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The use of vermicompost in organic farming: overview, effects on soil and economics

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Abstract

Vermicomposting is a process in which earthworms are used to convert organic materials into humus-like material known as vermicompost. A number of researchers throughout the world have found that the nutrient profile in vermicompost is generally higher than traditional compost. In fact, vermicompost can enhance soil fertility physically, chemically and biologically. Physically, vermicompost-treated soil has better aeration, porosity, bulk density and water retention. Chemical properties such as pH, electrical conductivity and organic matter content are also improved for better crop yield. Nevertheless, enhanced plant growth could not be satisfactorily explained by improvements in the nutrient content of the soil, which means that other plant growth-influencing materials are available in vermicomposts. Although vermicomposts have been shown to improve plant growth significantly, the application of vermicomposts at high concentrations could impede growth due to the high concentrations of soluble salts available in vermicomposts. Therefore, vermicomposts should be applied at moderate concentrations in order to obtain maximum plant yield. This review paper discusses in detail the effects of vermicompost on soil fertility physically, chemically and biologically. Future prospects and economy on the use of organic fertilizers in the agricultural sector are also examined.

Keywords: earthworms; vermicomposting; organic fertilizer; nutrients; plant development; waste management

INTRODUCTION

Waste management systems are significantly influenced by socio-economic, political and environmental factors, including population growth, consumption pattern and technological development of waste systems.[1] Thus, in many countries, both energy and waste management systems are changing.[2] For example, European countries such as Austria and Netherlands are shifting away from landfilling and move towards recycling because of scarcity of land and the value of wastes.[3] Currently, a number of studies have been conducted by different researchers on the 'zero waste' concept,[4] because the importance of sustainability is being emphasized globally so that the needs of the present generation can be met without compromising the ability of future generations to meet their own needs.[5] The 'zero waste' concept may involve reutilization of organic residues produced from agriculture, municipal and industrial wastes as resources rather than treatment or disposal of the wastes directly.[6]

Biological processes such as composting and vermicomposting have been widely recognized in converting organic materials into nutrient-rich fertilizer and soil conditioner.[4] The composting process is a spontaneous biological decomposition of organic wastes in an aerobic environment.[7] Similarly, vermicomposting is also an organic waste decomposition process but with the addition of earthworms to aid the waste stabilization process. This process involves symbiotic interaction between earthworms (e.g. *Eisenia fetida*, *Eudrilus eugeniae* and *Perionyx excavatus*) and microorganisms to produce a stable, homogeneous and humus-like end product known as vermicompost.[7,8] Earthworms condition the substrate and alter the biological activity for further biochemical degradation of organic matter by microorganisms.[9] In general, vermicompost is physically, nutritionally and biochemically improved over traditional compost[10] because the mineralization rate of organic matter is accelerated and a higher degree of humification can be obtained through vermicomposting.[11] Also, in comparison with composting, vermicomposting of organic wastes yields two useful products, namely earthworm biomass and vermicompost, which are produced in less processing time.[7]

By combining both composting and vermicomposting, the integrated process can be made an option for biodegrading solid wastes. Generally, the integrated system between composting and vermicomposting is used to enhance pathogen control and produce organic fertilizer at a faster rate than either of the individual processes. The composting stage in this integrated system ensures that the produced fertilizer meets the Environmental Protection Agency's temperature requirement for killing pathogens[12] during the thermophilic phase, while the subsequent vermicomposting process reduces particle size and increases nutrient availability at a higher rate due to the activity of the earthworms.[13] Fornes *et al.*[14] compared the physical and chemical characteristics of tomato crop waste for composting, vermicomposting and a combination of both processes. It can be deduced that composting, vermicomposting and a combination of both were suitable options for organic waste management and valuable for horticultural purposes. A recent study conducted by Wang *et al.*[15] reported that combined composting and vermicomposting with reed straw

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and zeolite addition would be a recommended method to dispose of duck manure and reduce ammonia and greenhouse gas emissions, as well as to provide nutrient-rich products as organic fertilizers.

Excessive use of inorganic fertilizers without organic supplements not only deteriorates the physical and chemical properties of soil but also pollutes the surrounding environment.[16] For example, the use of inorganic fertilizer can cause excessive leaching of nutrients and salinity-induced plant stress.[17] Manivannan *et al.*[16] found that the application of inorganic fertilizer alone on soil significantly reduced the total microbial activity, porosity, particle and bulk density of soil. Schulz and Glaser[18] also concluded that an addiction of inorganic fertilizer to a sandy soil under high precipitation was useless as most of the nutrients were leached rapidly, with severe negative effects for economy and water contamination. However, a recent study showed that the combined use of organic and inorganic fertilizers maintained the highest soil quality index (SQI) of 1.10, followed by an application of 100% organic fertilizer (SQI = 1.08).[19] On the other hand, the application of vermicompost can directly modify the physicochemical properties of agricultural soil, which is advantageous to the development of plants as a whole.[20]

Vermicomposting itself cannot be considered as a new technology. In respect to various solid waste management strategies, vermicompost is gaining interest as a greener replacement or integration with chemical fertilizers to maintain and further improve soil quality.[7] However, recent studies on the responses of vermicompost to the properties of soil and plant growth are generally limited. Researchers who investigated the effect of vermicompost on soil properties and plant growth include Singh and Wasnik,[21] Bachman and Metzger,[22] Lazcano *et al.*[23] and Shahi.[24] Thus, in this review paper, the nutrients in vermicompost and its effects on the physicochemical and biological properties of the soil are discussed.

NUTRIENTS IN VERMICOMPOST

Total nutrient contents in vermicompost depend upon the characteristics of the raw material.[25] However, the macronutrients and micronutrients in vermicompost are generally higher than in traditional compost produced from the same raw material (Table 1).[26–29] This is because, although raw material is mainly decomposed by microorganisms, earthworms also influence the process as they may affect microbial activity by grazing directly on the microorganisms.[30] Furthermore, raw material which has undergone vermicomposting is generally more granular in shape, with greater surface area due to the digestion and fragmentation by the earthworms.[31,32] These activities may enhance organic matter turnover rate and productivity of microbial communities, thereby enhancing the rate of decomposition as compared to the biodegradation system without the presence of earthworms.[30] In fact, vermicompost contains a rich source of macro- and micronutrients, vitamins, enzymes, antibiotics, growth hormones and immobilized microflora, which are readily soluble in the water.[33,34]

Carbon is the main element present in organic matter. Nutrient balance in vermicomposts is based on the quality of C and C/N ratio.[35] C/N ratio is an indicator of vermicompost maturity.[29] A C/N ratio of <20 indicates an advanced degree of organic matter stabilization and reflects a satisfactory degree of organic waste maturity. Part of the carbon is released as carbon dioxide during the vermicomposting process, while the production of mucus

Table 1. Nutrient composition of various derivatives of vermicompost and compost

Nutrient content	Kitchen Waste		Green and pruning residues		Cane trash		Weeds		Vegetable market waste		Paddy straw		Market waste		Floral waste	
	VC	C	VC	C	VC	C	VC	C	VC	C	VC	C	VC	C	VC	C
Organic carbon (%)	10.30	7.37	–		24.62	24.22	23.88	23.12	23.92	23.05	24.16	23.89	~22.0–36.0	~15.0	~13.0–20.0	~8.0
Nitrogen (%)	0.85	0.70	2.05	2.20	1.14	0.98	1.88	0.98	2.11	1.81	1.12	0.96	~1.1–1.9	~0.8	~0.6–1.0	~0.4
Phosphorus (%)	0.15	0.09	0.42	0.38	0.46	0.31	1.01	0.31	1.22	0.89	0.43	0.22	~0.5–0.7	~0.4	~0.8–1.2	~0.7
Potassium (%)	–	–	1.21	0.83	1.61	1.52	1.31	1.52	1.45	1.23	1.64	1.60	~0.7–0.9	~0.6	~0.2–0.4	~0.1
Calcium (%)	1.96	1.79	2.02	3.02	–	–	–	–	–	–	–	–	~4.5–6.0	~4.0	~1.0–2.5	~0.5
Magnesium (%)	0.80	0.68	0.51	0.41	–	–	–	–	–	–	–	–	~0.7–1.0	~0.6	~0.4–0.6	~0.2
Zinc (mg/kg)	–	–	57	165	61	36	81	52	89	61	58	33	–	–	–	–
Copper (mg/kg)	–	–	–	–	28	18	36	22	57	31	24	19	–	–	–	–
Iron (mg/kg)	–	–	6549	7095	294	188	294	245	412	306	284	174	–	–	–	–
Manganese mg/kg)	–	–	286	289	32	19	32	38	98	85	36	22	–	–	–	–
References	26		27		28		28		28		28		29		29	

VC, vermicompost; C, compost.

and nitrogen excrements contribute to the increment in nitrogen levels, thus reducing the C/N ratio of the vermicompost.[36] Apart from C/N ratio, NO_3/NH_4^+ ratio is also a reliable indicator to provide information on the maturity and stability of organic fertilizer.[37] Total nitrogen consists of inorganic forms of nitrogen, namely NH_4-N (ammoniacal nitrogen) and NO_3-N (nitrate nitrogen). During the vermicomposting process, high levels of NH_4^+ are released and converted into NO_3 through the nitrification process. The nitrification process is indicative of a stable vermicompost. A decrease in NH_4^+ and an increase in NO_3 led to an overall increase of the NO_3/NH_4^+ ratio, which is an indication of the maturity of the vermicompost.[37] The maturity and stability of vermicomposts could also be determined using physical tests such as the colour of the substrates[31,32] and scanning electron microscopy (SEM) images,[31,32] as well as biological tests such as enzyme activities,[38] microbial population[39] and germination index.[38]

