THE SCIENCE OF VERMICULTURE: THE USE OF EARTHWORMS IN ORGANIC WASTE MANAGEMENT

Clive A. Edwards & Norman Q. Arancon

Soil Ecology Laboratory, The Ohio State University, Columbus, Ohio, U.S.A.

CONTENTS

I. INTRODUCTION

Earthworms are segmented invertebrates that inhabit soils and organic wastes. They are hermaphrodites and usually reproduce by mating, each partner fertilizing the other. After mating they retract their bodies through the "saddle" or clitellum and pass it over their heads. Each cocoon contains one or more eggs that can survive adverse conditions, hatching when environmental conditions are favorable. Some species are able to produce viable cocoons parthenogenetically without mating. Earthworms take from one to eight months to become sexually mature and continue to reproduce at regular intervals through their lives which can be up to several years. They require moisture and aerobic conditions for survival and reproduction.

The importance of earthworms in the breakdown of organic matter and the release of the nutrients that it contains has been known for a long time (Darwin 1881). It has been demonstrated clearly that some species of earthworms are specialized to live in decaying organic matter and can degrade it into fine particulate materials, rich in available nutrients, with considerable commercial potential as plant growth media or soil amendments (Edwards and Bohlen 1996). For instance, earthworms are able to process sewage sludges and solids from wastewater; brewery wastes; processed potato wastes; waste from the paper industries; wastes from supermarkets and restaurants; animal wastes from poultry, pigs, cattle, sheep, goats, horses, and rabbits; as well as horticultural residues from dead plants, yard wastes, and wastes from the mushroom industry. (Edwards and Neuhauser, 1988)

Research into vermicomposting and commercial projects has been developed in many countries, including England, France, the Netherlands, Germany, Italy, Spain, Poland, the United States, Cuba, Mexico, the Bahamas, China, Japan, the Philippines, India and other parts of Southeast Asia, including Australia, New Zealand, America Samoa, and Hawaii, and many countries in South America (Edwards 2004).

Currently, the leading research programs into vermiculture and vermicomposting are at the Soil Ecology Laboratory at The Ohio State University (OSU) in Columbus; at the University of Vigo in Spain, led by Jorge Dominguez; at the University of Agricultural Sciences in Bangalore, India, led by Dr. Radha Kale; and at the Instituto de Ecologia, Mexico, led by Dr. Isabelle Barois and Dr. Aranda.

II. **BIOLOGY OF VERMICOMPOSTING EARTHWORMS**

a) The nutrition of earthworms

•Earthworms obtain their nutrition from microorganisms, especially fungi and also nematodes
•The grinding action of earthworm's gizzard increases surface area of the organic matter and promotes microbial activity in organic wastes as they pass through earthworm guts
•Earthworm feeding favors aerobic microorganisms at the expense of anaerobic microbes
•Vermicomposts are very much more microbially-active than the parent organic wastes with diverse microbial communities

b) Species of earthworms suitable for vermiculture

Six earthworm species have been identified as potentially the most useful species to break down organic wastes. These are *E. fetida* (and the closely-related *Eisenia andrei*), *Dendrobaena veneta*, and *Lumbricus rubellus* from temperature regions and *Eudrilus eugeniae, Perionyx excavatus,* and *Perionyx hawayana* from the tropics. Other species can be used but these species are the commonest. The survival, growth, mortality, and reproduction of these species have been studied in detail in the laboratory, in a range of organic wastes, including pig, cattle, duck, turkey, poultry, potato, brewery, paper, and activated sewage sludge. All of the species tested could grow and survive in a wide range of different organic wastes, but some were much more prolific, others grew more rapidly, and yet others attained a large biomass quickly; those were all characters contributing in different ways to the practical usefulness of the earthworms in producing vermicomposts or being used as animal feed protein. However, there were many species-specific differences in the biology and ecology of these earthworms.

Most organic wastes can be broken down by earthworms, but some organic wastes have to be pretreated in various ways to make them acceptable to the earthworms, and earthworms will not grow equally well in all organic wastes.

It is important to be able to predict the numbers of live young earthworms that emerge from the cocoons of each species. Cocoons from five species of earthworms, *D. veneta, E. fetida, E. eugeniae, P. excavatus,* and *P. hawayana,* were collected and allowed to hatch (Edwards 2004). Individual cocoons were kept in organic wastes, under nonstressed conditions at 25˚C, and were checked twice per week to determine the numbers of cocoons that had hatched and the numbers of earthworm hatchlings that were produced per cocoon. It was concluded that *E. fetida* produced 6 cocoons per earthworm per week (19 young earthworms), *D. veneta* produced 5 cocoons (19 young earthworms), *E. eugeniae* produced 11 cocoons (20 young earthworms), *P. excavatus*) produced 24 cocoons (13 young earthworms), and *P. hawayana* produced 10 cocoons (9.5 young earthworms) per parent earthworm.

Edwards (1988) reported on the life cycles and optimal conditions for growth and survival of *E. fetida, D. veneta, E. eugeniae,* and *P. excavatus* in animal and vegetable wastes. Each of the four earthworm species differed considerably in terms of responses to and tolerance of different temperatures. The optimum temperature for growth of *E. fetida* was 25˚C, with a temperature tolerance from 0˚ to 35˚C. *D. veneta* had a lower temperature optimum and was less tolerant of extreme temperatures. The optimum temperatures for *E. eugeniae* and *P. excavatus* were also about 25˚C, but they died at temperatures below 9˚C and above 35˚C. The optimum temperatures for cocoon production for all species were much lower than those for growth. These four species also differed in their optimum moisture requirements from those of *E. fetida,* but the differences were not great. The range over which the earthworms grew optimally was quite narrow, with optimal growth at 80 to 85˚C moisture content, with considerable decreases in rates of growth at moisture contents lower than 70% and higher than 90%. However, *D. veneta* was able to withstand a much wider range of moisture contents than the other species, such as *P. excavatus*.

All four species of earthworms were very sensitive to ammonia and did not survive long in organic wastes containing much ammonia (e.g., fresh poultry litter). They also died in wastes containing large quantities of inorganic salts which had a high conductivity. Laboratory experiments showed that both ammonia and inorganic salts have very sharp cutoff points between toxic and nontoxic levels (i.e., <0.5 mg per ram ammonia and <0.5% salts). However, organic wastes that have too much ammonia soon became acceptable after the ammonia was removed by a period of composting or when both excessive ammonia and salts were washed out of the waste. Earthworms were relatively tolerant of pH, but when given a choice in a pH gradient, they moved toward the more acid materials, with an apparent pH preference of 5.0. The optimal conditions for breeding *E. fetida* are summarized in as follows. These do not differ much from those suitable for the other species.

