EFFECTS OF VERMICOMPOSTS ON PLANT GROWTH

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a. Introduction

The use of organic matter such as animal manures, human waste, food wastes, yard wastes, sewage sludges and composts has long been recognized in agriculture as beneficial for plant growth and yield and the maintenance of soil fertility. The new approaches to the use of organic amendments in farming have proven to be effective means of improving soil structure, enhancing soil fertility and increasing crop yields. Organic matter are excellent source of plant-available nutrients and their addition to soil could maintain high microbial populations and activities (Pascual et. al. 1997; Zink and Allen 1998) with increased values of biomass C, basal respiration, biomass C:total organic C ratio, and metabolic quotient (qCO_2). Crop yields have increased with the corresponding improvements in soil quality from additions of organic matter. Significant yield increases using mulches from coffee husks (Bwamiki, 1998) and increases in productivity using animal manures and hay residues (Johnston et al. 1995) have been reported. Their important roles in the soil and their potentially positive effect on crop yields have made organic amendments a valuable component of farm fertilization and management programs in alternative agriculture. Forms of organic matter used include crop residues as mulches, among others.

Traditional composting of organic matter wastes has been known for many years but new methods of thermophilic composting have become much more popular in organic waste treatment recently since they eliminate some of the detrimental effects of organic wastes in the soil. Composting has been recognized as a low cost and environmentally sound process for treatment of many organic wastes (Hoitink, 1993). Furthermore, the rapid decomposition and raised temperatures during composting produce a relatively homogeneous, odor-free, pathogen-free and easy-to-handle product. Bevacqua and Mellano (1993) reported that compost-treated soils had lower pHs and increased levels of organic matter, primary nutrients, and soluble salts. In crop studies, Bryan and Lance (1991) found that tomatoes grown in compost-amended soils yielded more. Maynard (1993) also reported increases in fruit yield of compost-amended plants compared with those growing in soil alone. Other benefits from the use of compost include the possible reduction of hazards from nitrate leaching into groundwater compared to those from inorganically fertilized controls (Maynard, 1989). Furthermore, composting and composts have been reported to suppress plant pathogens. Hoitink and Fahy (1986) reported that composts were suppressive to soilborne plant diseases such as *Pythium* damping-off and *Rhizoctonia* damping-off. Population development of *Helicotylenchus spp.* and *Pratelynchus dianthus* (D’Errico and Di Maio, 1980) were suppressed by composts made from municipal refuse. Composts have also been reported to enhance population development of beneficial nematodes such as *cephaloids* and *rhabditids* (saprophagous nematodes).

A process related to composting which can improve the beneficial utilization of organic wastes is vermicomposting. It is a non-thermophilic process by which organic materials are converted by earthworms and microorganisms into rich soil amendments with greatly increased microbial activity and nutrient availability.

Vermicomposts are products derived from the accelerated biological degradation of organic wastes by earthworms and microorganisms. Earthworms consume and fragment the organic wastes into finer particles by passing them through a grinding gizzard and derive their nourishment from microorganisms that grow upon them. The process accelerates the rates of decomposition of the organic matter, alter the physical and chemical properties of the material, leading to a humification effect in which the unstable organic matter is fully oxidized and stabilized (Albanell et al., 1988; Orozco et al., 1996). The end product, commonly referred to as vermicompost is greatly humified through the fragmentation of the parent organic materials by earthworm sand colonization by microorganisms (Edwards and Neuhauser; Edwards, 1998).

Vermicomposts are finely divided peat-like materials with high porosity, aeration, drainage, water-holding capacity (Edwards and Burrows, 1988). They have greatly increased surface areas, providing more microsites for microbial decomposing organisms, and strong adsorption and retention of nutrients (Shi-wei and Fu-zhen, 1991). Albanell et al. (1988) reported that vermicomposts tended to have pH values near neutrality which may be due to the production of CO_2 and organic acids produced during microbial metabolism. They also reported that their moisture content was reduced progressively during vermicomposting giving final moisture contents between 45% and 60%, the ideal moisture contents for land-applied composts (Edwards 1983).

Vermicomposts have been described by several authors as humus-like materials and their degree of humification has been investigated fairly thoroughly. The humifying capacity of earthworms, in the production of vermicomposts, was reported by Businelli et al. (1983) after *Lumbricus rubellus* processed a range of mixtures: cow and rabbit dungs, cattle and horse dungs, cow and sheep dungs and municipal waste compost. Elvira et al (1996) reported that humification rates were increased significantly in paper-pulp mill sludge worked by *Eisenia andrei*. The transformations into humic compounds by passage through the earthworm gut revealed that the rates of humification of ingested organic matter were intensified during earthworm gut transit (Kretzschmar, 1984). Orlov and Biryukova (1996) reported that vermicomposts contained 17-36% of humic acid and 13-30% fulvic acid of the total concentration of organic matter. Senesi et al. (1992) compared the quality of humic acids present in vermicomposts, with those found in natural soils, using spectroscopic analysis procedures. They demonstrated that the metal-humic acid-like substances containing appreciable amounts of iron and copper, present in organic materials processed by earthworms, are similar to the humic acids common in soils and other sources irrespective of the nature of the parent material. This indicated that vermicomposting can produce considerable amounts of humic acid and as far as their metal complexation properties and behavior are concerned.

Among their superior chemical attributes, Edwards and Burrows (1988) reported that vermicomposts, especially those from animal waste sources, usually contained more mineral elements than commercial plant growth media, and many of these elements were changed to forms more that could be readily taken up by the plants, such as nitrates, exchangeable phosphorus, and soluble potassium, calcium, and magnesium. Orozco et al. (1994) reported that coffee pulp, increased the availability of nutrients such as phosphorus, calcium and magnesium, after processing by *Eisenia fetida*. Phosphorus was 64% higher in vermicomposts than in the original organic material which was suggested to be due to increased phosphatase activity from the direct action of gut enzymes and indirectly by the stimulation of microorganisms. Werner and Cuevas (1996) reported that most vermicomposts contained adequate amounts of macronutrients and trace elements of various kinds but were dependent on the sources of the earthworm feedstock. Businelli et al (1984) reported similar differences in chemical compositions of the vermicompost based on the substrate used. In their experiments, the highest elemental values were recorded in vermicomposts from cattle and horse manure mixture with 38.8% organic carbon, 2.7% total N and 1080 mg/kg NO_3-N. The lowest elemental concentrations were recorded in the municipal waste compost with only 9.5% organic carbon, 1.0% total N and 503 mg/kg NO_3-N. Edwards (1988) also reported large amounts of minerals in earthworm-processed animal wastes compared with those in a commercial compost. The wastes they investigated were separated cattle solids, separated pig solids, cattle solids on straw, pig solids on straw, duck solids on straw, and chicken solids on shavings. These materials contained mineral contents (% dry weight) ranging from 2.2–3.0 N, 0.4-2.9 P, 1.7-2.5 K, and 1.2-9.5 Ca compared to those of a commercial plant growth medium (Levington Compost) which only had 1.80, 0.21, 0.48 and 0.94 for N, P, K and Ca, respectively. The quantity and quality of the nutrients in vermicomposts can be explained by accelerated mineralization of organic matter, breakdown of polysaccharides and a higher rate of humification achieved during vermicomposting (Elvira et al., 1996; Albanell et al., 1988). In investigations into the bioconversion of solid paper-pulp mill sludge by earthworms, it was reported that total carbohydrate content decreased while total extractable carbon, non-humified fraction and humification rates increased by the end of the experiment.

