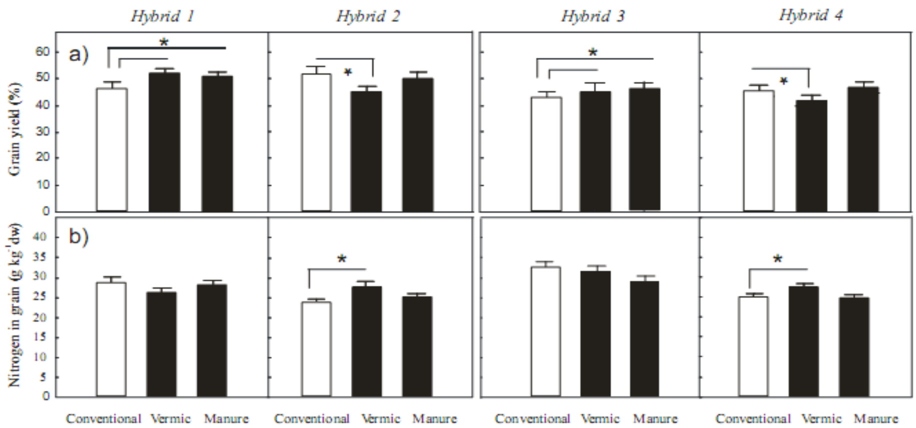

Figure 3. Grain yield (a) and N content (b) of the marketable ear of the sweet corn hybrids grown under the different fertilization treatments evaluated: conventional (100% inorganic NPK), vermicompost (75% inorganic + 25% organic NPK), and manure (75% inorganic + 25% organic NPK). Asterisks and bars indicate significant differences at $P< 0.05$. Values are means ± SE (Modified from Lazcano et al. 2011).

However, this depended on the hybrid considered, and significant decreases in grain content of the ears were also observed after the application of vermicompost. As well as the effects on grain content, the addition of vermicompost resulted in different grain chemical composition than in response to inorganic fertilizer. Plants cultivated with vermicompost had higher N contents in the grain although this was observed only in two of the four hybrids assayed (Figure 3). There were no differences in the P and K contents of the grain between the different fertilization treatments.

3.2. Effects of Vermicompost in Soil Biochemical and Microbiological Properties

Regarding the nutrient content of the soil at harvest there were no differences in $N\text{-}NH_4^+$, $N\text{-}NO_3^-$ or K_2O_5 between the fertilizing treatments and doses applied (Table 2). However, the PO_4^- content of the soil was significantly higher in the plots to which vermicompost was added than in the plots that received only inorganic fertilizers or manure (Table 2). However, this only took place at the high doses applied, whereas there were no differences between the treatments at the normal dose.

β-Glucosidase, protease and alkaline phosphomonoesterase enzyme activity rates were significantly higher in the soil plots amended with vermicompost and manure than in those treated with inorganic fertilizer (Figure 4). Fertilization with vermicompost and manure also favored growth of microorganisms in the soil. Bacterial growth increased significantly after application of the high doses of vermicompost and manure, although fungal growth was not affected (Figure 5). Organic amendments promoted microbial growth, which resulted in a higher soil microbial biomass, although only in the plots treated with manure (Figure 6a). The increase in soil microbial biomass was due exclusively to an increase in Gram-negative bacteria, as shown by the increased concentration of the PLFAs biomarkers for this microbial group (Figure 6b).

Table 2. Content of available plant macronutrients at harvest in the soils subjected to the different fertilization regimes. Values represent least square means ± standard error. Different letters within the same row indicate significant differences at P<0.05

	Normal			High		
	Conventional	Vermicompost	Manure	Conventional	Vermicompost	Manure
$N\text{-}NH_4^+$ (µg g dw^{-1})	4.66 ± 1.1a	5.19 ± 1.1a	4.70 ± 1.1a	6.23 ± 1.1a	5.25 ± 1.1a	4.60 ± 1.1a
$N\text{-}NO_3^-$ (µg g dw^{-1})	28.82 ± 8.8a	30.22 ± 8.8a	30.19 ± 8.8a	38.32 ± 8.8a	30.24 ± 8.8a	25.66 ± 8.8a
K_2O (%)	4.66 ± 0.0a	4.69 ± 0.0a	4.65 ± 0.0a	4.65 ± 0.0a	4.63 ± 0.0a	4.65 ± 0.0a
PO_4^- (µg g dw^{-1})	161.39 ± 4.0bc	164.32 ± 4.0b	162.38 ± 4.0bc	152.4 ± 4.0c	177.17 ± 4.0a	166.55 ± 4.0 ab