Table 1. Optimal conditions for breeding *Eisenia fetida* in organic wastes

Factor	**Requirements**
*Temperature	
-preferred	-15-24˚C (59-77˚F)
-limits	-0-35˚C (32-95 ˚F)
*Moisture content	
-preferred	-80-90%
-limits	-60-90%
*Ammonia content	Low <0.5mg/g
*Salt content	Low (<0.5 mg/kg)
*pH	>5 < 9
*Oxygen needs	Aerobic

Life cycles

The life cycles of the two most important species, *E. fetida*and *E. eugeniae* are summarized in Figs.

Figure 1. Life cycle of *Eisenia fetida*

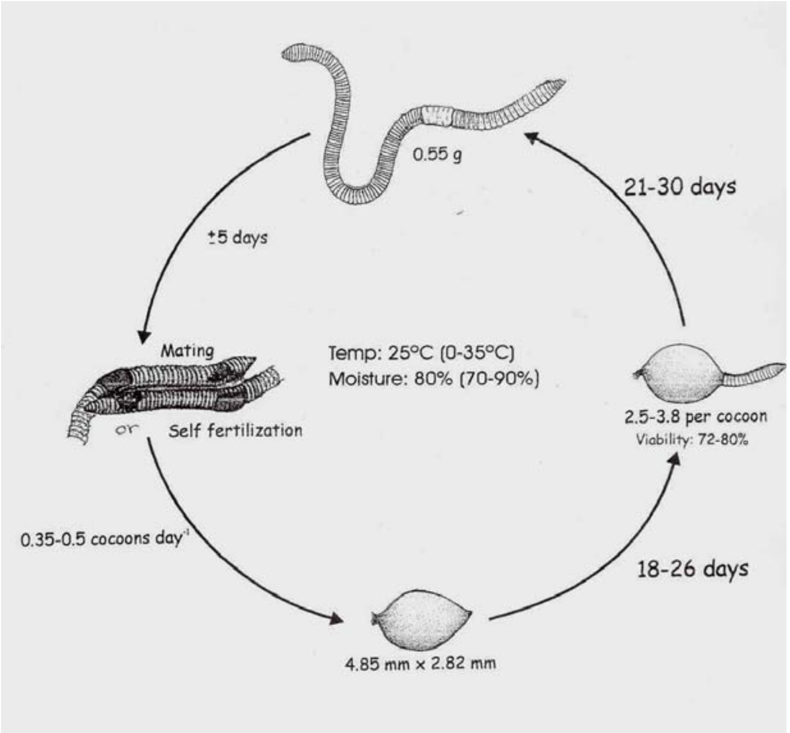
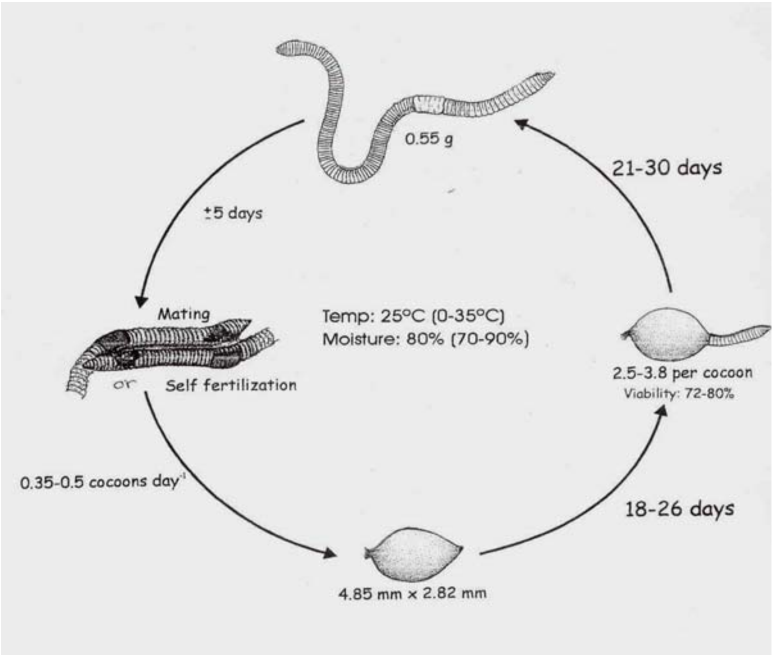


Figure 2. Life cycle of *Eudrilus eugeniae*



c) **Suitable organic wastes for earthworm processing**

Farm	Industrial/Urban
•Chicken	•Brewery
•Turkey	•Potato
•Duck	•Paper
•Horse	•Sewage
•Cattle	•Restaurant
•Pig	•Food market
•Rabbit	•Yard waste (leaves and grass)

d) **Vermicomposts**

Vermicomposts are organic materials, broken down by interactions between earthworms and microorganisms, in a mesophilic process (up to 25˚C), to produce fully-stabilized organic soil amendments with low C:N ratios. They also have a high and diverse microbial and enzymatic activity, fine particulate structure, good moisture-holding capacity, and contain nutrients such as N, K, P, Ca and Mg in forms readily taken up by plants. They contain both plant growth hormones and humic acids which can act as plant growth regulators.

e) **Principles of vermicomposting**

Production of vermicomposts can be outdoors in suitable climate conditions or indoors in buildings or plastic tunnels. For maximum productivity optimal environmental conditions should be maintained.

•Species of organic waste-consuming earthworms such as *Eisenia fetida, Dendrobaena veneta* and *Eudrilus eugeniae* and *Perionyx excavatus* are used
•Organic materials are added to systems in thin layers (2.5-5.0 cm)
•Earthworms require aerobic conditions and remain in the top 10-15 cm of a system—moving up as new organic matter is added to the surface.
•Temperature should be maintained ideally at 20-25˚C
•Moisture content should be 75%-90%
•Never cover beds with impermeable materials, such as plastic, which prevent oxygenation

III. **VERMICOMPOSTING TECHNOLOGY**

Vermicomposting systems using earthworms range from very simple methods involving low technology such as windrows, waste heaps, or containers, through moderately complex to completely automated continuous flow reactors (Edwards, 2004). The basic principle of all successful vermicomposting systems is to add the wastes at frequent intervals in small, thin layers to the surface of the system and allow the earthworms to move up and concentrate themselves in the aerobic upper 15 cm of waste and continue to move upward as each successive waste layer is added. Many of the operations involved in vermicomposting can be mechanized; a suitable balance is needed between the costs of mechanization and the savings in labor that result. The key to combining maximum productivity of vermicompost with the greatest rates of earthworm growth is to maintain aerobicity and optimal moisture and temperature conditions in the waste and to avoid wastes with excessive amounts of ammonia and salts. The addition of organic wastes in thin layers avoids overheating through thermophilic composting, although enough usually occurs to maintain suitable temperatures for earthworm growth during cold winter periods. Hence, for year-round production, to maintain a reasonable temperature in temperate climates, the processing should always be done under cover, although heating is not usually necessary if the waste additions are managed well with addition of thicker layers during cold periods to provide some degree of thermophilic composting. Temperature may need to be decreased under cover in summer with fans.