Vermicomposts have many outstanding biological properties. They are rich in bacteria, actinomycetes, fungi (Edwards, 1983; Tomati et al., 1987; Werner and Cuevas, 1996) and cellulose-degrading bacteria (Werner and Cuevas, 1996). In addition, Tomati et al. (1983) reported that earthworm castings, obtained after sludge digestion, were rich in microorganisms, especially bacteria. Nair et al (1997) compared the microorganisms associated with vermicomposts with those in traditional composts. The vermicomposts had much larger populations of bacteria (5.7×10^7), fungi (22.7×10^4) and actinomycetes (17.7×10^6) compared with those in conventional composts. The outstanding physico-chemical and biological properties of vermicomposts makes them excellent materials as additives to greenhouse container media, organic fertilizers or soil amendments for various field horticultural crops.

b. Effects of vermicompost on growth of greenhouse crops

Many greenhouse experiments at the Ohio State University and elsewhere have demonstrated that vermicomposts can have consistently positive effects on plant germination growth and yields. Edwards and Burrows (1988) reported that vermicomposts increased ornamental seedling emergence compared with those in control commercial plant growth media, using a wide range of test plants such as pea, lettuce, wheat, cabbage, tomato and radish. In similar investigations, ornamental shrubs such as *Eleagnus pungens, Cotoneaster conspicua, Pyracantha, Viburnum bodnantense, Chaemaecyparis lawsonia, Cupressocyparis leylandii and Juniperus communis* usually grew better in vermicompost-supplemented mixtures than in a commercial plant growth medium when transplanted into larger pots or grown outdoors. They also reported that some ornamental plants such as chrysanthemums, salvias and petunias flowered earlier in vermicomposts compared to those grown in a commercial planting media. Plants grew better even in response to a 5% substitution of a 50:50 mixture of pig and cattle manure vermicomposts into a range of levels of a commercial plant growth medium. In greenhouse pot trials by Buckerfield et al (1999), using 0% to 100% mixtures of vermicompost and sand, similar increased growth trends were reported. Although the germination of radishes decreased with increasing vermicompost concentrations radish harvest weights were increased proportionally to the application rates of vermicomposts, with the yields of plants in 100% vermicompost being up to ten times greater than those in 10% vermicompost. Research at the Soil Ecology Laboratory, of The Ohio State University has shown consistently acceleration of germination of a wide range of crops by vermicomposts. Buckerfield (1999) reported that vermicompost applications inhibited germination initially, but subsequently weekly applications of the diluted extracts improved plant growth and increased radish yields significantly by up to 20%. The growth of tomatoes, lettuces, and peppers were reported to be best at substitution into soils at rates of 8-10%, 8%, and 6%, respectively, using duck waste vermicompost and peat mixture (Wilson and Carlile, 1989). At higher vermicompost substitution rates, same inhibition of growth that occurred was attributed to higher electrical conductivity (salt content) and excessive nutrient levels. Subler et al (1998) reported increased plant growth in commercial media, Metro-Mix (MM360), with a range of vermicomposts of substituted compared to growth in traditional composts from biosolids and yard waste traditional composts using tomatoes and marigolds as test plants. Metro-Mix 360 is prepared from vermiculite, Canadian sphagnum peat moss, bark ash and sand, and contains a starter nutrient fertilizer in its formulation. In Subler's experiments, increases in chlorophyll contents in response to vermicomposts were observed at early stages of marigold growth. Later, increases in leaf areas and significant increases in the total plant weights were reported in 10% vermicompost and 90% Metro Mix 360 combinations compared with 100% MM360. Significant increases in tomato seedling weights after substitution of 10 % and 20% vermicompost into MM360 were also reported. Raspberries grown in commercial media substituted with 20% pig manure vermicompost had much larger shoot dry weights compared with plants that received a complete inorganic fertilizer. In investigations in U.K. by Scott (1988), using hardy nursery stocks of *Juniperus, Chamaecyparis,* and *Pyracantha,* 20-50% substitution of vermicomposts from cattle manure, pig manure, and duck waste into MM360, with regular application rates of nutrients, produced better growth than plants grown in a peat: sand mixture used as a control. In the second year of this experiment, there were variable responses among the test crops used but 25% of all three types of animal waste used with the addition of a controlled release fertilizer, Osmocote (18:11:10), produced increased growth of *Juniperus sabina tamariscifolia*.

The effects of a variety of vermicomposts produced from cow manure, sheep manure, poultry manure, goat manure (mixed with carpet underfelt, lawn clippings, cardboard, and domestic waste), kitchen scraps, cardboard (mixed with wheat, maize, meat, lucerne and linseed meals, rice pollard and oat hulls), and pig wastes on plant growth were investigated by Handreck (1996) after mixing *Pinus radiata* bark and quartz sand in the growth media to which 30% of each of the vermicomposts was added. He reported that all the mixtures increased the dry weights of stocks (*Mathiola incana)* compared those in the control receiving no vermicompost. Similar trends in the germination of tomatoes and peppers grown in vermicomposts mixed with a commercial peat/sand planting medium have been reported. Chan and Griffiths (1988) reported stimulating effects of pig manure vermicomposts on the growth of soybeans (*Glycine max),* particularly in terms of increased root lengths, lateral root numbers, and internode lengths of seedlings. In another rooting experiment, that used vermicomposts improved in the establishment of vanilla (*Vanilla planifolia)* cuttings better than other growth media such as mixtures of coir pith and sand (Siddagangaiah et al., 1996). Similar responses in growth were observed from cloves (*Syzygium aromaticum*) and black peppers (*Piper nigrum*) sown into 1:1 mixtures of vermicompost and soil (Thankamani et al, 1996). Black pepper cuttings raised in vermicomposts were significantly taller and had more leaves than those grown in commercial potting mixtures. Plant heights, numbers of branches, and the longest taproots were on cloves grown in the vermicompost mixtures. Vadiraj et al (1993) reported enhanced growth and dry matter yield of cardamom (*Electtaria cardamomum)* seedlings in vermicomposted forest litter compared with that in other growth media tested. Vermicomposts produced from coir dust increased the yields of onions (*Allium cepa)* (Thanunathan, 1997).