According to Chauhan and Joshi,[40] increases in nitrogen, potassium and phosphorus were observed in the treatment using *Eisenia fetida* in vermicomposting of some dangerous and toxic weeds. Nath *et al.*[41] reported that there were significant increases in total nitrogen, total phosphorus, total potassium and total calcium in the final vermicompost using feedstock of different animal, agro and kitchen wastes by *Eisenia fetida*. Similar results were obtained by Gupta and Garg,[34] who showed that total nitrogen, total phosphorus and total potassium were higher in vermicompost of primary sewage sludge mixed with cow dung. Likewise, vermicompost derived from rice residues mixed with cow dung using *Eudrilus eugeniae* showed an increase in macronutrient content (such as calcium, magnesium, phosphorus and potassium) in a study by Shak *et al.*[42] Vermicompost acts as a bioinoculant by increasing the availability of the nitrogen and phosphorus through improving biological nitrogen fixation and phosphorus solubilization.[43]

An application of vermicompost stimulates root growth and facilitates nutrient absorption, and hence favours higher percentage yield.[43] Therefore, vermicompost generally contains higher and more soluble levels of major nutrients required for plant growth (Table 1) such as nitrogen, phosphorus, potassium, calcium and magnesium as compared to normal compost.[29] However, improvements in plant growth and increases in yields could not be entirely explained by the availability of macronutrients, as demonstrated by Arancon *et al.*[44] In their experiment, all vermicompost treatments were supplemented with inorganic fertilizers to equalize macronutrient availability at transplanting time. Since all plants received all needed nutrients, the contribution of nutrients from the mixtures on plant growth could be virtually eliminated as an influence factor. The result suggests that biologically active plant growth-influencing substances appeared as plant growth regulators or humic acids in the vermicomposts, which were also responsible for improving plant growth.[45]

Micronutrients, which are also known as trace elements, are required in small amounts to enhance plant growth. However, in higher concentration they are likely to have unfavourable effects on plant growth.[36] Earthworms are able to counter this effect by accumulating particular metals through their intestine as well as through the skin, hence reducing specific total potentially hazardous element.[46] Nevertheless, a high concentration of heavy metals could lead to earthworm mortality. For example, Domínguez-Crespo *et al.*[47] demonstrated 100% earthworm mortality at a Cd concentration of 643.86 mg kg^{-1}. Generally, the amount of heavy metals that could be accumulated in earthworm tissues is dependent on the earthworm species as well as the adaptability of the earthworms in the feed substrate (organic wastes). Earthworms are also more inclined to accumulate and regulate one type of heavy metal over another, such as Zn as compared to Cu.[47,48] Physiochemical factors such as pH, calcium concentration and organic matter content in the wastes also influence the accumulation of heavy metals in the gut of earthworms.[49] In short, the capacity of the earthworm to bioaccumulate a number of metals leads to lower concentrations of heavy metals in the vermicomposts , indirectly reducing the risk of entering the plant system and subsequently the food chain.[46]

EFFECT OF VERMICOMPOST ON SOIL FERTILITY

Vermicompost not only acts as a source of nutrients and organic matters, but it can also increase the size, biodiversity and activity of the microbial population in soil. In addition, vermicompost can positively affect the structure, nutrient turnover and many other properties of the soil.[16] Nowadays, the use of organic amendments is gaining popularity in sustainable crop production and soil nutrient management,[50] because long-term application of inorganic fertilizers without organic supplements could potentially damage the properties of soil.[16] For example, Biau *et al.*[51] showed that the application of mineral fertilizer alone over a 10-year period led to a higher residual nitrate content in the soil, which increased the risk of leaching. Conversely, Rasool *et al.*[52] showed that long-term application of balanced inorganic fertilizers resulted in decreased soil bulk density, and increased total porosity and water-holding capacity. Inorganic fertilizer also improved soil aggregation in deeper soil layers as well as increased the grain and straw yields of both maize and wheat. In their study, the use of farmyard manure (organic fertilizer) instead of inorganic fertilizer also resulted in similar improvements to the soil properties.[52] Thus organic fertilizer has the potential to become a good substitute for inorganic fertilizer[53] but the most recent studies have pointed out that an integration of organic and inorganic fertilizer could sustain soil fertility[21] and produce the best crops.[54]

Vermicompost is usually in the shape of a granular or spindle-like mass that may form a 2–3 cm high heap, as produced by *Eudrilus eugeniae* or *Perionyx excavatus*.[55] According to Lim *et al.*,[32] SEM showed two distinctive morphologies between initial waste mixture and final vermicompost of palm oil mill effluent amended with rice straw. The SEM image revealed that the initial waste mixture was characterized by long fibres, while the final vermicompost was more fragmented and porous,[32] in which case the latter is more suitable for use as an organic fertilizer. Vermicompost contains high level of plant growth hormones and soil enzymes, while enhancing the microbial populations in soil and retaining its nutrients over a longer period of time without having an adverse impact on the environment.[43,46] Thus vermicompost could be used either as soil additives or components of greenhouse bedding plant container media, for improving seed germination, enhancing seedling growth and development as well as increasing overall plant productivity.[56]

The effects of vermicompost on the growth of other plants have been evaluated by other researchers through various greenhouse and field studies, including cereals and legumes,[57] vegetables,[58,59] ornamental and flowering plants[60] and field crops.[61] Table 2 summarizes the effects of vermicompost, compost and inorganic fertilizer on the growth of various plants in terms of root and shoot dry weight, root/shoot ratio, number of leaves per plant, leaf area and the mean plant height.[16,22,43,50,62–75] Roy *et al.*[50] showed

Table 2. Effect of fertilizer (vermicompost/inorganic fertilizer/compost) on the growth of various plants

Plant	Concentration of vermicompost (VC)/ control	Feedstock of vermicompost/ control	Days after planting	Root dry weight	Shoot dry weight	Root/shoot ratio	Average number of leaves per plant	Leaf area (cm^2)	Mean plant height (cm)	Comments	References
'Queen Sophia' French Marigold	1:4 (VC:MM360)	Pig manure	12*	0.021 g	0.037 g	0.57	–	10.16	–	• Root and shoot dry weight are of seedling plugs	22
	Control	MM360	12*	0.018 g	0.042 g	0.43	–	12.62	–		
'Rutgers' tomato	1:4 (VC:MM360)	Pig manure	12*	0.012 g	0.053 g	0.23	–	10.71	–		
	Control	MM360	12*	0.009 g	0.040 g	0.23	–	8.41	–		
'California Wonder' pepper	1:4 (VC:MM360)	Pig manure	12*	0.005 g	0.023 g	0.22	–	8.20	–		
	Control	MM360	12*	0.017 g	0.031 g	0.55	–	11.48	–		
'Imperial' cornflower	1:4 (VC:MM360)	Pig manure	12*	0.007 g	0.011 g	0.64	–	2.74	–		
	Control	MM360	12*	0.007 g	0.011 g	0.64	–	2.44	–		
Tomato (*Lycopersicum esculentus*)	1:1 (VC:soil)	Sheep manure	100	–	–	–	127	–	70	–	62
	Control	Soil	100	–	–	–	133	–	64	–	
Bean (*Phaseolus vulgaris*)	1:1 (VC:NPK)	Sugar mill wastes	60	2.01 g per plot	5.80 g per plot	0.35	–	210.7	–	• VC application rate: 5 t ha^{-1} • NPK dose: 20:80:40 kg ha^{-1}	16
	NPK		60	1.42 g per plot	4.90 g per plot	0.29	–	140.2	–	• NPK dose: 20:80:40 kg ha^{-1}	
	Control	Soil	60	0.87 g per plot	3.80 g per plot	0.23	–	91.8	–		
Chili (*Capsicum annum*)	VC	Banana leaves, cow dung	95	–	–	0.37	743	–	75	–	43
	Compost	Banana leaves, cow dung	95	–	–	0.42	493	–	61.5	–	
Zea mays	VC	Cow dung, crop/plant residues	60	86.03 kg ha^{-1}	1134.05 kg ha^{-1}	0.08	–	–	–	• VC application rate : 1 t ha^{-1}	50
	Compost	Cow dung, crop/plant residues	60	59.20 kg ha^{-1}	915.75 kg ha^{-1}	0.06	–	–	–	• Compost application rate: 2.25 t ha^{-1}	
	Control	Soil	60	71.23 kg ha^{-1}	601.25 kg ha^{-1}	0.12	–	–	–	–	
Phaseolus vulgaris	VC	Cow dung, crop/plant residues	60	43.98 kg ha^{-1}	1091.85 kg ha^{-1}	0.02	–	–	–	• VC application rate: 1 t ha^{-1}	
	Compost	Cow dung, crop/plant residues	60	34.80 kg ha^{-1}	754.0 kg ha^{-1}	0.05	–	–	–	• Compost application rate: 2.25 t ha^{-1}	
	Control	Soil	60	30.45 kg ha^{-1}	539.4 kg ha^{-1}	0.06	–	–	–	–	
Abelmoschus esculentus	VC	Cow dung, crop/plant residues	60	10.66 kg ha^{-1}	175.15 kg ha^{-1}	0.06	–	–	–	• VC application rate: 1 t ha^{-1}	
	Compost	Cow dung, crop/plant residues	60	16.48 kg ha^{-1}	135.45 kg ha^{-1}	0.12	–	–	–	• Compost application rate: 2.25 t ha^{-1}	