a) <u>Ground beds or windrows</u>

Outdoor windrows or beds, either in heaps or in beds with low simple walls, are the most common type of process generally used. The size of such beds is flexible, but the width of the beds should not exceed 8 ft (2.4 m), which allows the entire bed to be inspected easily. Because there is no need to walk on the bed, many suitable surface coverings and construction materials can be used. The length is less important and depends on the ground area available. They should not be laid directly on soil because soil particles would be picked up with the processed vermicompost. Concrete areas are ideal for earthworm processing systems because they provide a firm surface for tractor operations. However, it is essential for precautions to be taken to prevent too much water from entering the beds and to allow excess water to drain away from the bed easily. Often, the wastes on such floor beds are covered with some permeable material such as canvas or bamboo sheets, which permit watering and need be only removed for addition of new waste materials. Windrows and floor beds process organic wastes relatively slowly, often taking 6 to 12 months for complete processing. During this period, there may be significant losses of plant nutrients through volatilization or leaching. The major drawback to windrows are the difficulties in harvesting the vermicompost and the need for a trommels or other labor-intensive separation stages to recover earthworms from the vermicompost before it is used. Although the initial capital outlay, other than land, is low, large areas of land are needed, labor costs are high, and the rates of processing are slow.

<u>Benefits</u>:
- •Low capital outlay
- •Easily managed

<u>Drawbacks</u>
- •Labor intensive
- •Needs large areas of land
- •Slow vermicompost processing time
- •Considerable loss of nutrients though leaching and volatilization
- •Difficult to harvest vermicompost without earthworms, i.e., involves losses of earthworms

b) <u>Container or vermicomposting box crate systems</u>

Vermicomposting is often done in boxes, containers or trays of a wide range of sizes which maybe stacked. However, such systems are labor-intensive, it is difficult to add water if they are stacked and still need labor-intensive separation of earthworms from the processed vermicomposts.

Benefits	•Needs relatively little space
Drawbacks	•Considerable expenditure on containers and moving equipments •Difficult to maintain optimal moisture conditions with water sprays •Labor intensive •Harvesting of vermicompost without earthworms difficult--separation of earthwormsfrom waste necessary

c) <u>Domestic waste processing systems</u>

Small scale systems of vermicomposting for the disposal of household wastes have been used extensively in homes and schools in the U.S., Canada, and elsewhere. They range from simple containers, with perforated lids for aeration, to more sophisticated commercially-produced stacking systems of different sizes and complexity, including circular stacking systems such as the Can-O-Worms and the Worm Wigwam System, a rectangular stacking system called Worm Factory, and small reactor systems such as the Eliminator, which has a breaker bar and collection drawer at the base. These systems have attracted the interest of some urban waste authorities, who have encouraged home owners to use them and sometimes provided them free of cost if they do not put food wastes into the garbage.

In Australia, a very successful vermicomposting toilet has been designed and is used extensively in state parks.

d) <u>Wedge systems of vermicomposting</u>

Wedge systems (Edwards, 2004) are based on adding successive thin layers (5 to 10 cm) or organic waste at a 45˚ angle from a vertical removable barrier. The wedge system can be any width or length but is limited in height to about 1.2. to 1.5 m for ease of loading. It should be situated on concrete or some other solid surface. The system starts with an initial layer of partially vermicomposted biosolids or other organic waste containing 9 kg (wet weight) of *E. fetida* (or other species) per m^2 to a depth of about 15 cm. The surface is kept moist to a depth of 15 cm. (80% moisture content) by a fine water spray as required.

The earthworms move progressively from the older layers of fully processed organic waste into the fresh material at the wedge surface that is added daily so that the entire earthworm population is always concentrated in the top 15-20 cm below the leading surface. At convenient intervals (e.g., 1 to 2 months), the removable barrier is taken away and replaced about 60 cm behind the leading face of the wedge, so that no earthworms are removed when the waste is collected. All of the processed waste behind this barrier can be removed with front loader machinery and collected free of earthworms for subsequent drying to 35 to 45% moisture, sieving, and packaging. Processing of wastes in a wedge system takes about 3 to 4 months.

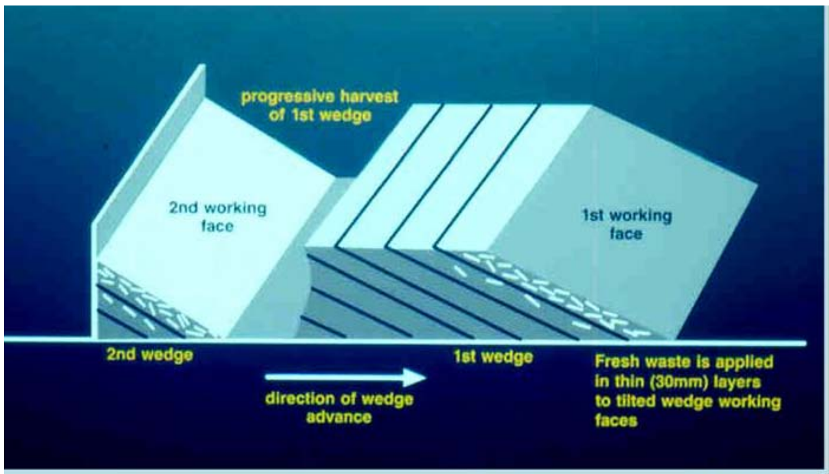


Figure 3. The Wedge Vermicomposting System

Benefits
- •Low capital outlay
- •Needs labor than windrows
- •Faster processing time
- •Much less leaching of nutrients
- •Easy to harvest vermicompost without earthworms

Drawbacks
- •Moderate processing time
- •Need for machinery
- •Need for covered structure

e) Automated, continuous flow vermicomposting reactors

This technology was designed at the U.K. National Institute of Agricultural Engineering by a team of biologists and engineers (Clive A. Edwards, Keith Fletcher, Roger V. Phillips and Jim Price). These reactors consist of large containers 1m deep raised on legs above the ground. This allows organic wastes to be added in thin layers to the surface from mobile gantries, at 1- to 2-day intervals, and the vermicomposts can be collected mechanically through the mesh at the bottom using manual power or electrically driven breaker bars, which travel up and down the length of the system on a winch. Waste released on to the floor can be brought from under the reactor to one end by hydraulically driven flap scraper systems, of the kind used to collect manure from dairy cows in barns. Such reactors can range from medium-technology systems using manually-operated loading and waste collecting systems to completely automated, electrically or hydraulically-driven, continuous flow reactors, which have been operated successfully in the U.K., U.S.A., and Australia for several years. The earthworm populations in such reactors tends to reach an equilibrium biomass of about 9 kg per m^2. Such reactors can process fully the whole 1-m depth of suitable organic wastes they contain in about 30 to 45 days. Economic studies have shown that such reactors have a much greater economic potential to produce high-grade vermicomposts with few material losses very quickly and much more efficiently than windrows or ground beds with no need to separate earthworms from vermicompost. A single reactor 40mm long 2.4 m wide can process about 1,000 tons of waste per year or 3 tons per day.