Atiyeh (1999) demonstrated in work from OSU that vermicompost produced from pig manure substituted into Metro-Mix 360, at a range of concentrations increased vegetable and ornamental seedling growth, even at low concentrations, when all the nutrients needed by the crops were available. However, the larger percentages of vermicomposts substituted into the soilless commercial growth medium (MM360) did not always improve plant growth possibly because of salt content or other factors. They demonstrated further, that as little as 5% of vermicompost substituted into MM360 was enough to produce dramatic growth responses of test crops. Significant increases in the growth of tomato seedlings in 10% vermicompost from pig waste and 90% MM360 commercial medium occurred compared with those of plants grown in 100% Metro-Mix 360, 100% peat/perlite mixture or 100% coir/perlite mixture (Atiyeh et al 2000). Substitution of MM360 with 10%, 20%, and 50% vermicompost into these media all stimulated plant growth significantly, independent of nutrient supply, with significant increases in plant height and root and shoot biomass. Atiyeh et al (2000b) reported that the substitution of Metro-Mix 360 by 10% or 50% pig manure vermicompost increased the dry weights of tomato seedlings significantly compared to those grown in 100% Metro-Mix 360. The largest marketable fruit yields obtained were in response to a mixture of 80% Metro-Mix 360 and 20% vermicompost. Lower concentrations of vermicomposts (less than 50%) into the MM360 usually produced greater growth effects than those of large amounts: 20% vermicompost substitution resulted in 12.4% more tomato fruit weights than those in MM360 and substitutions of 10%, 20% and 40% vermicompost reduced the proportions of non-marketable fruits significantly and produced larger tomato fruits (Figure 1). Mixtures containing 25% and 50% pig manure in 75% and 25% Metro-Mix 360 increased the rates of seedling growth of tomatoes and greater increases in seedling growth were recorded with 5% pig manure substitution into MM360, when inorganic nutrients were supplied daily (Atiyeh et al, 2001).

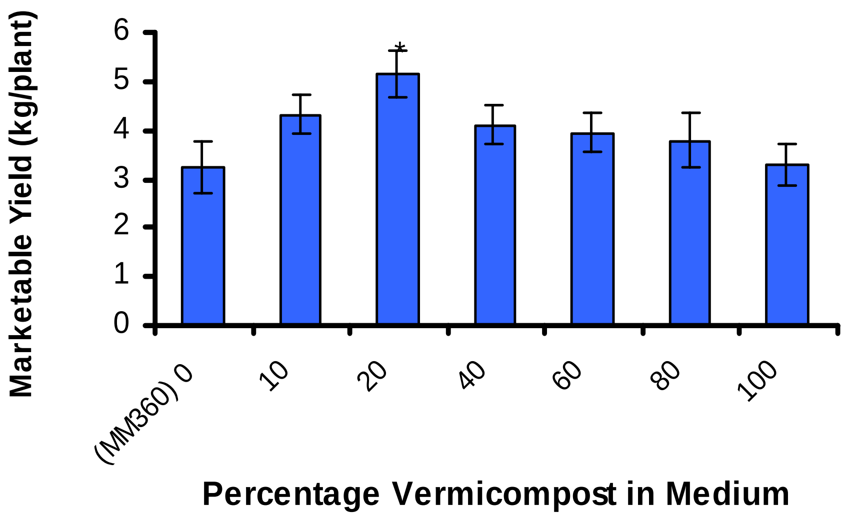
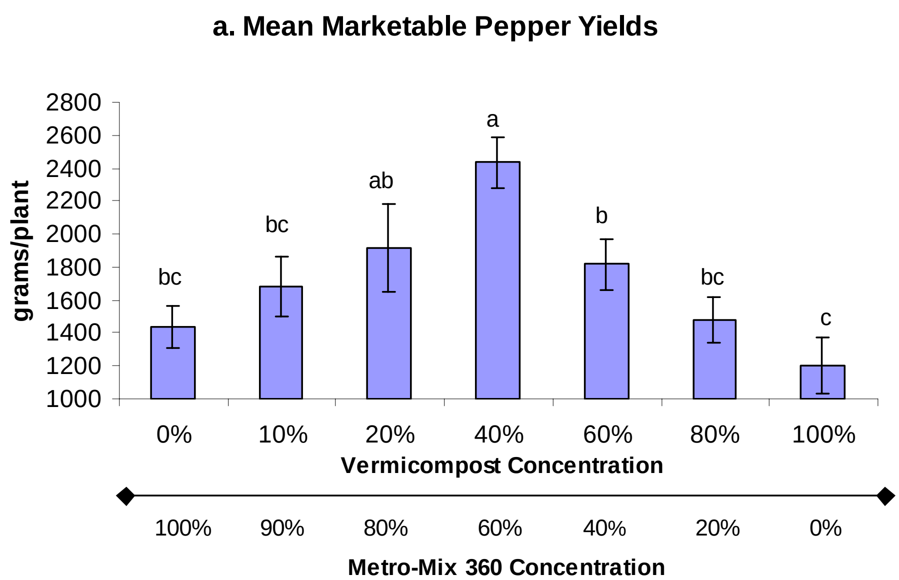


Figure 1. Marketable yields of tomatoes grown in the greenhouse in a range of mixtures of vermicompost and a commercial medium Metro-Mix 360 (with all necessary nutrients supplied). (From Atiyeh et al, 2001)

More recently, substitution of Metro-Mix 360 by 30% or 40% pig manure vermicomposts produced more vegetative growth and flowers of marigolds in mixtures containing 40% pig manure vermicompost (Atiyeh et al, 2002). Pig manure substitutions ranging from 20% up to 90% into MM360 produced marigold plants with significantly more roots. Peppers produced greater fruit yields when grown in mixtures containing 40% food waste vermicomposts and 60% MM360 (Figure 4) (Arancon et al, 2004).



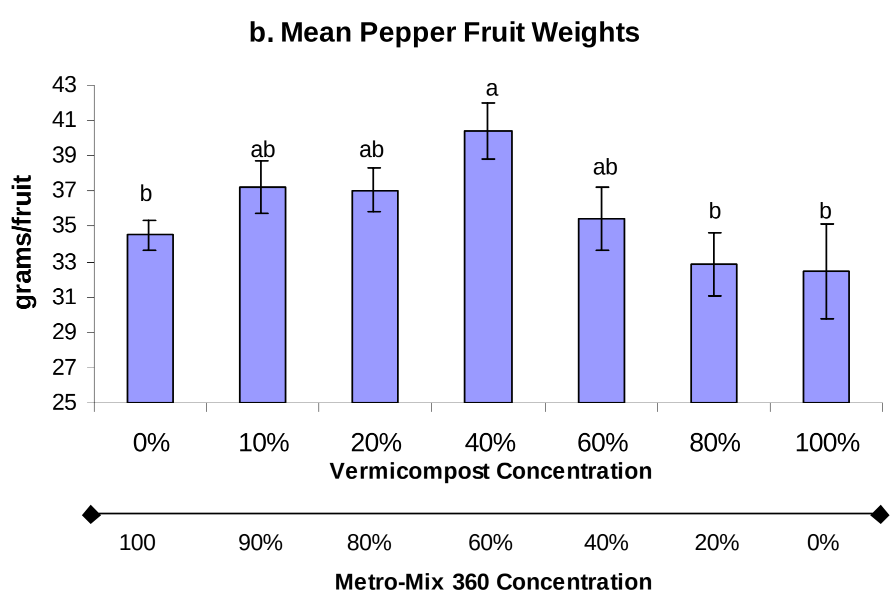


Figure 2. a) Marketable yields and average fruit weights of peppers in the greenhouse

Using petunias as test plants, most flowers were produced in mixtures containing 40% food waste vermicompost and 60% MM360. or 40% paper waste vermicompost and 60% MM360 (Figure 6) When cow manure vermicompost was used, petunias produced more flowers in mixtures containing 20% vermicompost and 80% MM360 (Arancon et al, unpublished data).