Table 2. Continued

Plant	Concentration of vermicompost (VC)/control	Feedstock of vermicompost/control	Days after planting	Root dry weight	Shoot dry weight	Root/shoot ratio	Average number of leaves per plant	Leaf area (cm^2)	Mean plant height (cm)	Comments	References
	Control	Soil	60	7.25 kg ha^{-1}	70.30 kg ha^{-1}	0.10	–	–	–	–	
Bean (*Phaseolus vulgaris*)	1:181 (VC:soil)	Biosolid, manure	60	2.1 g	–	–	14	–	59	–	63
	Inorganic fertilizer		60	1.7 g	–	–	11	–	45	–	
	Control	Soil	60	1.3 g	–	–	11	–	39	–	
Bean (*Phaseolus vulgaris*)	1:12 (VC:soil)	Wastewater sludge	117	1.4 g	5.0 g	0.28	–	–	32.3	–	64
	Control	Soil	117	1.2 g	3.8 g	0.32	–	–	30.5	–	
Okra (*Abelmoschus esculentus*)	1:50 (VC:soil)	Cattle dung, grass clippings	42	–	–	–	12	–	39.33	–	65
	Control	Soil	42	–	–	–	9	–	31.67	–	
Marigold	1:4 (VC:soil)	Cow dung	130	–	–	–	–	–	~23.0	–	66
	Control	Soil	130	–	–	–	–	–	~9.2	–	
'Chandler' strawberry	VC	Vegetable waste, cow dung	180	–	–	–	–	501.9	–	• VC application rate: 7.5 t ha^{-1}	67
	Control	Inorganic fertilizer (NPK^+)	180	–	–	–	–	411.2	–	• NPK dose: 120:170:150 kg ha^{-1}	
Cicer arietinum	VC	–	75	–	–	–	~ 60	–	–	• VC application rate: 148 t ha^{-1}	68
	Control	Soil	75	–	–	–	~30	–	–	–	
Pisum sativum var. *arvense*	VC	–	75	–	–	–	~25	–	–	• VC application rate: 148 t ha^{-1}	
	Control	Soil	75	–	–	–	~15	–	–	–	
French bean (*Phaseolus vulgaris* L.)	125:1 (VC:NPK)	Crop residues, cow dung	145	0.229 g per plant	4.887 g per plant	0.05	17.3	624.4 cm^2 per plant	–	• NPK dose: 75:125:10 kg ha^{-1}	69
	VC	Crop residues, cow dung	145	0.218 g per plant	3.805 g per plant	0.06	15.2	504.9 cm^2 per plant	–	• VC application rate: 5 t ha^{-1}	
	Control	NPK (30:50:40 kg ha^{-1})	145	0.221 g per plant	3.231 g per plant	0.07	14.0	307.8 cm^2 per plant	–	–	
Pisum sativum	VC	–	28	10.42 g	–	–	51	–	18	–	70
	Pitcompost	–	28	6.22 g	–	–	46	–	12	–	
	Control	Soil	28	3.19 g	–	–	28	–	10	–	
Lettuce (*Lactuca sativa* L.)	1:9 (VC:soil)	Cattle manure	60	3.51 g per plant	–	–	26.83	–	–	–	71
	Inorganic fertilizer		60	2.12 g per plant	–	–	27.00	–	–	–	
	Control	Soil	60	3.00 g per plant	–	–	23.83	–	–	–	

Table 2. Continued

Plant	Concentration of vermicompost (VC)/control	Feedstock of vermicompost/control	Days after planting	Root dry weight	Shoot dry weight	Root/shoot ratio	Average number of leaves per plant	Leaf area (cm^2)	Mean plant height (cm)	Comments	References
Jatropha curcas L.	VC		365	1.99	–	–	–	36	–	–	72
	Control	Soil	365	1.96	–	–	–	20	–	–	
Pak choi	VC	Chicken manure	35	~0.5 g per plant	~2.9 g per plant	0.17	–	520 cm^2 per plant	–	–	73
	Compost	Chicken manure	35	~0.2 g per plant	~2.5 g per plant	0.08	–	590 cm^2 per plant	–	–	
Primula (*Primula acaulis* subsp. Oriental)	1:20 (VC:greenhouse medium)		117	~1.20 g	–	–	21.3	–	–	–	74
	Control	Greenhouse medium	117	~0.90 g	–	–	23.7	–	–	–	
Pansy (*Viola × wittrockiana* subsp. Delta)	1:20 (VC:greenhouse medium)		117	0.08 g	–	–	84.6	–	–	–	
	Control	Greenhouse medium	117	~0.16 g	–	–	73.0	–	–	–	
Amashito pepper (*Capsicum annum* var. *glabriusculum*)	VC	Grass, cocoa husks	173		–	–	20.6	–	26.7	–	75

*Days after emergence.
MM360, Metro Mix 360, The Scotts Co., Marysville, OH, USA; NPK, N P_2O_5 K_2O fertilizer.

that plant height, shoot and root weight were highest in the vermicompost-treated plots as compared to compost or soil plots. Most of the investigations have confirmed that vermicompost has significant beneficial effects on plant growth.[76] Furthermore, incorporation of earthworms into the soil structure may lead to a major impact on physical and chemical properties in the soil, as well as the activity of other organisms such as nematodes and collembolans living within it.[77] The combination of vermicompost and inorganic fertilizer (NPK) also yielded higher leaf area, shoot and root weight for *Phaseolus vulgaris* as compared to vermicompost or inorganic fertilizer alone.[16,69]

EFFECTS OF VERMICOMPOST ON THE PHYSICOCHEMICAL PROPERTIES OF SOIL

Vermicompost could improve the physical structure of the soil such as porosity, aeration, drainage, resistance to corrosion and infiltration,[45,78] thus providing a better medium for root growth.[17] For example, Manivannan *et al.*[16] found that the use of vermicomposts improved the physical properties of soil, which further increased the growth, yield and quality of beans. Earlier studies have shown that vermicompost appeared to be enriched with polysaccharides. In the soil, polysaccharide acted as a cementing substance, which caused aggregate stability,[79] to create and maintain the soil structure for better aeration, water retention, drainage and aerobic conditions. The maintenance of soil structure is very useful for root development and nutrient availability to the plants.[16] The addition of mucus secretion from the earthworm's gut and microorganisms in the gut enhances the aggregate stability of the soil.[55] An increase in water retention capacity of soil is due to the absorbent organic matter in vermicomposts, which holds only the necessary amount of water required by the plant roots.[78] A reduction in bulk density of the soil treated with vermicompost was also noted by Manivannan *et al.*[16] Decreases in particle and bulk densities were mainly due to the enhanced microbial population and activity, which resulted in the formation of aggregates and increased porosity of the soil.[16] Also, vermicomposts have been reported with a higher base exchange capacity and a larger increase in oxidation potential.[46]

Vermicompost could serve as a naturally produced, slow-release source of plant nutrients and their amendment has been shown to increase plant dry weight[80] and plant nitrogen uptake.[16] Vermicompost contains nutrients in forms that are readily taken up by plants, such as nitrates, exchangeable phosphorus and soluble potassium, calcium and magnesium,[16,33] with most of the nitrogen in the nitrate, NO_3^- form rather than the ammoniacal form.[60,76] Although chemical fertilizers have more nutrients listed than vermicomposts, the ability of plants to absorb nutrients from chemical fertilizers is restricted owing to the nutrients that are not broken down in a form ready for plant absorption.[78] Also, Lazcano *et al.*[23] found that the effect of vermicompost on plants was dependent on its dosage as well as plant species and genotype. Thus the best way to supply nutrients to the plant is by ensuring the appropriate level of chemical fertilizer and/or vermicompost in one specific plant. For instance, Kalantari *et al.*[56] found that the best corn growth occurred in both 3% vermicompost + sulfate and 3% vermicompost treatments. In addition, due to the slow release of nutrients such as organic nitrogen from vermicomposts, plants are less susceptible to pest attacks.[81] A considerable decrease in attacks by jassid (*Empoasca verri*) and aphid (*Aphis craccivora*) was reported by Rao[82] in response to field applications of vermicomposts. Possible reasons include changes in nutrient characteristics and balance of plants in response to vermicomposts.

Manivannan *et al.*[16] also showed that the available N, P, K, total Ca, Mg, Na, Zn, Fe, Cu and Mn were significantly increased in soil treated with vermicompost. Similarly, Pramanik *et al.*[83] and Doan *et al.*[53] showed that an application of vermicompost increased the mineralizable nitrogen and available phosphorus content in the soil. Vermicompost usually has a lower C/N ratio, indicating that it is more suitable for use as a soil amendment.[17] In fact, vermicomposts can be extremely rich in available nutrients depending on the parent material, allowing not only an instantaneous supply of plant nutrients but also increasing reserves for future crops.[78] A very common problem associated with nutrients in soils is that they are easily leached away. However, Bhattacharjee *et al.*[84] reported that the application of vermicompost reduced the loss of nutrients through leaching from the soil by changing the physiochemical properties of the soil. Masciandaro *et al.*[85] reported that at the end of the experimental period the amount of nitrates in cow manure vermicompost was lower due to plant absorption, hence decreasing the risk of NO_3^- nitrogen leaching from the organic amendment.

The use of vermicompost must be carried out with caution, because Warman and AngLopez[86] found that although percentage germination of radish, marigold and upland cress increased with maturation of the vermicompost, the addition of vermicompost to the soil or water often resulted in poorer germination as compared to the control. They hypothesized that organic substances in the vermicompost, rather than soluble salts, might contribute to phytotoxicity . The reduction in growth and productivity after incorporation of vermicomposts at high concentrations could be due to the reduced aeration and porosity in the medium, increased salt concentrations as well as high concentrations of heavy metal and phytotoxic substances.[58,66] Atiyeh *et al.*[76] reported that when the concentration of vermicompost in the potting medium approached 100%, high concentrations of soluble salts in the vermicompost and poor porosity or aeration in the medium would affect root growth and proliferation. Also, immature vermicompost is harmful to plants. Thus the use of immature vermicompost indirectly causes inhibition of seed germination, root destruction and inhibition of plant growth.[87]