Benefits	*Quick returns of capital outlay (1 -2 years) *Rapid waste turnover times *Low labor requirements *Relatively little space needed *Little loss of nutrients *Easy harvesting of vermicomposts without earthworms
Drawbacks	*High capital outlay *Requirement for good management and of moisture and temporature

IV. VERMICOMPOSTS IN CROP PEST & DISEASE CONTROL

a) Plant disease suppression by vermicomposts

(i) Solid vermicomposts

Traditional composting is a thermophilic process reaching temperatures 55˚-70˚C that promotes microbial activity selectively, whereas vermicomposting is a mesophilic method and promotes greatly increased activity by a wide range and diversity of microorganisms. We have considerable evidence from our research at OSU of much greater microbial activity and biodiversity in vermicomposts than in thermophilic composts. Our laboratory, greenhouse and field research provide evidence that vermicomposts have an even greater potential for disease suppression than traditional thermophilic composts. For instance, general evidence of decreases in plant disease incidence and of pathogen suppression has been recorded in studies involving 28 species of crop plants grown in vermicomposts.

In greenhouse experiments in the Soil Ecology Laboratory at OSU, there was significant suppression of *Pythium* and *Rhizoctonia* resulting from substituting low rates (10 to 30%) of vermicompost into horticultural bedding mixtures. Suppression of diseases of field crops was achieved with low application rates of vermicomposts. The diseases suppressed in the field were *Verticillium* wilt on strawberries and *Phomopsis* and powdery mildew (*Sphaerotheca fulginae*) on grapes.

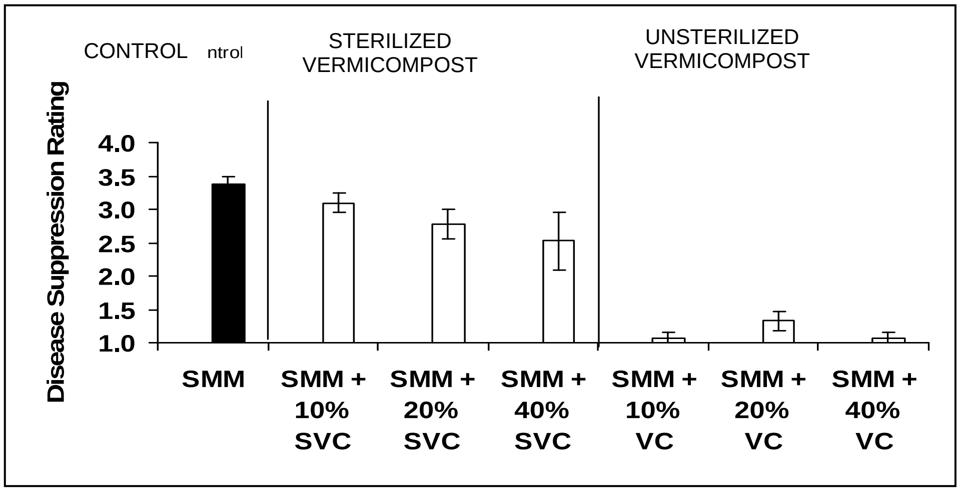


Figure 4. Suppression of *Pythium* on cucumbers by vermicomposts in the greenhouse. MM = MM360; S= Sterile; VC = Vermicompost

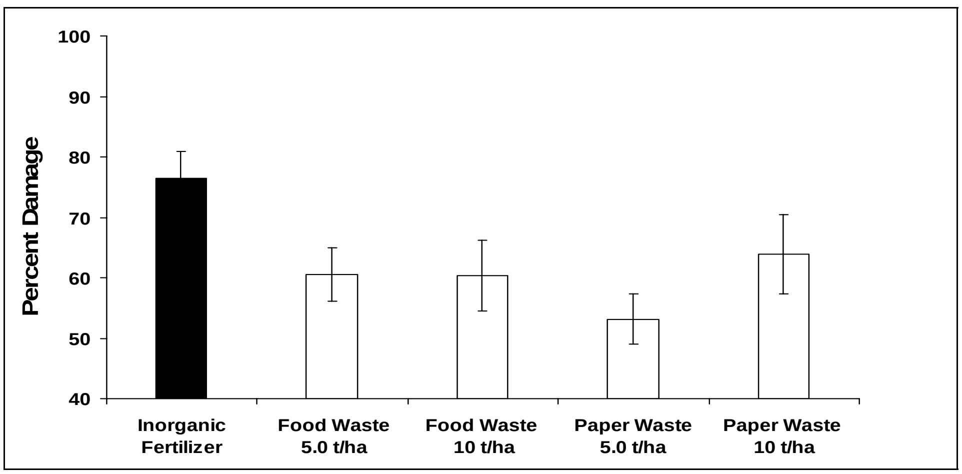


Figure 5. Suppression of *Verticillium* on grapes by food waste vermicomposts in the field.

ii) Vermicompost 'teas'

Aqueous extracts from vermicomposts (teas) have suppressed plant pathogens such as *Plectosporium, Verticillium,* and *Rhizoctonia* significantly in laboratory and greenhouse experiments organized by our research group at OSU.

Preparation of aqueous vermicompost extracts ('teas')

There are many ways of producing aqueous extracts—including on farm and commercial processing Methods include:

- Passing water through vermicomposts
- Standing vermicomposts in water (1-7 days)
- Modifications of these methods
    - -Aeration
    - -Addition of other materials
    - -Addition of organic substrates (not recommended)

Preparation of aqueous vermicompost extracts ('teas') in our experiments

We used a one part vermicompost to ten parts of water mixture and stood the solids in mesh bags in water for 24 hours with stirring but no aeration. We have some data that indicate that aeration benefits the effectiveness and longevity of 'teas'.