Figure 3. Number of flowers of petunias grown in food waste vermicompost and MM360.

The increased yields of peppers or flowering of marigolds were not associated with the amounts of available mineral-N, nor amounts of microbial biomass, during the later growth and fruiting stages of peppers, marigolds or tomatoes since all plants were provided with needed nutrients (Atiyeh et al, 2002; Arancon et al, 2005). For instance, the assimilation of nitrogen into the shoot tissues of peppers was not correlated positively with the yields of peppers. All treatments in the greenhouse experiments were watered with nutrient solutions regularly, which eliminate nutrients as the major contributing factor in increasing yields of tomatoes or peppers. However, it is possible that other growth-enhancing factors, resulting from the introduction of smaller concentrations of food waste vermicompost into Metro-Mix 360 may have caused the growth change. These factors could include: improvements of in the physical structure of the container medium, increases in enzymatic activities, increased numbers of beneficial microorganisms or biologically-active plant growth-influencing substances such as plant growth regulators and humic acids.

c. Effects of vermicomposts on growth of field crops

A number of field experiments have reported positive effects of quite low application rates of vermicomposts to field crops. These applications were comparable with rates that improved growth on the same crops in greenhouse experiments. When cabbage was grown in compressed blocks made from pig waste vermicompost, after transplanting to the field they were larger and more mature at harvest compared to those grown in commercial blocking material (Edwards and Burrows, 1988). In a field experiment applying cassava peel mixed with guava leaves and vermicomposts from poultry droppings, Mba (1983) reported more shoot biomass and increased seed yields of cowpeas. Masciandro et al (1997), investigated the effects of direct applications of vermicomposts produced from sewage sludge into the soil as well ferti-irrigation with humic extracts from vermicomposts. They reported a greater growth index of garden cress (*Lepidium sativum)* treated with vermicomposts than in control treatments with no vermicompost applications. Soil analyses after the vermicompost applications showed marked improvements in the overall physical and biochemical properties of the soil. A surface application of vermicompost derived from grape marc, spread under grape vines covered with a straw and paper mulch increased yields of a grape variety Pinot Noir by 55% (Buckerfield and Webster, 1998). The increases in yields included large increases in both bunch-weights and bunch numbers and no losses in flavor. In an experiment at a second site, vermicompost applications from animal manures, under straw mulch, increased Chardonnay grape yields by up to 35% and vermicompost applications tended to have greater effects on yields when applied under mulches than when applied directly to the soil surface possibly through degradation of vermicompost on exposure to sun and air. In later experiments Webster reported that a single application of vermicompost to grapes still had positive effects on yields for 5 years. Venkatesh et al (1999) reported that yields of Thompson Seedless grapes were significantly greater when vermicomposts were applied. Seyval grapes produced greater marketable yields, more fruit clusters per vine and bigger berry sizes after applications of food waste and paper waste vermicomposts at rates of 2.5 t/ha or 5 t/ha supplemented with inorganic fertilizers (Arancon et al, unpublished data). Vadiraj et al (1998) compared vermicomposts application rates of 5 t/ha up to 25 t/ha in 5 t/ha increments on growth of three varieties of coriander. The responses to the vermicompost applications differed for all three varieties tested. However, he reported RCr-41 produced the most herbage among the three. Maximum herbage yields from all three were occurred 60 days after sowing. The varieties RCr-41, Bulgarian, and Sakalespur Local attained largest yields at vermicompost applications rates of 15T/ha, 10-25T/ha, and 20T/ha, respectively.

Some field experiments have involved amending soils with vermicomposts in conjunction or combination with recommended inorganic fertilization programs. Vermicomposts applied at 12 t/ha to field soils together with 100% or 75% of the recommended application rate of inorganic fertilizers increased yields of okra (*Abelmoschus esculentus* Moench) significantly (Ushakumari et al, 1999). Amending soils with vermicomposts, applied at rates of 2 kg/plant, together with 75% of the recommended rate of inorganic fertilizers, promoted shoot production of bananas (Athani et al, 1999). Vermicompost applications to field soils combined with 50% of the recommended inorganic fertilizers increased the yields of tomatoes (Kolte et al, 1999). Increased wheat yields were obtained from the residual fertility in soils that had been treated with 50% vermicompost and 50% inorganic fertilizers the previous year (). Vasanthi and Kumaraswamy (1999) reported increased yields of rice after amending soils with vermicomposts at rates of 5t/ha or 10t/ha supplemented with recommended application rates of inorganic fertilizer. A lower application rate of 2t/ha vermicomposts plus recommended amounts of inorganic fertilizers, increased tomato yields to a level similar to those of tomatoes in soils treated with 4 t/ha vermicomposts and 50% of the recommended rates of inorganic fertilizers (Patil et al, 1998). Tuberlets from a true potato seed line, produced the greatest marketable yields, after amending the soils with 75% of the recommended inorganic fertilizers and 2.5 t/ha vermicomposts (Mrinal et al., 1998). Sunflowers (*Hilianthus annuus*) yielded most after soil treatments with 50% of the recommended application rates of inorganic fertilizer and 5t/ha or 10t/ha of vermicomposts (Devi et al., 1998). Peas (*Pisum sativum*) increased yields and production after amending soils with 100% of the recommended application rate of inorganic fertilizers, in combination with vermicomposts produced from farm manures applied at rates of 10t/ha to soils (Ramachandra et al., 1998). Zende et al (1998) reported increased yields of sugarcane after amending soils with vermicomposts at rates of 5t/ha together with 100% of the recommended application rate of inorganic fertilizers. Mulberry (*Muros sp*) growth increased after amending soils with vermicomposts applied at rates of 10t/ha together with 100% of the recommended application rates of inorganic fertilizers to soils (Murakar et al, 1998). Flowering of China aster (*Callistephus chinensis* L.) increased when it was grown in soils amended with 10 t/ha vermicomposts, produced from farm manures, together with 100% of the recommended application rate of inorganic fertilizers. (Nenthra et al, 1999).