Vermicompost can be used as a bio-remedial measure to reclaim problems in soils, especially acid soils, because of the near-neutral to alkaline pH of vermicompost and the suppression of labile aluminium.[43] However, Gutiérrez-Miceli *et al.*[62] found that there was no change in pH when vermicompost was applied to soil, whereas both Atiyeh *et al.*[76] reported a decrease in pH when vermicompost was applied. Manivannan *et al.*[16] also reported a slight decrease in pH of vermicompost-treated soil and postulated that the decrease might be due to the acidifying effects of organic acids produced during the course of decomposition of organic amendments and/or the increased permeability and leaching of salts. Another study conducted by Lazcano and Domínguez[74] reported that increasing amounts of commercial vermicompost produced higher pH values but lower pH with increasing amounts of pig slurry vermicompost. Differences in the changes of pH in soil reported by different researchers seem to be related to the different types of vermicompost and/or soil characteristics.[63] For example, Férnandez-Bayo *et al.*[88] showed that an addition of vermicomposts increased soil pH in the case of acidic soil but reduced soil pH in alkaline soil. These studies led to the observation that the addition of vermicomposts changed the soil pH to neutral levels. Nevertheless, pH ranging between 6 and 7 seems to promote the availability of nutrients to the plants,[16] hence making vermicompost a suitable soil amendment. Gutiérrez-Miceli *et al.*[62] reported that both concentrations of NH_4^+ and NO_2^- were low but NO_3^- concentrations were high in soil incorporated with vermicompost, indicating that ammonification and nitrification were not inhibited. On the other hand, some studies proved that fresh vermicomposts contain high levels of ammonium, but the existence of a large population of autotrophic nitrifiers (*Nitrosomonas* and *Nitrobacter*) will cause rapid nitrification, resulting in stable levels of both nitrogen forms (NH_4^+ and NO_3^-) due to organic matter protection in the vermicomposts.[46,89] Ammonium ions can be adsorbed on to the negative charges of the substrates, leached, taken up by plants, or converted to nitrates via aerobic nitrification processes due to increased microbial activity in vermicompost-substituted substrates, thereby providing a slow release of nitrates.[76]

Due to changes in the distribution of K between exchangeable and non-exchangeable K forms, the availability of K is increased considerably during the vermicomposting process. As a matter of fact, earthworms cannot increase the total amount of K but can make the nutrients more available.[78] Thus vermicomposts have a higher level of available nutrients for plants as compared to soil. It has also been suggested that earthworms can increase metal mobility, though further studies are required.[55] Through the action of earthworms, the rate of nutrient recycling is increased, and thus the available quantity of nutrients, such as K, to the plants is enhanced as well. Other chemical analyses of vermicomposts indicate higher amounts of nutrients in available forms such as magnesium, nitrogen, phosphorus and potassium than those in the parent substrate. This phenomenon makes vermicomposts suitable for agricultural application with adhesive effects for the soil and stimulators for plant growth.[46]

Electrical conductivity (EC) of vermicompost is dependent on the raw materials used for vermicomposting and is also related to their ion concentration.[62] EC was observed in soils treated with vermicompost where ragi and cowpea were grown.[16,90] The reduction in EC could be due to stabilization of the raw materials.[91] Similarly, Aityeh *et al.*[76] reported a decrease in EC at the end of the growth study, indicating that high soluble salt concentrations in vermicompost produced from pig manure were successfully leached. An addition of vermicompost to the soil increased the exchangeable Ca^{2+} concentration, which led to higher $Na^+ - Ca^{2+}$ exchange at the soil's cation exchange sites, allowing higher leaching of exchanged Na^+ and subsequently lower EC of soil.[92] In addition, vermicompost helps improve the porosity of soil and infiltration rate, which also enhances salt leaching.[54] Fernández-Gómez *et al.*[93] suggested that vermicompost with EC values lower than 1.5 (stabilized material) and 4.0 dS m^{-1} are suitable for application as growing media and for organic soil amendments, respectively.

Vermicompost is reported to show hormone-like activity, and this has been hypothesized to result in greater root initiation, root biomass, plant growth and development, as well as morphology changes in plants grown in vermicompost-amended media. There is some likelihood that the enhanced plant growth is due to the presence of plant hormone-like activity produced by microflora during vermicomposting, and also the presence of metabolites as a result of secondary metabolism.[22] Vermicomposts contain plant growth hormones such as auxins, gibberellins and cytokinin produced by microorganisms during the process of vermicomposting.[67,94] These substances may be partially responsible for the increases in germination, growth and yield of plants, since there is clear evidence from greenhouse trials that they could produce significant growth effects independent of nutrients.[44,94] It was shown that earthworm activity could promote the production of cytokinins and auxins in organic waste dramatically.[45] Tomati *et al.*[95] also reported that earthworm-digested sewage sludge was rich in microorganisms, especially bacteria, and contained large amounts of plant hormones. Other researchers also demonstrated that plant growth hormones extracted from vermicomposts could have significant effects on plant growth.[96,97]

Plant hormones are dose specific and play a fundamental role in plant metabolism. They could influence plant growth and development as well as crop quality significantly, although the hormones are present at very low concentrations.[76] Previous experiments reported that some of the slower growth rates of plants when applied with vermicomposts showed a response to higher concentrations of plant growth hormones such as auxins and humic acids, which were produced by microorganisms in the vermicomposts. Auxins can increase growth at lower concentrations, but they can also reduce the rates of growth and development of plants when applied at high concentrations beyond the optimum value. For example, the optimum percentage of vermicompost for promoting maximum growth of petunia was approximately 30–40%, but a higher percentage of vermicompost (>40%) would in fact dwarf the growth of petunia.[45,96]

The stimulation of plant germination and growth is due to the reduction in total and monomeric phenolic compounds. The mineralization of lignin–cellulose substrates and the metabolic processes of plants stimulate the release of phenolic monomers, hence explaining the reduction in these compounds.[85] Consistent results were obtained by Hachicha *et al.*,[98] who revealed a direct connection between polyphenol content and toxicity. Masciandaro *et al.*[85] also demonstrated that a large reduction in toxicity of olive mill wastewater at the end of the vermicomposting process stimulated seed germination and plant growth.

Apart from plant growth hormones, humic acids could also be responsible for the enhanced growth patterns of plants.[96] Stimulations of root growth, increased proliferation of root hairs and enhancement of root initiation by humic acids have commonly been reported by several other researchers.[94,96] Masciandaro *et al.*[99] reported positive growth responses of plants after adding humic material extracted from vermicomposts. Similarly, Canellas *et al.*[100] confirmed the role of humic acid extracted from vermicompost as plant root growth promoters. These humic substances occur naturally in mature animal manure, sewage sludges or paper mill sludges, but their amounts and rates of productions are increased greatly through vermicomposting.[101]

Vermicompost contains high amounts of humic acid and biologically active substances such as plant growth regulators.[16,102] Most studies have reported that substitutions of 20–40% of vermicomposts in a commercial growth medium have beneficial effects on germination, plant growth and yield.[102] It seems very likely that vermicomposts, which consist of an amalgamate of humified earthworm faeces and organic matter, could stimulate plant growth. Beyond that, mineral nutrients are produced because of the effects of the humic substances present in vermicomposts and because of the plant growth regulators associated with humic acids.[94] Atiyeh *et al.*[94] also stated that consistent enhancements in plant growth were mainly due to their humic acid content in vermicomposts, and not nutrient changes. Nevertheless, humic acid has been shown to increase nutrient accumulation in conditions of limited nutrient availability and when additional nutrients were supplied.[22]

The positive influence of humic acids on plant growth and productivity could be due to hormone-like activities of the humic acids through their involvement in cell respiration, photosynthesis, oxidative phosphorylation, protein synthesis and various enzymatic reactions.[94] Plant growth hormones can be adsorbed on to the complex structure of humic acids, which are produced very rapidly in vermicomposts.[103] Both plant growth hormones and humic acids may act together to increase plant growth.[45]

EFFECTS OF VERMICOMPOST ON THE BIOLOGICAL PROPERTIES OF SOIL

Recent studies found that the levels of soil organic matter, soil microbial biomass and activities were enhanced by using organic fertilizers such as vermicompost.[16] An increase in plant growth could also be attributed to biological effects, such as increases in beneficial enzymatic activities and populations of beneficial microorganisms, as well as the presence of biologically active plant growth-influencing substances such as plant growth regulators or plant hormones[104] and humic acids[97] in the vermicomposts. Table 3 shows the microbial population in the vermicomposts produced from different wastes.[25,39,73,105–108]

Dehydrogenase enzyme activity, which is often used as a parameter to measure the respiratory activity of the microbial community, was found to be greater in vermicompost as compared to commercial medium.[76] There was initially a significantly lower dehydrogenase activity in the soil, occurring in vermicompost-treated plots at the time of transplanting. This phenomenon could be due to an inhibitory effect, resulting from the introduction of 'foreign' soil microorganisms from the vermicomposts to the exotic microflora.[96] This phenomenon, in turn, has triggered competition among the microorganisms. The application of vermicompost as a bioinoculant helps introduce beneficial microorganisms into the rhizosphere of the plant, which then stimulates the nitrogenase enzyme responsible for nitrogen fixation of atmospheric nitrogen in legumes. Thus the nitrogen status of the soil will be enriched, thereby increasing the availability of nitrogen in the soil.[43] Likewise, increased P availability due to the increase in solubility of P by higher phosphatase activity could also be achieved by vermicompost application.[43] Dinesh *et al.*[109] showed that a mixture of organic manures (farmyard manure, vermicompost, neem cake and ash) and biofertilizer application to soil increased the activities of dehydrogenase, acid phosphatase and β-glucosidase. β-Glucosidase and phosphatase are enzyme activities of special interest when processes of organic matter stabilization are being monitored, since they are hydrolytic enzymes involved in the C and P cycles, respectively.[110] These soil biochemical parameters are considered potential indicators of soil quality.[109]

Vermicompost application also suppresses the growth of many parasitic fungi, such as *Pythium*, *Rhizoctonia* and *Verticillium*, and as a result many plant diseases are suppressed when vermicompost is applied in ample quantity in the field.[67] Vermicomposts are also shown to suppress plant parasitic nematodes and enhance the activity of vesicular arbuscular mycorrhizae.[44,94] Statistically, *Eisenia fetida* reduced the population of plant-parasitic nematodes by more than 60% in soil cultures, 98.8% in casts and 50% in cultures with alfalfa root tissue. Also, it was found that the populations of plant parasitic nematode were reduced by introducing eight lumbricid species.[111] Hyvönen *et al.*[112] commented that