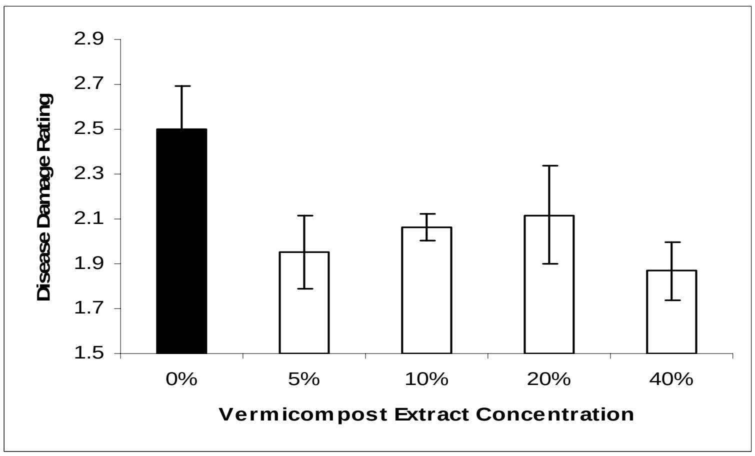


Figure 6. Suppression of *Verticillium* on tomatoes by vermicompost 'teas' in the greenhouse

iii) Conclusions on suppression of plant pathogens by vermicomposts and vermicompost aqueous extracts

Small substitutions of vermicomposts into horticultural plant growth media in the greenhouse and small amendments of vermicomposts in the field can suppress a wide range of plant pathogens significantly. This suppression is removed by sterilization of the vermicompost or 'tea'. Although precise mechanisms of suppression still need to be identified it is almost certainly based on the very high microbial activity and diversity in vermicomposts.

b) **<u>Suppression of plant parasitic nematodes by vermicomposts</u>**

There is considerable evidence that vermicomposts can suppress attacks and damage by plant parasitic nematodes.

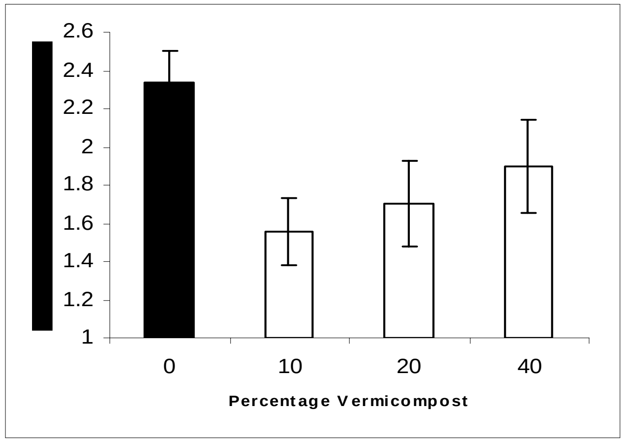


Figure 7. Suppression of *Meloidogyne* by vermicomposts in the greenhouse

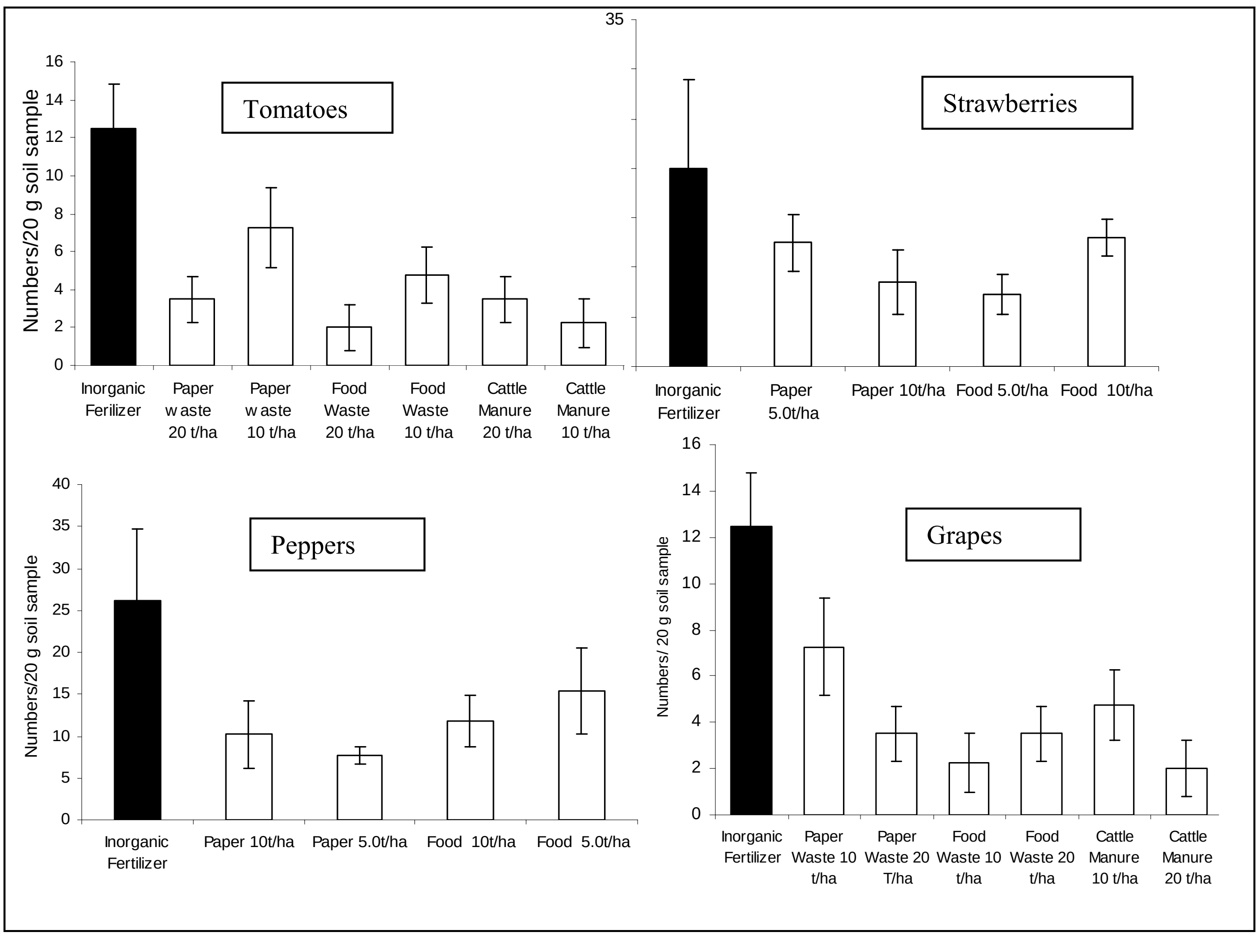


Figure 8. Suppression of plant parasitic nematodes by vermicomposts in the field

c) **Suppression of arthropod pests by vermicomposts**

Recent experiments in the Soil Ecology Laboratory at OSU have demonstrated clearly that vermicomposts can suppress attacks and damage by arthropod pests to a range of vegetables very significantly.