Arancon et al (2002) reported significantly increased growth and yields of field tomatoes (*Lycopersicon esculentum*) and peppers *(Capsicum anuum grossum*) when vermicomposts, produced commercially from cattle manure, food waste or recycled paper, were applied to field plots at rates of 20 t/ha and 10 t/ha in 1999 and at rates of 10 t/ha and 5 t/ha in 2000 (Figure 4) compared with those receiving equivalent amounts of inorganic fertilizer.

Food waste and recycled paper vermicomposts were applied at rates of 10 t/ha and 5 t/ha in 2000 to strawberries (*Fragaria spp*.). All of the vermicompost-treated plots were supplemented with inorganic fertilizers to equalize the available N levels in all plots at transplanting. The marketable tomato yields in the vermicompost (plus fertilizers) plots were consistently and significantly greater than those from inorganic-fertilizer only treated plots. There were significant increases in shoot weights, leaf areas and marketable fruit yields of pepper plants grown in plots that were treated with vermicomposts compared to those of plants grown in inorganic fertilizers. Leaf areas, numbers of strawberry suckers, numbers of flowers, shoot weights, and marketable fruit yields of strawberries all increased significantly in response to supplemented vermicompost applications compared to those from strawberries that received inorganic fertilizers only (Arancon et al, 2004) (Figure 5).

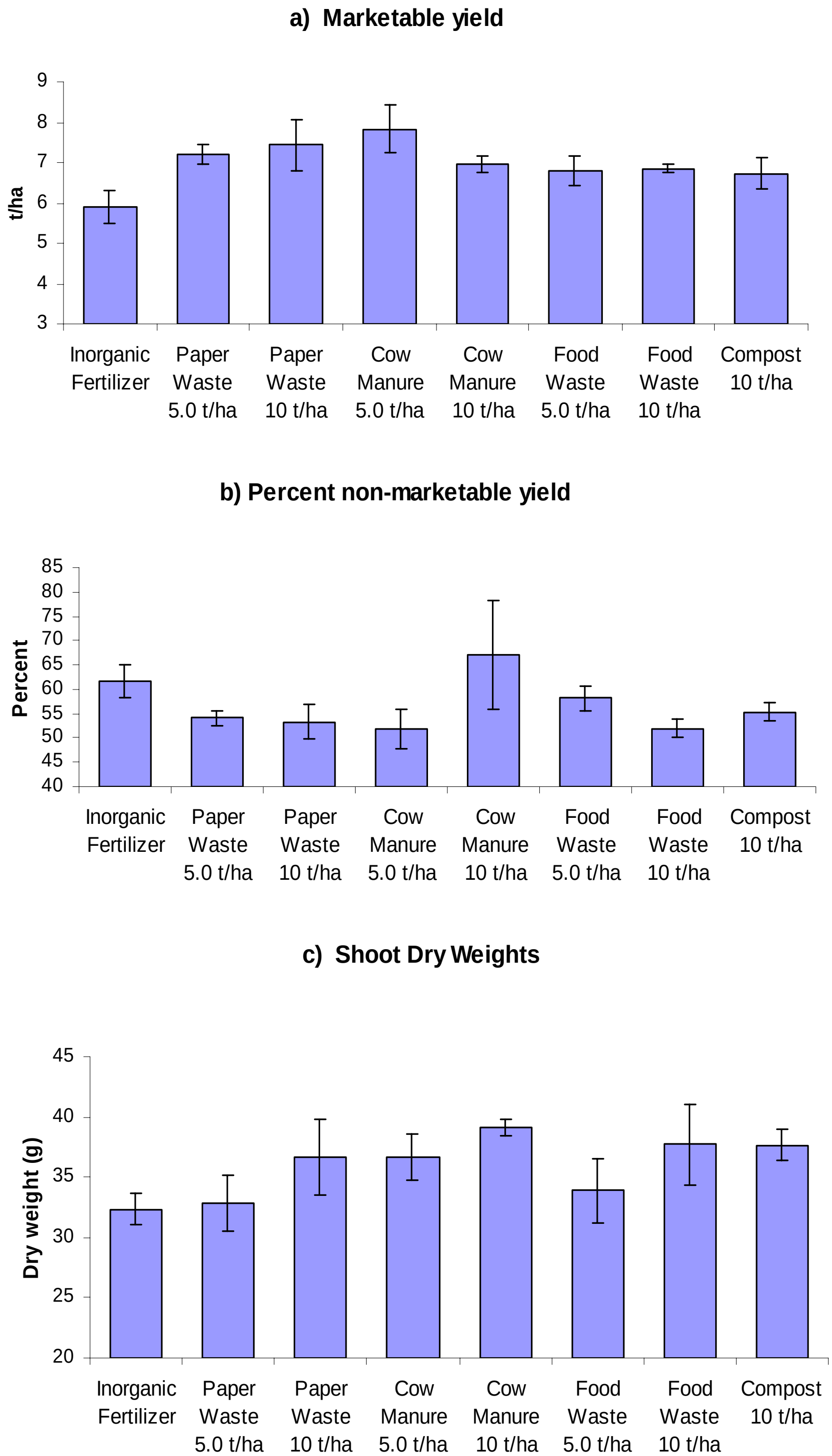


Figure 4. Marketable yields, percentage non-marketable yields and shoot dry weights (Means ± SE) of peppers at harvest in 2000. Columns designated with same letter(s) are not significantly different at $P < 0.05$.

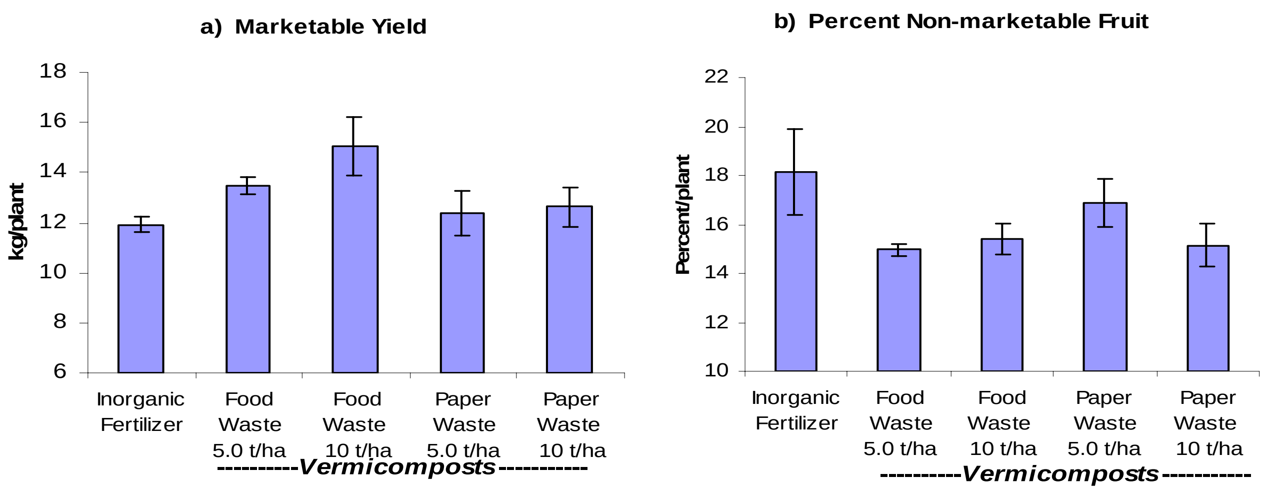


Figure 5. Marketable and percentage of non-marketable yields of strawberries at Piketon, OH. (Arancon et al, 2004)