Table 3. Microbial counts in various derivatives of vermicompost

	Microbial population					
	Bacteria		Fungi			
Waste	Active	Total	Yeast and mould	Total	Actinomycetes	References
Kitchen waste(cfu × 10^3 mL^{-1})	–	8	5000	–	–	25
Chicken manure(μg mL^{-1})	43.8	–	–	18.5	–	73
Paper mill sludge and cow dung	–	450–500	–	18–26	750–900	105
(cfu × 10^5 g^{-1})						
Herbal pharmaceutical waste and cow dung	–	500–1750	–	5–40	400–3000	39
(cfu × 10^5 g^{-1})						
Remarks	Source of diet to earthworms Solubilize nutrients, stimulates plant growth[106] Nitrogen fixation[107]		Promote soil fertility Suppress plant diseases[108]		Waste mineralization and organic matter decomposition[39]	–

the presence of active *Dendrobaena octaedra*, and as a consequence of predation rather than competition for the same food intake (bacteria or protozoa), resulted in a reduction of plant parasitic nematode populations. Likewise, Senapati[113] reported that a reduction of 20–50% in the number of plant parasitic nematodes in the presence of the tropical earthworm *Lampito mauritii*. Therefore, the community of nematodes, which was dominated by bacterivores, was lowered by more than 50% due to earthworm activity.[111]

Generally, vermicompost provides larger particulate surface areas that help provide many microsites for microbial activities and stronger retention of nutrients.[46,67] In general, composts stimulate nutrient uptake and assimilation as well as displaying hormone-like activity.[22] According to Arancon *et al.*,[44] the improvements in plant growth and increases in fruit yields could be due partly to large increases in soil microbial biomass after vermicompost applications, leading to production of hormones or humates in the vermicomposts, which could be considered as plant growth regulators. The fact that vermicompost treatment has favourably affected biomass accumulation is due to the better synchrony of nutrient release and uptake, as evidenced by the significant positive correlation between biomass accumulation and nutrient mineralization pattern but negative correlation between productivity and available nitrogen in the soil.[50] Chaoui *et al.*[17] showed that the slower release of fertilizers increased plant biomass, which was more synchronized with the plant's requirements. Vermicomposts were also less likely to produce salinity stress as compared to compost and synthetic fertilizers.

In general, these plant growth-regulating materials are produced by the action of earthworms[67] and microbes such as fungi, bacteria and actinomycetes.[114] According to Atiyeh *et al.*,[76] microorganisms not only mineralize complex substances into plant available nutrients but can also synthesize a whole series of biologically active substances, including plant growth regulators. Nevertheless, scientific data on the type of extent of growth effects caused by plant growth regulators (which are due to soil microbial activity) from vermicomposts are still sparse.

ECONOMIC ANALYSIS OF ORGANIC FERTILIZER IN AGRICULTURE SECTOR

Over the last few years, the global demand for fertilizer has continued to increase. In 2011/12, the world fertilizer demand increased by an estimated 14.3% (177.0 Mt) following the downturn in 2008/09. The demand for fertilizer is strongly correlated with high agricultural commodity prices. Farmers respond to attractive international prices for crops like maize, wheat and soybean by attempting to increase their productivity. Subsequently, this decision leads to an increase in fertilizer consumption. It is forecast that by the year 2016/17 the world demand for fertilizer will reach 192.8 Mt.[115] The use of chemical fertilizers alone, which has long been promoted for its higher productivity in agriculture, is now being called into question. It is increasingly being realized that the intensive use of chemical fertilizers proves to be counterproductive in the long run. The use of chemical fertilizers on the soil over a longer period of time may affect its ability to sustain healthy plant growth and crop production. Besides, chemical based water-soluble fertilizer has a tendency to leach out, leaving soil hungrier for nutrients.[116] Therefore, alternatives to chemical fertilizers, such as organic fertilizers, are becoming increasingly important in the agricultural sector.[117]

Organic agriculture or organic farming involves production systems that avoid the use of any synthetic or chemical fertilizers, pesticides and genetically modified organisms.[118,119] Organic fertilizers are derived mainly from the remains or by-products of biological organisms, manure and sewage sludge.[117] For example, both composting and vermicomposting are used to bio-convert a variety of organic wastes into composts and vermicomposts, respectively, which could be used as growing media or soil enhancers.[14]

The emergence of organic agriculture can be traced back as far as 1924 in Germany. Since then, organic agriculture has grown tremendously as new ideas for using natural resources rationally, protecting the environment and, most importantly, ensuring a sustainable development of agriculture, emerge. Both governmental and non-governmental organizations have been promoting organic agriculture for decades, leading to a rapid growth of organic agriculture worldwide.[118]

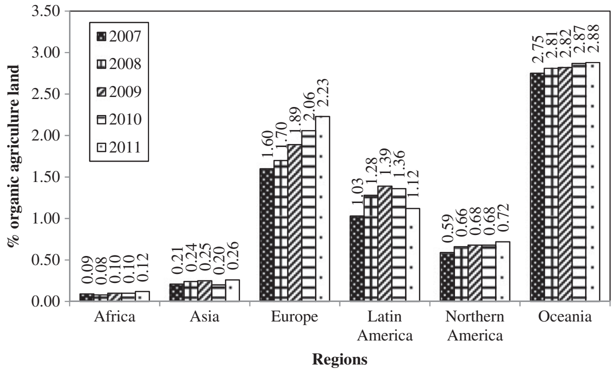

Figure 1. Percentage of organic agriculture land for the different regions from 2007 to 2011.[120]

Figure 1 shows the percentage of organic agricultural land for the different regions, i.e. Africa, Asia, Europe, Latin America, North America and Oceania, from the years 2007–2011.[120] There was a general increase in organic agricultural land across all regions, indicating a shift towards a more sustainable future. Organic agriculture is known to improve soil quality and fertility, control soil erosion, provide healthier food and contribute to the economy – specifically the rural economy. In the UK, the market for organic produce has grown from £100 million in 1993/94 to approximately £1.9 billion in 2006.[121,122] It also reduces negative environmental effects from intensive agriculture,[119] thus minimizing environmental pollution, reducing nutrient losses on farms and contributing to the economy.[118]

Generally, the economic profitability of an agricultural system can be measured through crop yield, gross margin, net return and cost–benefit ratio. In short, the farmer's profit is directly proportional to crop yield price and inversely proportional to the cost of production. Farmers often lack control over prices they receive for their products or the prices they pay for their production input. Thus, in order to maximize their profitability, higher crop yield provides the greatest opportunity for reducing production costs.[123] As for organic farming, its economic profitability is also characterized by reduced water use, nutrient contamination by pesticides, reduced soil erosion, lower carbon emissions and increased biodiversity to maximize profits.[118]

According to Behera *et al.*,[118] organic agriculture produces the same crop variants as those produced from conventional farming methods, but it involves 50% less expenditure on fertilizer and energy while retaining 40% more topsoil. Chouichom and Yamao[117] reported that organic agriculture costs were approximately 33.5% less than conventional methods. However, no significant differences were found in harvest amount and market prices of rice between organic agriculture and conventional methods. In short, organic agriculture costs less and does not seem to affect the productivity of rice. A study on the effect on farm returns due to the shift from chemical-based agriculture to organic while keeping productivity constant was done by Ghosh.[116] The research showed that substitution of chemical fertilizers with organic fertilizers may not, on the whole, hurt the income in most households. Also, the use of organic fertilizers seemed to be feasible as it managed to sustain crop yield levels.

In another study, Lobley *et al.*[122] focused on the economic aspects of rural development in relation to employment, purchases and sales of organic and non-organic agriculture. This study revealed that organic agriculture promoted employment which contributed to rural development. The organic agriculture businesses employed an average of 6.4 people per farm as compared to 4.8 people for non-organic agriculture. Organic agriculture also had a lower value of total purchases (£25 million) as compared to non-organic agriculture (£30 million). In farm sales, organic agriculture generates lower revenue per farm as compared to non-organic agriculture. If the values of sales generated per hectare were used as a basis for comparison, organic agriculture was proven to be better, with a revenue of £2837 ha^{-1} as compared to £1857 ha^{-1} for non-organic farming. Lobley *et al.*[122] also took into consideration the median values of the revenues and showed that only a handful of organic farms generated higher sales per hectare, whereas most organic farms performed at a similar level to non-organic farms.

Research into combining organic fertilizer with chemical fertilizer was also done by Kearney *et al.*[124] They found that by combining manure and inorganic fertilizers, there was a 26% increase in yield and a 40% increase in market value as compared to the use of inorganic fertilizer or manure alone. The input ratio of manure to inorganic fertilizer was also proven to be flexible, as there were no significant differences in biomass or market value for the various combinations. Thus the amount of manure and inorganic fertilizer could be adjusted in response to price fluctuations. There was a substantial increase in economic benefits to farmers when considering equivalent economic investment in fertility inputs.[124] Similarly, Dass *et al.*[125] conducted a 3-year study on the growth of winter vegetables such as bell pepper and cabbage using various nutrient management systems. Of all the nutrient management strategies used, the system that combined both inorganic fertilizers and vermicompost was found to produce the highest crop yield. The combination of inorganic fertilizers with vermicompost system also yields the highest gross revenues and gross margin. In the same study, the nutrient management systems encompassing inorganic fertilizer, vermicompost and cow manure also had relatively high crop yields, gross revenues and gross margins.[125]

CONCLUSION AND FUTURE PROSPECTS

The availability of macronutrients and micronutrients is generally higher in vermicompost than in the traditional compost and inorganic fertilizer, indicating that vermicompost is a better supplement to improve and stimulate plant growth. Thus vermicompost has a huge potential for use on agricultural crops. In the near future, vermicomposts should be largely and extensively applied to agricultural land to replace or, alternatively, combine with inorganic fertilizers.

Vermicompost is shown to improve soil fertility in terms of physical and chemical properties of the soil. Physical improvements include better aeration, porosity and bulk density of the soil. Chemical properties such as pH, electrical conductivity and organic carbon content are also enhanced for better plant growth. However, it is found that the nutrient factor of vermicomposts does not provide sufficient evidence to fully explain the enhanced plant growth, suggesting that there are other plant growth-influencing materials in vermicomposts that could be responsible. These plant growth-influencing substances include humic acids, and plant growth hormones such as auxins, gibberellins and cytokinins. Although vermicomposts have been shown to improve plant growth, the application at high concentrations of vermicomposts could lead to slower plant growth, implying that vermicomposts should be applied at appropriate concentrations in order to obtain maximum plant yield.