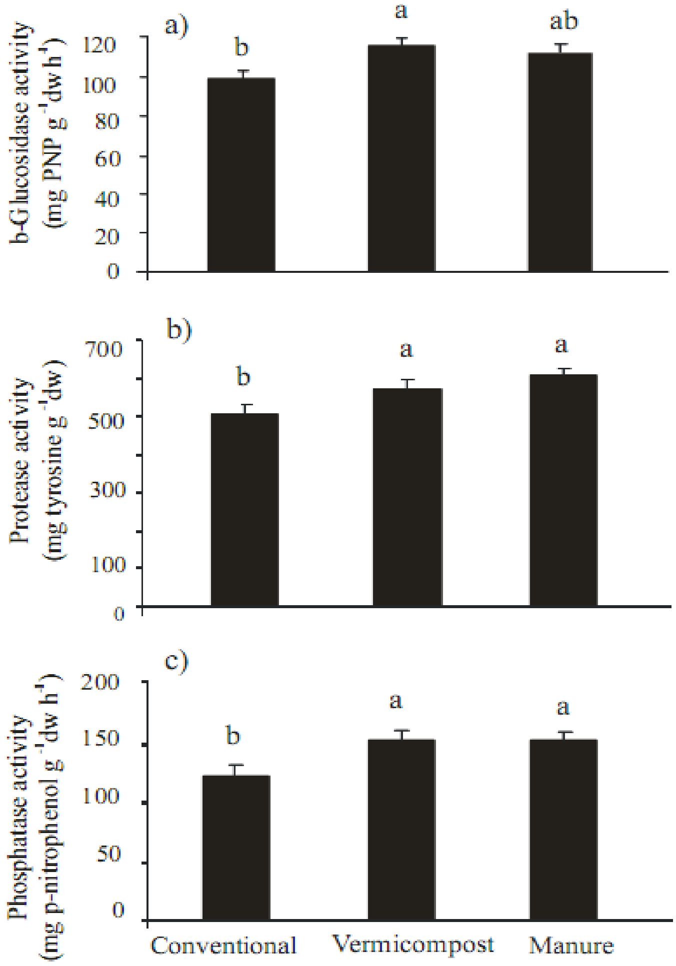

Figure 4. β-Glucosidase (a), protease (b), and phosphatase (c) enzyme activity of the soil amended with the different fertilization treatments evaluated: conventional (100% inorganic NPK), vermicompost (75% inorganic + 25% organic NPK), and manure (75% inorganic + 25% organic NPK). Bars are means ± standard error. Different letters indicate significant differences at P<0.05. (Modified from Lazcano et al. under review).

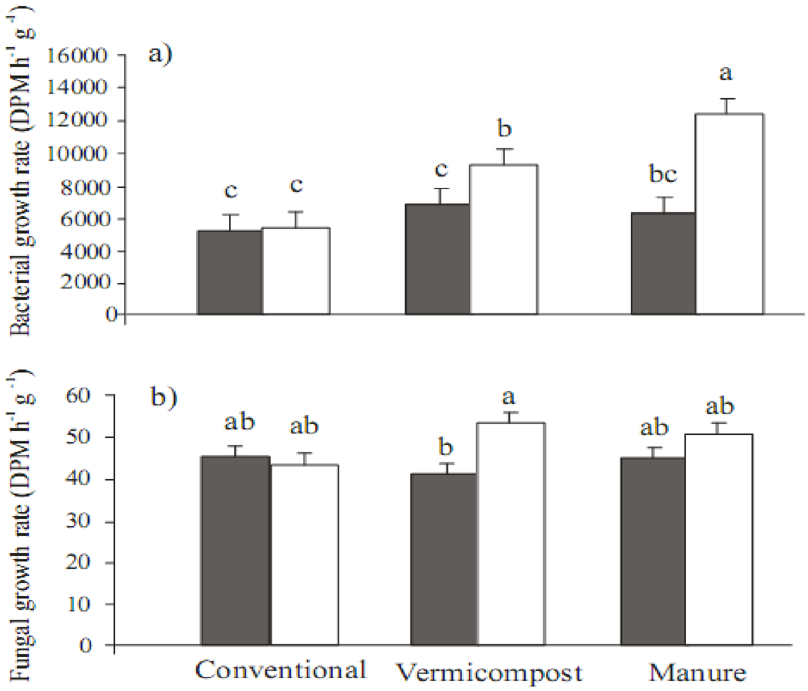

Figure 5. Bacterial and fungal growth (Modified from Lazcano et al. under review).