c. Physico-chemical changes in soils in response to vermicompost applications

The improvements in growth and yields of crops grown in potting media in greenhouses or in field soils that had been substituted or amended with vermicomposts could be attributed to several factors. Firstly vermicomposts contribute to improvements in physico-chemical and biological characteristics of the planting media or field soils that favored better plant growth. For instance, incorporating pig manure vermicomposts, into a commercial bedding plant medium, Metro-Mix 360, decreased total porosity, percentage air space, pH and ammonium concentrations significantly whilst bulk density, container capacity, electrical conductivity, overall microbial activity and nitrate concentrations increased significantly in response to increasing substitutions of vermicomposts into MM 360 (Atiyeh et al, 2001). The changes in pH reported contrasted with those from the work of Tyler et al (1993) who reported increases in substrate pH in response to increasing concentrations of composted turkey litter added to a plant container medium. The electrical conductivity, representing salt content, increased linearly in response to increasing concentrations of pig manure vermicomposts in planting media mixtures, (Atiyeh et al, 2001); and Klock (1997) reported that electrical conductivity of planting media substituted with vermicomposts increased in the range of 1.3 to 2.8 times over those untreated control. Since most of the mineral nitrogen in vermicompost is usually in the nitrate form (Atiyeh et al., 2001; Orozco et al., 1996; Benetiz, 1999), it was not surprising that amounts of nitrates in the planting media increased with the increasing vermicompost concentrations (Atiyeh et al., 2001).

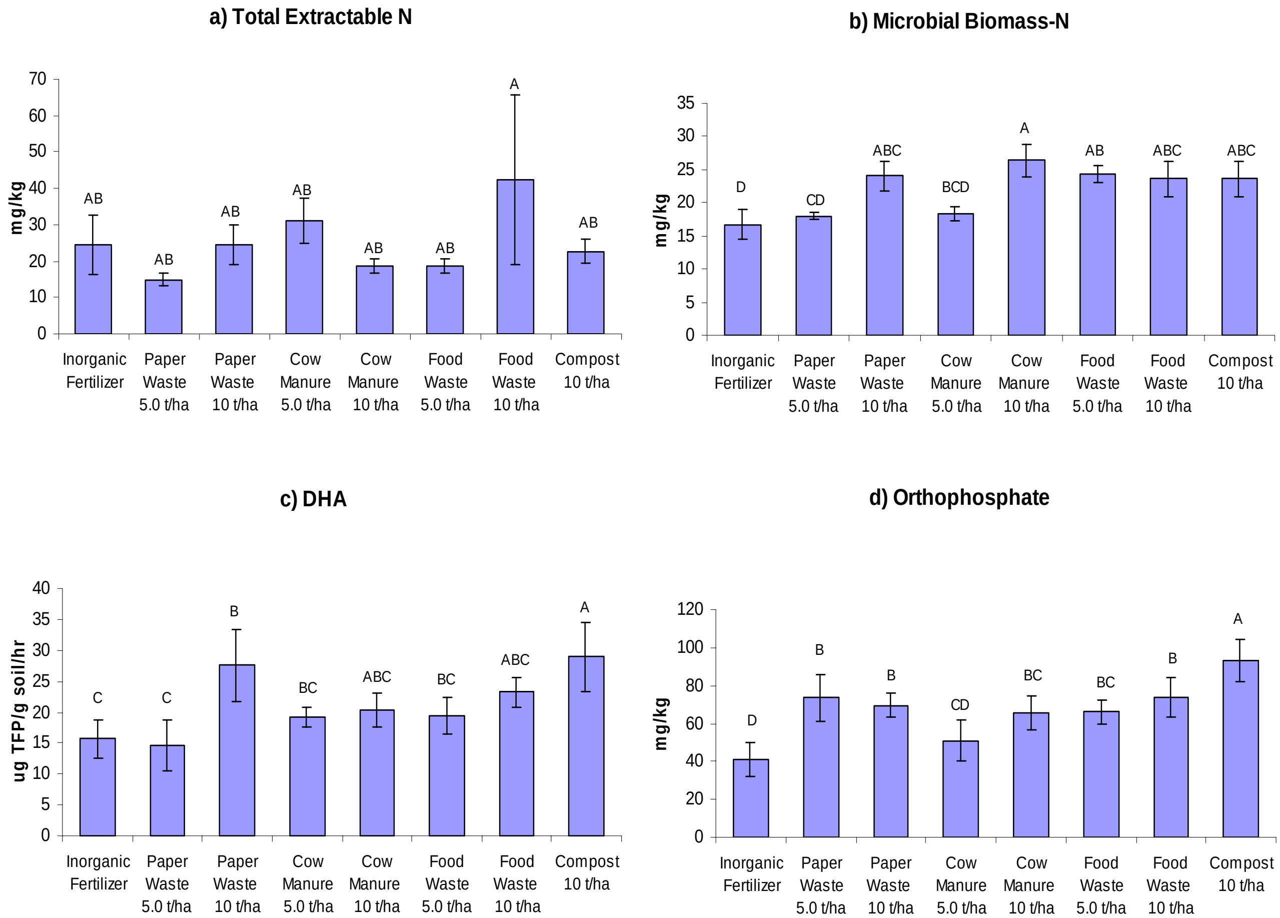


Figure 6. Nitrate-N, microbial biomass-N, dehydrogenase activity and orthophosphates (Means ± SE) in soils planted with pepper at harvest in 2000. Columns designated with same letter(s) are not significantly different at $P < 0.05$.