Interactions among earthworms, microorganisms in soil and vermicomposts are all interdependent, and the relationships among all of them are of major importance in producing a high quality of organic fertilizers. Some species of microorganisms are not digested, and hence the population size is enhanced in the gut and finally in the casts. However, some species of microorganisms are killed during passage through the gut of earthworms. These microorganisms are the food source of earthworms. Generally, an increase in microbial populations in vermicomposts is significant, resulting in richer microbial diversity, populations and activities in vermicomposts. However, some recent studies showed that although vermicompost is apparently more effective than compost in improving soil rehabilitation, the positive effect of vermicompost on soil chemical properties could be reduced in the presence of exotic or endogeic earthworms.[53,126] The reasons of this negative effect are still unclear but Jouquet *et al.*[127] suggested two interesting hypotheses: (a) a lower degradability of vermicompost as compared to compost and a possible competition for nutrients among microorganisms, plants and earthworms; (b) a modification of soil physical parameters and a reduction of soil bulk density or hydraulic conductivity.

In addition, as organic agriculture continues to grow at a global scale, organic fertilizer such as vermicompost are needed to sustain the yield and growth of organic crops as a whole. The future of organic farming involves improving and developing current technologies to improve fertilizer efficiency in term of nutrient supply and utilization of locally available organic fertilizer resources. The current use of organic fertilizer by farmers is still low due to its higher retail price as compared to synthetic fertilizer. Also, certain obstacles encountered by small-scale farmers cannot be dismissed: for instance, the lack of knowledge and experience in organic fertilizer use; poor ability to react to unpredicted external factors such as drought, sudden arrival of new diseases and pests; high certification cost; difficulty in assessing organic markers and bias of most legal structures in favour of conventional agriculture.[117,121] More research therefore needs to be conducted to address farmers' concerns. For example, innovative and effective agricultural service systems could be implemented and developed to educate and assist farmers on the mechanics of organic farming in order to address the insufficient knowledge and experience in sustaining an organic agricultural system.[123] The studies reported here have described several agricultural systems that utilize only chemical fertilizer, organic fertilizer or a combination of the two. These systems have been proven to be effective and are able to increase the profitability of a farm. The scarcity of economic analysis on these systems prompts for more research to examine the economic sustainability of these systems over the long term.

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REFERENCES

1 Zaman AU, Life cycle assessment of pyrolysis: gasification as an emerging municipal solid waste treatment technology. *Int J Environ Sci Technol* **10**:1029–1038 (2013).
2 Nouri J, Nouri N and Moeeni M, Development of industrial waste disposal scenarios using life-cycle assessment approach. *Int J Environ Sci Technol* **9**:417–424 (2012).
3 Marshall RE and Farahbakhsh K, Systems approaches to integrated solid waste management in developing countries. *Waste Manage* **33**:988–1003 (2013).
4 Zaman AU, Identification of waste management development drivers and potential emerging waste treatment technologies. *Int J Environ Sci Technol* **10**:455–464 (2013).
5 Wu TY, Mohammad AW, Lim SL, Lim PN and Hay JXW, Recent advances in the reuse of wastewaters for promoting sustainable development, in *Wastewater Reuse and Management*, ed. by Sharma SK and Sanghi R. Springer, Dordrecht, pp. 47–103 (2013).
6 Misselbrook TH, Menzi H and Cordovil C, Preface. Recycling of organic residues to agriculture: agronomic and environmental impacts. *Agric Ecosyst Environ* **160**:1–2 (2012).
7 Sim EYS and Wu TY, The potential reuse of biodegradable municipal solid wastes (MSW) as feedstocks in vermicomposting. *J Sci Food Agric* **90**:2153–2162 (2010).
8 Lim SL, Wu TY, Sim EYS, Lim PN and Clarke C, Biotransformation of rice husk into organic fertilizer through vermicomposting. *Ecol Eng* **41**:60–64 (2012).
9 Blouin M, Hodson ME, Delgado EA, Baker G, Brussaard L, Butt KR *et al.*, A review of earthworm impact on soil function and ecosystem services. *Eur J Soil Sci* **64**:161–182 (2013).
10 Pramanik P, Ghosh GK, Ghosal PK and Banik P, Changes in organic-C, N, P and K and enzyme activities in vermicompost of biodegradable organic wastes under liming and microbial inoculants. *Bioresour Technol* **98**:2485–2494 (2007).
11 Garg VK and Gupta R, Optimization of cow dung spiked pre-consumer processing vegetable waste for vermicomposting using *Eisenia fetida*. *Ecotox Environ Safe* **74**:19–24 (2011).
12 Ndegwa PM and Thompson SS, Integrating composting and vermicomposting in the treatment and bioconversion of biosolids. *Bioresour Technol* **76**:107–112 (2001).
13 Yadav KD, Tare V and Ahammed MM, Integrated composting: vermicomposting process for stabilization of human faecal slurry. *Ecol Eng* **47**:24–29 (2012).
14 Fornes F, Mendoza-Hernández D, García-de-la-Fuente R, Abad M and Belda RM, Composting versus vermicomposting: a comparative study of organic matter evolution through straight and combined process. *Bioresour Technol* **118**:296–305 (2012).
15 Wang J, Hu Z, Xu X, Zheng B, Liu X, Pan X *et al.*, Emissions of ammonia and greenhouse gases during combined pre-composting and vermicomposting of duck manure. *Waste Manage* **34**:1546–1552 (2014).
16 Manivannan S, Balamurugan M, Parthasarathi K, Gunasekaran G and Ranganathan LS, Effect of vermicompost on soil fertility and crop productivity – beans (*Phaseolus vulgaris*). *J Environ Biol* **30**:275–281 (2009).
17 Chaoui HI, Zibilske LM and Ohno T, Effects of earthworm casts and compost on soil microbial activity and plant nutrient availability. *Soil Biol Biochem* **35**:295–302 (2003).
18 Schulz H and Glaser B, Effects of biochar compared to organic and inorganic fertilizers on soil quality and plant growth in a greenhouse experiment. *J Plant Nutr Soil Sci* **175**:410–422 (2012).
19 Sharma KL, Sharma SC, Bawa SS, Singh S, Chandrika DS, Sharma V *et al.*, Combined effect of tillage and organic fertilization on soil quality key indicators and indices in alluvial soils of Indo-Gangetic Plains under rainfed maize–wheat system. *Arch Agron Soil Sci* doi:10.1080/03650340.2014.933319 (2014).
20 Nagavallemma KP, Wani SP, Lacroix S, Padmaja VV, Vineela C, Rao MB *et al.*, Vermicomposting: recycling wastes into valuable organic fertilizer. *J SAT Agric Res* **2**:20–37 (2006).
21 Singh M and Wasnik K, Effect of vermicompost and chemical fertilizer on growth, herb, oil yield, nutrient uptake, soil fertility, and oil quality of rosemary. *Commun Soil Sci Plant Anal* **44**:2691–2700 (2013).
22 Bachman GR and Metzger JD, Growth of bedding plants in commercial potting substrate amended with vermicomposts. *Bioresour Technol* **99**:3155– 3161 (2008).
23 Lazcano C, Revilla P, Malvar RA and Domínguez J, Yield and fruit quality of four sweet corn hybrids (*Zea mays*) under conventional and integrated fertilization with vermicompost. *J Sci Food Agric* **91**:1244–1253 (2011).