Demonstrations of effect of vermicomposts on arthropod pests

- Sucking arthropods -
    - Mealy bugs
    - Aphids
    - Two-spotted spider mites
- Chewing insects
    - Cabbage white caterpillars
    - Tomato hornworm
    - Cucumber beetles

(i) Sucking Insects

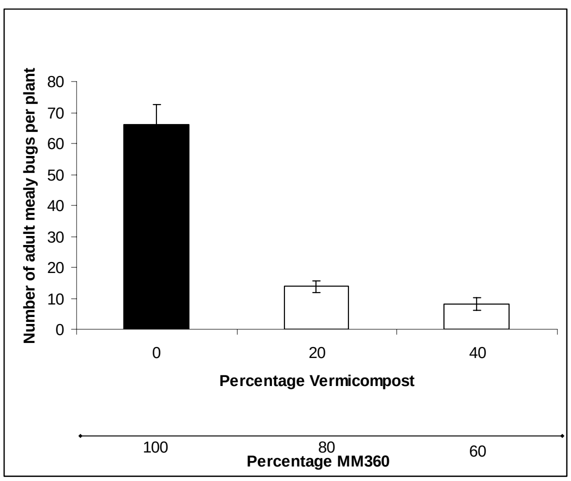


Figure 9. Suppression of aphid populations on peppers by vermicomposts in the greenhouse

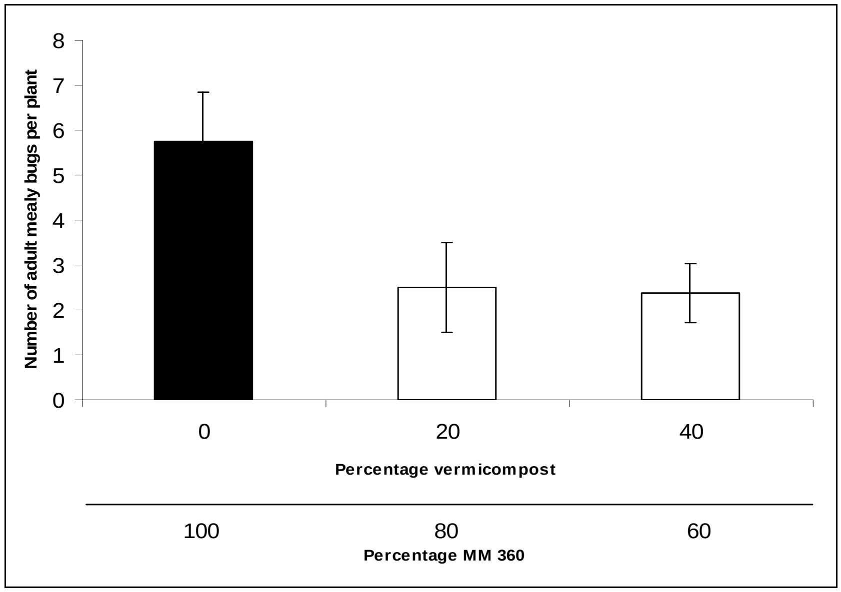


Figure 10. Suppression of mealy bug populations on tomatoes by vermicomposts in the greenhouse

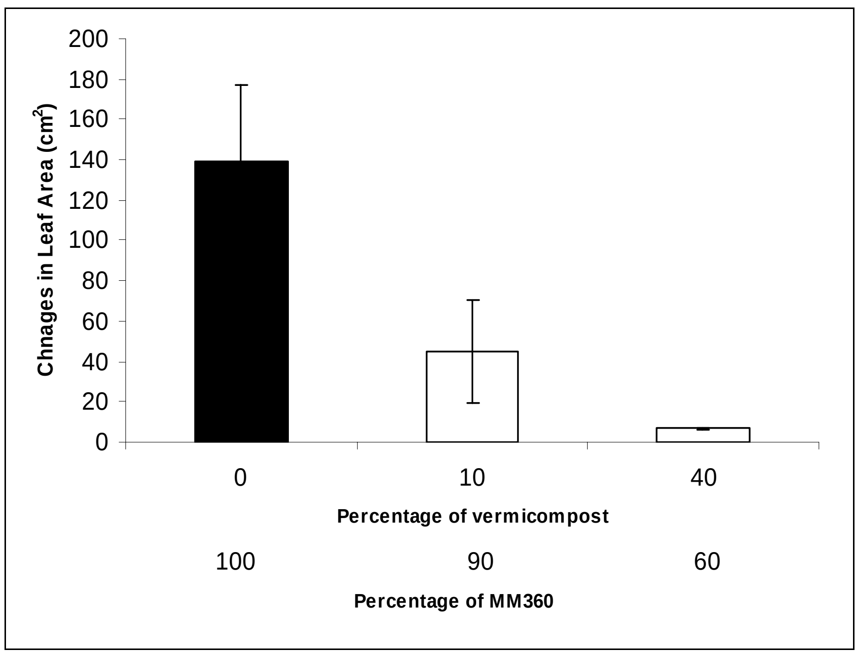
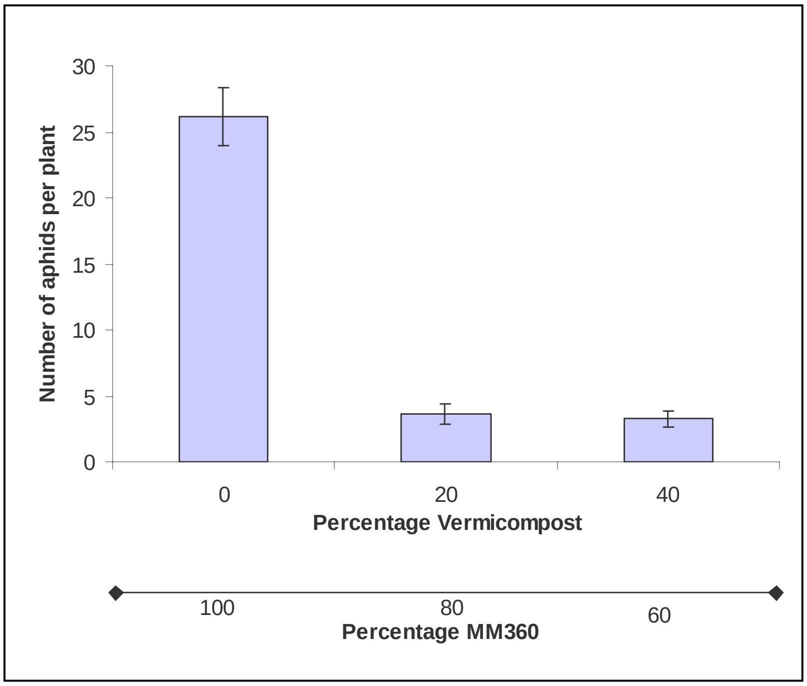


Figure 11. Suppression of leaf area losses due to two-spotted spider mites on bush beans by vermicomposts in the greenhouse

(a)



(b)