Reddy and Reddy (1999) reported significant increases in micronutrients in field soils after vermicompost applications compared to those in soils treated with animal manures. In other experiments, amounts of soil nitrogen increased significantly after incorporating vermicomposts into soils (Sreenivas et al, 2000; Kale et al, 1992; Nethra et al, 1999) and the amounts of P and K available also increased (Venkatesh et al, 1998). Field experiments at The Ohio State University (Arancon et al, 2002) demonstrated that soils treated with vermicomposts supplemented to recommended rates with inorganic fertilizers, and planted with tomatoes, had amounts of, total N, orthophosphates, dehydrogenase enzyme activity, and the microbial biomass, that were usually greater than those that received equivalent amounts of inorganic fertilizers only. In similar experiments planted with peppers, there was more microbial biomass N and orthophosphates in soils to which vermicomposts were applied than in those receiving inorganic fertilizers only (Figure 6). In soils planted with strawberries, the amounts of total extractable N, microbial biomass N and dissolved organic N were statistically similar, between all treatments at the end of the growth cycle of strawberries but there were more orthophosphates in those soils that received vermicompost treatments than in soils treated with inorganic fertilizers. Maheswarappa et al (1999) reported increased amounts organic carbon, improvements in pH, decreased bulk density, improved soil porosities and water-holding capacities, increased microbial populations and dehydrogenase activity of soils in response to vermicompost treatments.

e) Plant growth regulator production in vermicomposts

There is a very substantial body of evidence demonstrating that microorganisms, including bacteria, fungi, yeasts, actinomycetes and algae, are capable of producing plant growth hormones and plant growth regulators (PGRs) such as auxins, gibberellins, cytokinins, ethylene and abscisic acid in appreciable quantities (Arshad and Frankenberger, 1993; Frankenberger and Arshad, 1995). Many of the microorganisms that are common in the rhizospheres of plants can produce such plant growth-regulating substances, for instance Barea et al (1976) reported that, of 50 bacterial isolates obtained from the rhizosphere of various plants, 86% could produce auxins, 58% gibberellins and 90% kinetin-like substances. There have been many studies of the production of plant growth-regulating substances by mixed microbial populations in soil, but there are relatively few investigations into their availability to plants, and persistence and fate in soils or documenting reliably their effects on plant growth (Arshad and Frankenberger 1993).

Several workers have shown that PGRs can be taken up by plants from soil in sufficient quantities to influence plant growth. It was shown that auxins produced by *Azospirillum brasilense* could affect the growth of graminaceous plants (Kucey, 1988). There is increasing evidence that microbially-produced gibberellins can influence plant growth and development (Mahmoud et al., 1984; Arshad and Frankenberger, 1993). Increased vigor of seedlings has been attributed to microbial production of cytokinins by *Arthrobacter* and *Bacillus* spp in soils (Jagnow, 1987).

Since the process of vermicomposting increases microbial diversity and activity dramatically, it is possible that vermicomposts could be a definitive source of plant growth regulators produced by interactions between microorganisms and earthworms, which could contribute significantly to enhancement of plant growth, flowering and yields. The first suggestion that earthworms might produce plant growth regulators was by Gavrilov (1963). The presence of plant growth-regulating substances in the tissues of *Aporrectodea caliginosa, Lumbricus rubellus* and *Eisenia fetida* was confirmed by Nielson (1965) who isolated indole substances from earthworms and reported increases in growth of peas due to the earthworm extracts. He also extracted a similar substance that stimulated plant growth from *Aporrectodea longa, Lumbricus terrestris,* and *Dendrobaena rubidus* but his experiments did not exclude the possibility of PGRs that he found being produced by microorganisms living in the earthworm guts and tissues. Graff and Makeschin (1980) tested the effects of substances produced by *L. terrestris, A. caliginosa* and *E. fetida* on the dry matter production of ryegrass. They added eluates from pots containing earthworms to pots containing no earthworms planted with ryegrass.

They concluded that plant growth-influencing substances (PGIs) were released into the soil by all three species, but did not speculate further on the nature of these substances.

Tomati et al. (1983, 1987, 1988, 1990) Grappelli et al. (1987) and Tomati & Galli (1995) tested vermicomposts produced from organic wastes by the action of earthworms, as media for growing ornamental plants and mushrooms. They concluded that the growth increases that occurred in all of their experiments were much too large to be explained purely on the basis of the nutrient contents of the vermicomposts. Moreover the growth changes observed included stimulation of rooting, dwarfing, time of flowering, and lengthening of internodes. They compared the growth of *Petunia, Begonia*, and *Coleus* after adding aqueous vermicompost extracts, to adding auxins, gibberellins, and cytokinins, to soil and concluded that there was excellent evidence of potential hormonal effects produced by earthworm activity and this conclusion was supported by the high levels of cytokinins and auxins they found in the vermicomposts. Krishnamoorthy and Vajranabhaiah (1986) reported, in laboratory experiments involving large earthworm populations, that seven species of earthworms could promote the production of cytokinins and auxins in organic wastes very dramatically. They also demonstrated a significant positive correlations (r = 0.97) between earthworm populations, and the levels of cytokinins and auxins present in ten different field soils and concluded that levels of earthworm activity were linked strongly with PGR production. They reported that auxins and cytokinins produced through earthworm activity could persist in soils for up to 10 weeks although they degraded in a few hours if exposed to sunlight.

Edwards and Burrows (1988) reported that the increases in growth of 28 ornamentals and vegetables, in plant growth media produced by the processing of organic wastes by the earthworm *E. fetida*, was much greater than in commercially-available plant growth media, and was too much to be explained solely through influence of earthworm activity on plant nutrient quality and availability. They found that the *growth of ornamentals was influenced significantly* even when the earthworm-processed organic wastes were diluted 20:1 with other suitable materials and the *nutrient content balanced to that of comparable media*. Moreover, the growth patterns of the plants, including leaf development, stem and root elongation, as well as flowering by biennial ornamental plants, in the first season of growth, indicated the likelihood of some biological factor other than nutrients, such as the production of plant growth-influencing substances e.g. plant hormones, humic acids or free enzymes, being responsible. Scott (1988) reported that the growth of hardy ornamentals, *Chaemocyparis lawsonian Elaeagnus pungens Cuppressocypari leylandii*, *Pyracantha* spp. *Cotoneaster conspicus* and *Viburnum bodnantense* increased significantly after addition of low levels of earthworm-worked organic wastes to the growth media even when the nutrients in the two media were balanced.

Vermicomposts originating from animal manure, sewage sludges or paper-mill sludges have all been reported to contain large amounts of *humic substances* (Albanell et al., 1988; Petrussi et al., 1988; Senesi et al., 1992; Garcia et al., 1995; Masciandaro et al., 1997; Elvira et al., 1998). Studies of the effects of humic substances on plant growth, under conditions of adequate mineral nutrition, have consistently produced in positive growth effects (Chen and Aviad, 1990). For instance, applications of humic substances to soils increased the dry matter yields of corn and oat seedlings (Lee and Bartlett, 1976; Albuzio et al., 1994); numbers and lengths of tobacco roots (Mylonas and McCants, 1980); dry weights of shoots, roots, and nodules of soybean, peanut, and clover plants (Tan and Tantiwiramanond, 1983); vegetative growth of chicory plants (Valdrighi et al., 1996); and induced shoot and root formation in tropical crops grown in tissue culture (Goenadi and Sudharama, 1995).