24 Shahi SK, Effect of organic manures, inorganic fertilizers and biofertilizers addition on soil properties and productivity under onion (*Allium cepa* L.). *Plant Arch* **13**:381–387 (2013).
25 Yadav KD, Tare V and Ahammed MM, Vermicomposting of source-separated human faeces for nutrient recycling. *Waste Manage* **30**:50–56 (2010).
26 Bhat MR and Limaye SR, Nutrient status and plant growth promoting potential of prepared vermicompost. *Int J Environ Sci* **3**:312–321 (2012).
27 Morales-Corts MR, Gómez-Sánchez MÁ and Pérez-Sánchez R, Evaluation of green/pruning wastes compost and vermicompost, slumgum compost and their mixes as growing media for horticultural. *Sci Hortic* **172**:155–160 (2014).
28 Lakshmi CSR, Rao PC, Sreelatha T, Madahvi M, Padmaja G, Rao PV *et al.*, Manurial value of different vermicomposts and conventional composts. *Global Adv J Agric Sci* **2**:59–64 (2013).
29 Pattnaik S and Reddy MV, Nutrient status of vermicompost of urban green waste processed by three earthworm species: *Eisenia fetida*, *Eudrilus eugeniae*, and *Perionyx excavates*. *Appl Environ Soil Sci* article ID 967526 (2010).
30 Gómez-Brandón M and Domínguez J, Recycling of solid organic wastes through vermicomposting: microbial community changes throughout the process and use of vermicompost as a soil amendment. *Crit Rev Environ Sci Technol* **44**:1289–1312 (2014).
31 Lim PN, Wu TY, Clarke C and Daud NNN, A potential bioconversion of empty fruit bunches into organic fertilizer using *Eudrilus eugeniae*. *Int J Environ Sci Technol* doi:10.1007/s13762-014-0648-2 (2014).
32 Lim SL, Wu TY and Clarke C, Treatment and biotransformation of highly polluted agro-industrial wastewater from a palm oil mill into vermicompost using earthworms. *J Agric Food Chem* **62**:691–698 (2014).
33 Prabha ML, Waste management by vermitechnology. *Ind J Env Prot* **29**:795–800 (2009).
34 Gupta R and Garg VK, Stabilization of primary sewage sludge during vermicomposting. *J Hazard Mater* **153**:1023–1030 (2008).
35 De Araújo ASF, De Melo WJ and Singh RP, Municipal solid waste compost amendment in agricultural soil: changes in soil microbial biomass. *Rev Env Sci Biotechnol* **9** 41–49 (2010).
36 Khwairakpam M and Bhargava R, Bioconversion of filter mud using vermicomposting employing two exotic and one local earthworm species. *Bioresour Technol* **100**:5846–5852 (2009).
37 Domínguez J and Gómez-Brandón M, The influence of earthworms on nutrient dynamics during the process of vermicomposting. *Waste Manage Res* **31**:859–868 (2013).
38 Fernández-Gómez MJ, Romero E and Nogales R, Feasibility of vermicomposting for vegetable greenhouse waste recycling. *Bioresour Technol* **101**:9654–9660 (2010).
39 Singh D and Suthar S, Vermicomposting of herbal pharmaceutical industry waste: Earthworm growth, plant-available nutrient and microbial quality of end materials. *Bioresour Technol* **112**:179–185 (2012).
40 Chauhan A and Joshi PC, Composting of some dangerous and toxic weeds using *Eisenia foetida*. *J Am Sci* **6**:1–6 (2010).
41 Nath G, Singh K and Singh DK, Chemical analysis of vermicomposts/ vermiwash of different combinations of animal, agro and kitchen wastes. *Aust J Basic Appl Sci* **3**:3671–3676 (2009).
42 Shak KPY, Wu TY, Lim SL and Lee CA, Sustainable reuse of rice residues as feedstocks in vermicomposting for organic fertilizer production. *Environ Sci Pollut Res* **21**:1349–1359 (2014).
43 Padmavathiamma PK, Li LY and Kumari UR, An experimental study of vermi-biowaste composting for agricultural soil improvement. *Bioresour Technol* **99**:1672–1681 (2008).
44 Arancon NQ, Edwards CA, Bierman P, Metzger JD, Lee S and Welch C, Effects of vermicomposts on growth and marketable fruits of field-grown tomatoes, peppers and strawberries. *Pedobiologia* **47**:731–735 (2003).
45 Arancon NQ, Edwards CA, Babenko A, Cannon J, Galvis P and Metzger JD, Influences of vermicomposts, produced by earthworms and microorganisms from cattle manure, food waste and paper waste, on the germination, growth and flowering of petunias in the greenhouse. *Appl Soil Ecol* **39**:91–99 (2008).
46 Sharma S, Pradhan K, Satya S and Vasudevan P, Potentiality of earthworms for waste management and in other uses: a review. *J Am Sci* **1**:4–16 (2005).
47 Domínguez-Crespo MA, Sánchez-Hernández ZE, Torres-Huerta AM, Negrete-Rodríguez MLX, Conde-Barajas E and Flores-Vela A, Effects of the heavy metals Cu, Ni, Cd and Zn on the growth and reproduction of epigeic earthworms (*E. fetida*) during the vermistabilization of municipal sewage sludge. *Water Air Soil Pollut* **223**:915–931 (2012).
48 Lukhari T, Aatsinki M, Väisänen A and Haimi J, Toxicity of copper and zinc assessed with three different earthworms tests. *Appl Soil Ecol* **30**:133–146 (2005).
49 Wang L, Zheng Z, Zhang Y, Chao J, Gao Y, Luo X *et al.*, Biostabilization enhancement of heavy metals during the vermiremediation of sewage sludge with passivant. *J Hazard Mater* **244–245**:1–9 (2013).
50 Roy S, Arunachalam K, Dutta BK and Arunachalam A, Effect of organic amendments of soil on growth and productivity of three common crops viz. *Zea mays*, *Phaseolus vulgaris* and *Abelmonchus esculentus*. *Appl Soil Ecol* **45**:78–84 (2010).
51 Biau A, Santiyeri F, Mijangos I and Lloveras J, The impact of organic and mineral fertilizers on soil quality parameters and the productivity of irrigated maize crops in semiarid regions. *Eur J Soil Biol* **53**:56–61 (2012).
52 Rasool R, Kukal SS and Hira GS, Soil organic carbon and physical properties as affected by long-term application of FYM and inorganic fertilizers in maize–wheat system. *Soil Tillage Res* **101**:31–36 (2008).
53 Doan TT, Ngo TP, Tumpel C, Nguyen VB and Jourquet P, Interactions between compost, vermicompost and earthworm influence plant growth and yield: a one year greenhouse experiment. *Sci Hortic* **160**:148–154 (2013).
54 Srivastava PK, Gupta M, Shikha, Singh N and Tewari SK, Amelioration of sodic soil for wheat cultivation using bioaugmented organic soil amendment. *Land Degrad Dev* doi:10.1002/ldr.2292 (2014).
55 Kale RD and Karmegam N, The role of earthworms in Tropics with emphasis on Indian ecosystems. *Appl Env Soil Sci* article ID 414356 (2010).
56 Kalantari S, Ardalan MM, Alikhani HA and Shorafa M, Comparison of compost and vermicompost of yard leaf manure and inorganic fertilizer on yield of corn. *Commun Soil Sci Plant Anal* **42**:123–131 (2011).
57 Chan PLS and Griffiths DA, The vermicomposting of pre-treated pig manure. *Biol Wastes* **24**:57–69 (1988).
58 Atiyeh RM, Arancon NQ, Edwards CA and Metzger JD, Influence of earthworm-processed pig manure on the growth and yield of greenhouse tomatoes. *Bioresour Technol* **75**:175–180 (2000).
59 Atiyeh RM, Subler S, Edwards CA and Metzger JD, Growth of tomato plants in horticultural potting media amended with vermicomposts. *Pedobiologia* **43**:724–728 (1999).
60 Atiyeh RM, Subler S, Edwards CA, Bachman G, Metzger JD and Shuster W, Effects of vermicomposts and composts on plant growth in horticultural container media and soil. *Pedobiologia* **44**:579–590 (2000).
61 Buckerfield JC and Webster KA, Worm-worked waste boosts grape yields: prospects for vermicompost use in vineyards. *Aust NZ Wine Ind J* **13**:73–76 (1998).
62 Gutiérrez-Miceli FA, Santiago-Borraz J, Molina JAM, Nafate CC, Abud-Archila M, Llaven MAO *et al.*, Vermicompost as a soil supplement to improve growth, yield and fruit quality of tomato (*Lycopersicum esculentum*). *Bioresour Technol* **98**:2781–2786 (2007).
63 Valdez-Pérez MA, Fernández-Luqueño F, Franco-Hernandez O, Flores Cotera LB and Dendooven L, Cultivation of beans (*Phaseolus vulgaris L.*) in limed or unlimed wastewater sludge, vermicompost of inorganic amended soil. *Sci Hortic* **128**:380–387 (2011).
64 Fernández-Luqueño F, Reyes-Varela V, Martínez-Suárez C, Salomón-Hernández G, Yáñez- Meneses J, Ceballos-Ramírez JM and Dendooven L, Effect of different nitrogen sources on plant characteristics and yield of common bean (*Phaseolus vulgaris* L.). *Bioresour Technol* **101**:396–403 (2010).
65 Ansari AA and Sukhraj K, Effect of vermiwash and vermicompost on soil parameters and productivity of okra (*Abelmoschus esculentus*) in Guyana. *Afric J Agric Res* **5**:1794–1798 (2010).
66 Sangwan P, Garg VK and Kaushik CP, Growth and yield response of marigold to potting media containing vermicompost produced from different wastes. *Environmentalist* **30**:123–130 (2010).
67 Singh R, Sharma RR, Kumar S, Gupta RK and Patil RT, Vermicompost substitution influences growth, physiological disorders, fruit yield and quality of strawberry (*Fragaria × ananassa* Duch.). *Bioresour Technol* **99**:8507–8511 (2008).