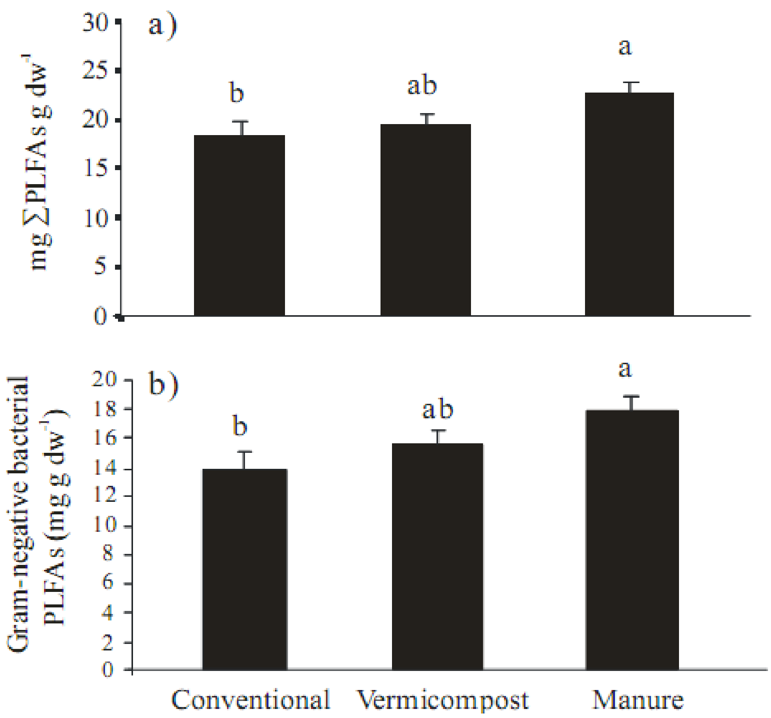

Figure 6. Microbial biomass and Gram negative bacteria (Modified from Lazcano et al. under review).

Replacement of 25% of the nutrients provided to the corn plants by Vermicompost maintains plant productivity at the same levels than 100% inorganic fertilization. In addition, vermicompost produces significant changes in soil biochemical and microbial properties promoting bacterial growth and increasing enzyme activity. In spite of the fact that the same amounts of N, P and K were provided with the three types of fertilizers at each dose, vermicompost amended plots exhibited higher phosphatase and phosphate levels, and the P content of the plants was higher than in soils with inorganic fertilization. The results presented here confirm that there is a large variation in vermicompost effects depending on the plant genotype. Therefore, within a given crop certain genotypes or varieties may be more suitable for organic or combined inorganic-organic cropping systems, than others.

CONCLUSIONS

Vermicompost can be described as a complex mixture of earthworm faeces, humified organic matter and microorganisms, which when added to the soil or plant growing media, increases germination, growth, flowering, fruit production and accelerates the development of a wide range of plant species. The enhanced plant growth may be attributed to various direct and indirect mechanisms, including biologically mediated mechanisms such as the supply of plant-growth regulating substances, and improvements in soil biological functions. Use of this type of organic fertilizer therefore has great potential; however some recent studies raise serious doubts about the general applicability of these results and propose a more complex model of action for these types of effects. Stimulation of plant growth may depend mainly on the biological characteristics of vermicompost, the plant species used, and the cultivation conditions. Extensive research on inorganic fertilization and plant breeding, carried out within the framework of conventional agriculture, has allowed agricultural producers to fine-tune nutrient inputs and plant needs in order to maximize yields. However, such detailed knowledge has not yet been attained as regards the interactions between plants and organic fertilizers in sustainable agriculture. Given the complex and variable composition of vermicompost in comparison with inorganic fertilizers and the myriad of effects that it can have on soil functioning, a clear and objective concept of vermicompost is required, and the complex interactions between vermicompost-soil-plant must be unraveled in order to maintain consumer confidence in this type of organic fertilizer.

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