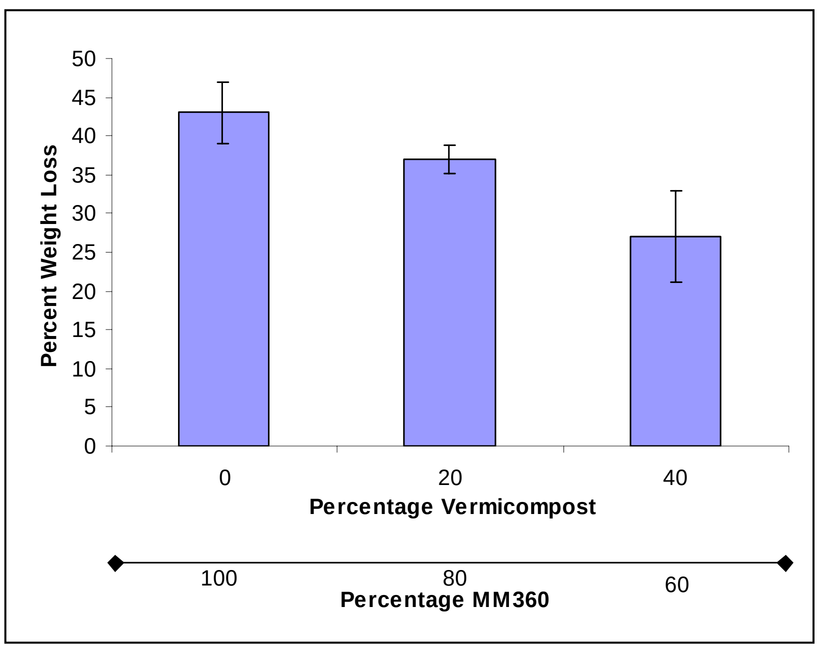


Figure 12. Aphid suppression in peppers planted in soil-less medium (MM360) substituted with vermicompost. A) Number of aphids in pepper plants B) Percentage decrease in shoot dry weights. Columns followed by the same letter do not differ significantly at $P \leq 0.05$.

(ii) Chewing insects

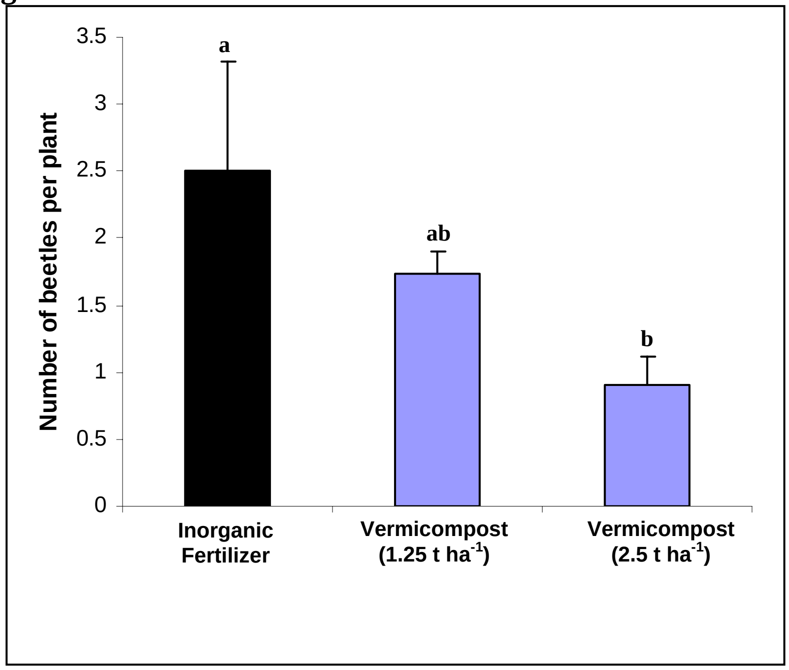


Figure 13. Numbers of striped cucumber beetles, *Acalymma vittatum,* per plant (Means ± SE) on cucumbers in the field in response to food waste vermicompost applications

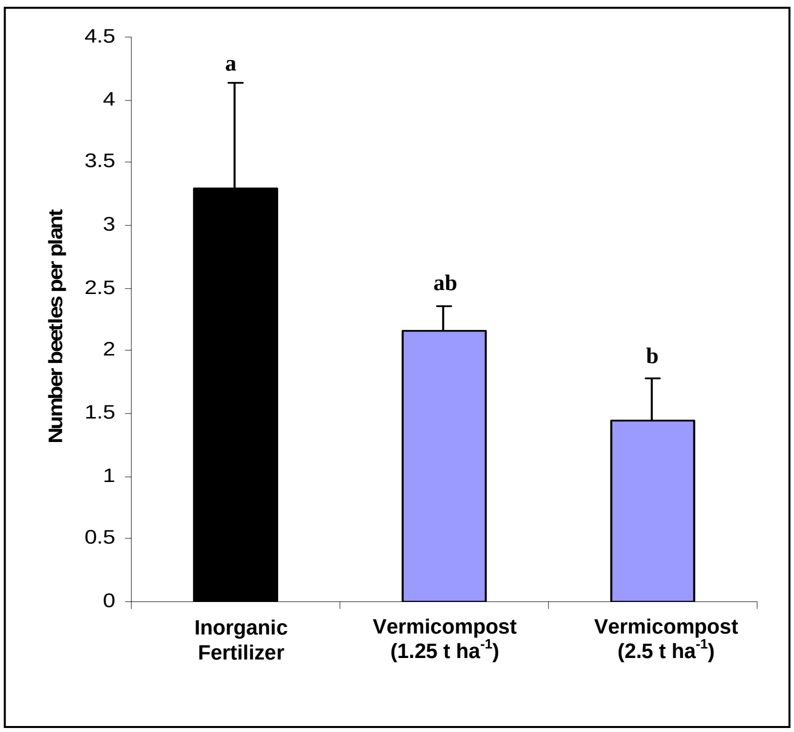


Figure 14. Total numbers of striped and spotted cucumber beetles together (Means ± SE) on cucumbers in the field in response to food waste vermicompost applications