68 Sinha J, Biswas CK, Ghosh A and Saha A, Efficacy of vermicompost against fertilizers on *Cicer* and *Pisum* and on population diversity of N_2 fixing bacteria. *J Environ Biol* **31**:287–292 (2010).
69 Singh BK, Pathak KA, Verma AK, Verma VK and Deka BC, Effects of vermicompost, fertilizer and mulch on plant growth, nodulation and pod yield of French bean (*Phaseolus vulgaris* L.). *Veg Crops Res Bull* **74**:153–165 (2011).
70 Khan A and Ishaq F, Chemical nutrient analysis of different composts (Vermicompost and Pitcompost) and their effect on the growth of a vegetative crop *Pisum sativum*. *Asian J Plant Sci Res* **1**:116–130 (2011).
71 Papathanasiou F, Papadopoulos I, Tsakiris I and Tamoutsidis E, Vermicompost as a soil supplement to improve growth, yield and quality of lettuce (*Lactuca sativa* L.). *J Food Agric Environ* **10**:677–682 (2012).
72 Patel D and Saraf M, Influence of soil ameliorants and microflora on induction of antioxidant enzymes and growth promotion of *Jatropha curcas* L. under saline condition. *Eur J Soil Biol* **55**:47–54 (2013).
73 Pant AP, Radovich TJK, Hue NV and Paull RE, Biochemical properties of compost tea associated with compost quality and effects on park choi growth. *Sci Hortic* **148**:138–146 (2012).
74 Lazcano C and Domínguez J, Effects of vermicompost as a potting amendment of two commercially-grown ornamental plant species. *Span J Agric Res* **8**:1260–1270 (2010).
75 Huerta E, Vidal O, Jarquin A, Geissen V and Gomez R, Effect of vermicompost on the growth and production of Amashito pepper, interactions with earthworms and rhizobacteria. *Compost Sci Util* **18**:282–288 (2010).
76 Atiyeh RM, Edwards CA, Subler S and Metzger JD, Pig manure vermicompost as a component of a horticultural bedding plant medium: effects on physiochemical properties and plant growth. *Bioresour Technol* **78**:11–20 (2001).
77 Bartlett MD, Briones MJI, Neilson R, Schmidt O, Spurgeon D and Creamer RE, A critical review of current methods in earthworm ecology: from individuals to populations. *Eur J Soil Biol* **46**:67–73 (2010).
78 Kumar A, *Verms and Vermitechnology*. APH, New Delhi (2005).
79 Edwards CA and Bohlen PJ, *Biology and Ecology of Earthworms* (3rd edn). Chapman & Hall, London (1996).
80 Edwards CA, Historical overview of vermicomposting. *BioCycle* **36**:56–58 (1995).
81 Edwards CA, *Earthworm Ecology*)2nd edn). CRC Press, Boca Raton, FL (2004).
82 Rao KR, Induced host plant resistance in the management of sucking insect pests of groundnut. *Ann Plant Prot Sci* **10**:45–50 (2002).
83 Pramanik P, Bhattacharya S, Bhattacharyya P and Banik P, Phosphorus solubilization from rock phosphate in presence of vermicomposts in Aqualfs. *Geoderma* **152**:16–22 (2009).
84 Bhattacharjee G, Chaudhuri PS and Datta M, Response of paddy (Var. Trc-87-251) crop on amendment of the field with different levels of vermicomposts. *Asian J Microbiol Biotechnol Environ Sci* **3**:191–196 (2001).
85 Masciandaro G, Macci C, Doni S and Ceccanti B, Use of earthworms (*Eisenia fetida*) to reduce phytotoxicity and promote humification of pre-composted olive oil mill wastewater. *J Sci Food Agric* **90**:1879–1885 (2010).
86 Warman PR and AngLopez MJ, Vermicompost derived from different feedstocks as a plant growth medium. *Bioresour Technol* **101**:4479–4483 (2010).
87 Abbasi T, Gajalakshmi S and Abbasi SA, Towards modeling and design of vermicomposting systems: mechanisms of composting/vermicomposting and their implications. *Ind J Biotechnol* **8**:177–182 (2009).
88 Fernández-Bayo JD, Nogales R and Romero E, Assessment of three vermicomposts as organic amendments used to enhance diuron sorption in soils with low organic carbon content. *Eur J Soil Sci* **60**:935–944 (2009).
89 Gopal M, Gupta A, Sunil E and Thosmas GV, Amplification of plant beneficial microbial communities during conversion of coconut leaf substrate to vermicompost by *Eudrilus* sp. *Curr Microbiol* **59**:15–20 (2009).
90 Srikanth K, Srinivasamurthy CA, Siddaramappa R and Parama VRR, Direct and residual effect of enriched compost, FYM, vermicompost and fertilizers on properties of an Alfisol. *J Ind Soc Soil Sci* **48**:496–499 (2000).
91 Lim PN, Wu TY, Sim EYS and Lim SL, The potential reuse of soybean husk as feedstock of *Eudrilus eugeniae* in vermicomposting. J Sci Food Agric **91**:2637–2642 (2011).
92 Oo AN, Iwai CB and Saenjan P, Soil properties and maize growth in saline and nonsaline soils using cassava–industrial waste compost and vermicompost with or without earthworms. *Land Degrad Dev* doi:10.1002/ldr.2208 (2013).
93 Fernández-Gómez MJ, Díaz-Raviña M, Romero E and Nogales R, Recycling of environmentally problematic plant wastes generated from greenhouse tomato crops through vermicomposting. *Int J Environ Sci Technol* **10**:697–708 (2013).
94 Atiyeh RM, Lee S, Edwards CA, Arancon NQ and Metzger JD, The influence of humic acids derived from earthworm-processed organic wastes on plant growth. *Bioresour Technol* **84**:7–14 (2002).
95 Tomati U, Grappelli A and Galli R, The presence of growth regulators in earthworm-worked wastes, in *On Earthworms*, ed. by Bonvicini Paglioi AM and Omodeo P. Modena, Italy, pp. 423–436 (1987).
96 Arancon NQ, Edwards CA and Bierman P, Influences of vermicomposts on field strawberries. Part 2. Effects on soil microbiological and chemical properties. *Bioresour Technol* **97**:831–840 (2006).
97 Arancon NQ, Edwards CA, Lee S and Byrne R, Effects of humic acids from vermicomposts on plant growth. *Eur J Soil Biol* **42**:65–69 (2006).
98 Hachicha S, Cegarra J, Sellami F, Hachicha R, Drira N, Medhioub K and Ammar E, Elimination of polyphenols toxicity from olive mill wastewater sludge by its co-composting with sesame bark. *J Hazard Mater* **161**:1131–1139 (2009).
99 Masciandaro G, Ceccanti B and Garcia C, Soil agro-ecological management: fertirrigation and vermicompost treatments. *Bioresour Technol* **59**:199–206 (1997).
100 Canellas LP, Dobbss LB, Oliveira AL, Chagas JG, Aguiar NO, Rumjanek VM *et al.*, Chemical properties of humic matter as related to induction of plant lateral roots. *Eur J Soil Sci* **63**:315–324 (2012).
101 Arancon NQ, Edwards CA, Bierman P, Welch C and Metzger JD, Influences of vermicomposts on field strawberries. Part 1. Effects on growth and yields. *Bioresour Technol* **93**:145–153 (2004).
102 Roberts P, Jones DL and Edwards-Jones G, Yield and vitamin C content of tomatoes grown in vermicomposted wastes. *J Sci Food Agric* **87**:1957–1963 (2007).
103 Canellas LP, Olivares FL, Okorokova-Façanha AL and Façanha, AR, Humic acids isolated from earthworm compost enhance root elongation, lateral root emergence, and plasma H^+-ATPase activity in maize roots. *Plant Physiol* **130**:1951–1957 (2002).
104 Subler S, Edwards C and Metzger J, Comparing vermicomposts and composts. *BioCycle* **39**:63–66 (1998).
105 Negi R and Suthar S, Vermistabilization of paper mill wastewater sludge using *Eisenia fetida*. *Bioresour Technol* **128**:193–198 (2013).
106 Ravindra NP, Raman G, Badri Narayanan K and Sakthivel N, Assessment of genetic and functional diversity of phosphate solubilizing fluorescent pseudomonads isolated from rhizospheric soil. *BMC Microbiol* **8**:230 (2008).
107 Han J, Sun L, Dong X, Cai Z, Yang H, Wang Y *et al.*, Characterization of a novel plant growth-promoting bacteria strain *Delftia tsuruhatensis* HR4 both as a diazotroph and a potential biocontrol agent against various pathogens. *Syst Appl Microbiol* **28**:66–76 (2005).
108 Anastasi A, Varese GC and Marchisio VF, Isolation and identification of fungal communities in compost and vermicompost. *Mycologia* **97**:33–44 (2005).
109 Dinesh R, Srinivasan V, Hamza S, Manjusha A and Kumar PS, Short-term effects of nutrient management regimes on biochemical and microbial properties in soils under rainfed ginger (*Zingibe officinale* Rosc.). *Geoderma* **173–174**:192–198 (2012).
110 Benítez E, Nogales R, Elvira C, Masciandaro G and Ceccanti B, Enzyme activities as indicators of the stabilization of sewage sludge composting with *Eisenia foetida*. *Bioresour Technol* **67**:297–303 (1999).
111 Domínguez J, Parmelee RW and Edwards CA, Interactions between *Eisenia andrei* (Oligochaeta) and nematode populations during vermicomposting. *Pedobiologia* **47**:53–60 (2003).
112 Hyvönen R, Andersson S, Clarholm M and Persson T, Effects of lumbricids and enchytraeids on nematodes in limed and unlimed coniferous mor humus. *Biol Fertil Soils* **17**:201–205 (1994).
113 Senapati BK, Biotic interactions between soil nematodes and earthworms. *Soil Biol Biochem* **24**:1441–1444 (1992).
114 Edwards CA, The use of earthworm in the breakdown and management of organic waste, in: *Earthworm Ecology*, ed. by Edwards CA. ACA Press, Boca Raton, FL, pp. 327–354 (1998).

115 International Fertilizer Industry Association (IFA), *Market Outlooks*. [Online]. Available: http://www.fertilizer.org/ifa/HomePage/FERTILIZERS-THE-INDUSTRY/Market-outlooks.html [2 March 2013].

116 Ghosh N, Reducing dependence on chemical fertilizers and its financial implications for farmers in India. *Ecol Econ* **49**:149–162 (2004).

117 Chouichom S and Yamao M, Organic fertilizer use in northeastern Thailand: an analysis of some factors affecting farmers' attitudes, *in* Sustainable Agriculture Development, ed. by Behnassi M, Shahid SA and D'Silva J. Springer, Berlin, pp. 185–196 (2011).

118 Behera KK, Alam A, Vats S, Sharma HP and Sharma V, Organic farming history and techniques, in *Sustainable Agriculture Reviews*, ed. by Lichtfouse E. Springer, Berlin, pp. 287–328 (2012).

119 Klaus VH, Kleinebecker T, Prati D, Gossner MM, Alt F, Boch S *et al.*, Does organic grassland farming benefit plant and arthropod diversity at the expense of yield and soil fertility? *Agric Ecosyst Environ* **177**:1–9 (2013).

120 FiBL (Research Institute of Organic Agriculture), *Dynamic data table with key data from the FiBL-IFOAM Survey*. [Online]. Available: http://www.organic-world.net/statistics-data-tables-dynamic.html?&L=0 [1 March 2013].

121 Azadi H and Ho P, Genetically modified and organic crops in developing countries: a review of options for food security. *Biotechnol Adv* **28**:160–168 (2010).

122 Lobley M, Butler A and Reed M, The contribution of organic farming to rural development: an exploration of the socio-economic linkages of organic and non-organic farms in England. *Land Use Policy* **26**:723–735 (2009).

123 Gareau SE, Economic analysis of conventional and alternative nutrient management approaches, in *Advances in Citrus Nutrition*, ed. by Srivastava AK. Springer, Berlin, pp. 415–424 (2012).

124 Kearney S, Fonte SJ, Salomon A, Six J and Scow KM, Forty percent revenue increase by combining organic and mineral nutrient amendments in Ugandan smallholder market vegetable production. *Agron Sustain Dev* **32**:831–839 (2012).

125 Dass A, Lenka NK, Patnail US and Sudhishri S, Integrated nutrient management for production, economics and soil improvement in winter vegetables. *Int J Veg Sci* **14**:104–120 (2008).

126 Jouquet P, Plumere T, Doan Thu T, Rumpel C, Tran Duc T and Orange D, The rehabilitation of tropical soils using compost and vermicompost is affected by the presence of endogeic earthworms. *Appl Soil Ecol* **46**:125–133 (2010).

127 Jouquet P, Blanchart E and Capowiez Y, Utilization of earthworms and termites for the restoration of ecosystem functioning. *Appl Soil Ecol* **73**:33–40 (2014).