During the last decade, the biological activity of humic substances, particularly those derived from earthworm feces in plant growth, have been investigated extensively (Dell'Agnola and Nardi, 1987; Nardi et al., 1988; Muscolo et al., 1993, 1996, 1999). Dell'Agnola and Nardi (1987) reported hormone-like effects of depolycondensed humic fractions obtained from the feces of the earthworms *Allolobophora rosea* and *Allolobophora caliginosa*. Treating carrots cells with humic substances, obtained from the feces of the earthworm *A. rosea*, increased their growth and induced morphological changes similar to those induced by auxins (Muscolo et al., 1999). It seems very likely that vermicomposts, which consist of an amalgam of humified earthworm feces and organic matter, can stimulate plant growth considerably beyond that produced by mineral nutrients because of the effects of the humic substances present in the vermicomposts.

Humates can be extracted from organic materials such as vermicomposts by a classic acid/alkali fractionation technique (Valdrighi et al., 1996) yielding approximately 4g humic acids per kg of vermicompost (Atiyeh et al., 2001). Typical growth responses, that they obtained after treating plants with humic substances, include increased growth in response to increasing concentrations of humic substances, but with a decrease in growth at higher concentrations of the humic materials (Atiyeh et al, 2000) (Figure 7). This pattern resembles that of increasing application of increasing vermicompost rates to tomatoes (Atiyeh et al., 2001) (Figure 4).

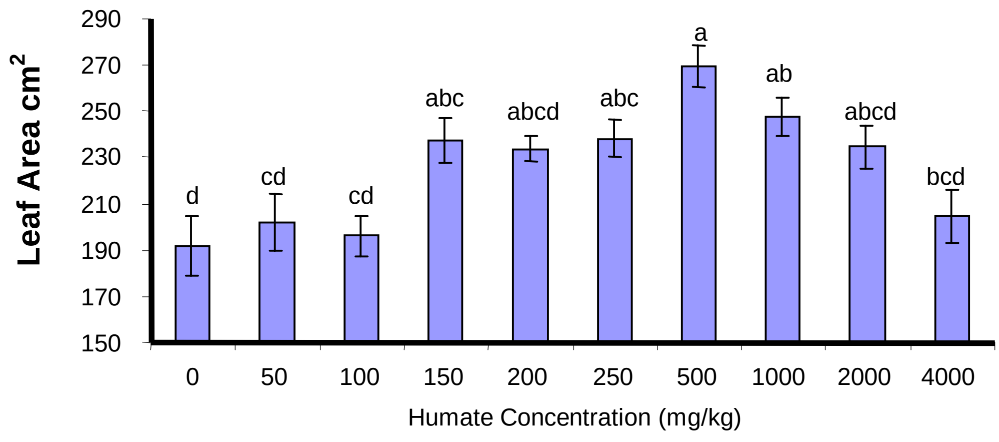


Figure 7. Effects of humic acid extracts from pig manure vermicompost, applied to a soil-less potting medium at different concentrations, on tomato leaf area (with all needed nutrients supplied). (From Atiyeh et al, 2000).

Such stimulatory effects of humic substances at low concentrations has been explained by various theories, the most convincing of which hypothesizes a "direct" action on the plants, which is hormonal in nature, together with an "indirect action" on the metabolism of soil microorganisms, the dynamics of soil nutrients, and soil physical conditions (Cacco et al., 1984; Nardi et al., 1988; Albuzio et al., 1989; Casenave de Sanfilippo et al., 1990; Chen and Aviad, 1990; Muscolo et al., 1993, 1996, 1999). However, none of these hypotheses provide a completely satisfactory explanation of how humic substances influence plant growth.

The possibility that PGRs may become adsorbed on to humic fractions so that any growth response is a combined PGR/humic one which was hypothesized by Edwards (1998) and Atiyeh et al (2001), has been convincingly confirmed by research by Canella et al. (2000) who identified exchangeable auxin groups attached to humic acids in extracts from cattle manure, following a structural analysis. The humic acid extracts enhanced root elongation, lateral root emergence and plasma membrane H+ -ATPase activity of maize roots. In field experiments (Arancon et al, 2002) reported similar increases in growth and yields of tomatoes, peppers and strawberries in and the contribution of nutrients in the significant increases of growth and yield of the field crops was eliminated as a possibility, since all treatments were supplemented with inorganic fertilizers to equalize initial nutrient contents of the soil. Vermicomposts contain very rich and diverse microbial populations (Edwards, 1983; 2004). Their applications to soils may have added to the indigenous soil microorganism populations, activity and diversity, resulting in much larger, richer and diverse soil microbial populations. Some microorganisms can form synergistic relationships in plant rhizospheres, by acting as root extensions, thereby increasing the capacity of plants to utilize soil moisture and nutrients, and at the same time they benefit from plant root exudates. Other byproducts of microbial activities known to promote plant growth, include producing antibiotics, disease antagonists and plant growth influencing substances such as hormones and humates. Research reports have shown that some microorganisms, such as the *pseudomonads* are antagonistic to plant pathogens and by this mechanism simply microbial competition can induce resistance to plant diseases. Such effects were demonstrated in experiments on the suppression of *Verticillium wilt* on strawberries, powdery mildew and Phomopsis on grapes in the field and suppression of *Pythium* and *Rhizoctonia* on cucumbers and radishes in the laboratory (Chaoui et al, 2002).

The production of plant growth hormones, such as indole acetic acid (IAA), gibberellins and cytokinins, as well as other PGRs such as humates are some of the byproducts of the increased microbial activities promoted by earthworms which probably directly influence plant growth and yields. Several workers have reported the presence of humates and plant growth hormones such as auxins, gibberillic acids and cytokinins in vermicomposts. Bioassays in our laboratory have demonstrated the presence of plant-growth-influencing substances (PGIs), in the forms of hormones occurring in aqueous extracts from vermicomposts, as well as humic acids obtained in base extracts from vermicomposts. When these extracts were applied in relatively small amounts, plant produced significant positive effects on plant growth and these positive effects were very similar to those of plant growth-hormone treatments on plants. This may explain the results of greenhouse trials, when plants that were grown in commercial soilless growth media such as MM360 and substituted at different rates with vermicomposts, germinated, flowered and fruited better than in the in the control media despite full nutrient applications in all treatments (Atiyeh 2000a, 2000b, 2001). In field experiments, the presence of such PGIs could also explain the increases in growth and yield that occurred even at the lowest rate of vermicompost applications (2.5 t/ha) (Arancon et al, 2002).

Conclusions

When used at lower substitution rates, vermicomposts can increase growth, flowering and yields of vegetable and ornamental crops. Similarly, vermicomposts applied at very low rates e.g. 2.5 t/ha or 5 t/ha can significantly increase growth and yields of highly valuable vegetable and fruits crops in the field. The effects of vermicomposts on plants are not solely attributed to the quality of mineral nutrition is provided but also to its other growth regulating components such as plant growth hormones and humic acids. Furthermore, the application of vermicomposts in the field enhances the quality of soils by increasing microbial activity and microbial biomass which are key components in nutrient cycling, production of plant growth regulators and protecting plants soil-borne disease and arthropod pest attacks.

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