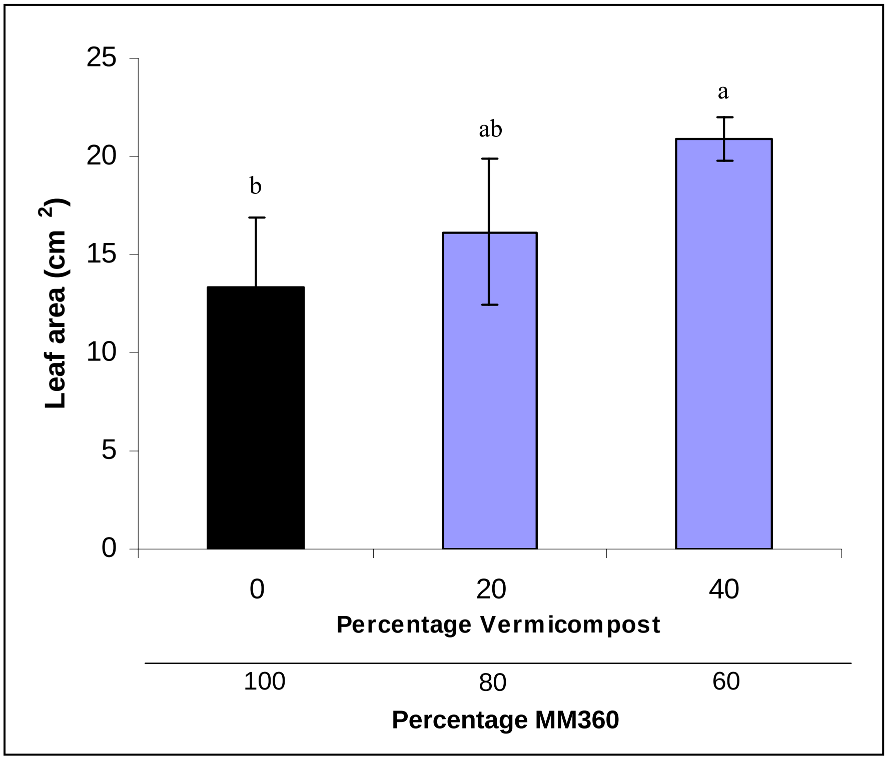


Figure 15. Leaf areas of cucumber seedlings (Means ± SE) after exposure to striped cucumber beetle (*Acalymma vittatum)* infestations in greenhouse cages for 2 days, in response to substitutions of vermicompost into MM360

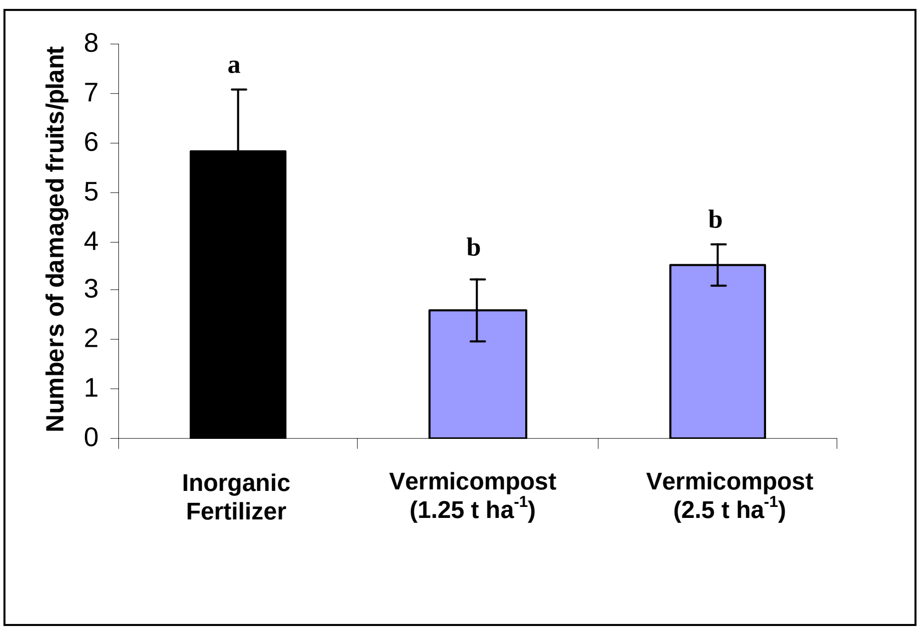


Figure 16. Hornworm caterpillar damage (Mean ± SE) to tomato fruits in the field, in response to food waste vermicompost applications

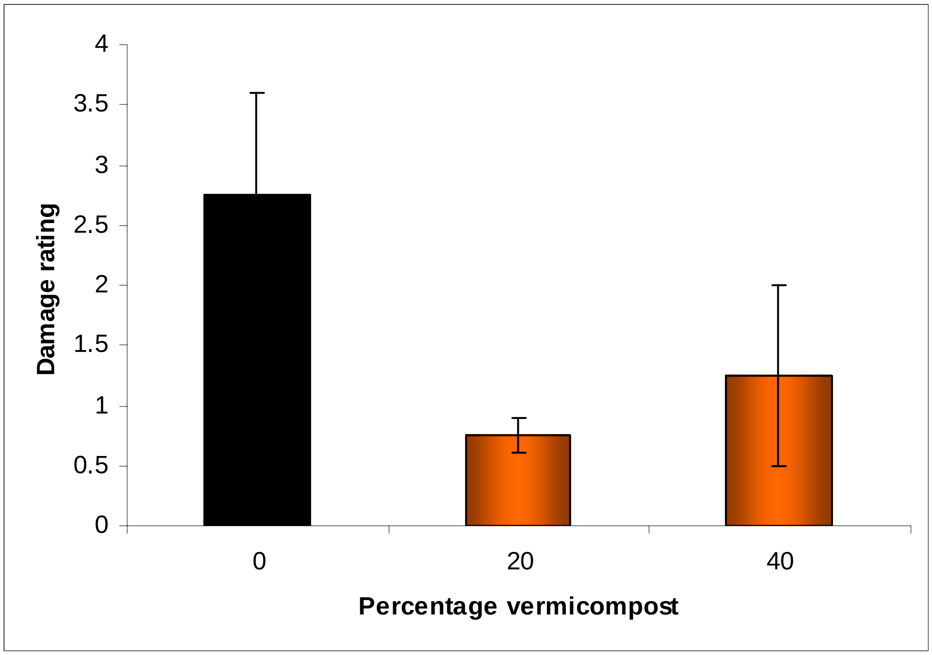


Figure 17. Damage ratings (Means ± SE) of hornworm caterpillar (*Manduca quinquemaculata*) infestations on tomatoes grown in MM360/food waste vermicompost mixtures with all necessary nutrients in the greenhouse.

d) Conclusions on suppression of plant pathogen, plant parasitic nematode, and arthropod pests by vermicomposts

Treatments of growing media or soil with small amendments of different sources of vermicomposts can suppress plant pathogens and plant parasitic nematodes significantly, through microbially-based mechanisms. Hence, vermicomposts have considerable potential in integrated pest management programs, since one application can control the types of pest.

V. EARTHWORMS AS A PROTEIN SOURCE FOR ANIMAL FEED

Many mammals and birds prey on earthworms in nature. It has been suggested that earthworms contain sufficient high quality protein to be considered as bred animal food, and this potential of earthworms in animal feed has been confirmed by full analyses of the body tissues of earthworms, which show the kinds of amino acids that they contain and the nature of the other chemical body constituents.

Analyses of the constituents of the tissues of different species of earthworms show clearly that the essential amino acid spectrum for earthworm tissues, as reported by different authors, compares well with those from other currently used sources of animal feed protein, and that the mean amounts of essential amino acids recorded are very adequate for a good animal feed. In addition, earthworm tissues contain a preponderance of long-chain fatty acids, many of which cannot be synthesized by nonruminant animals and also have an adequate mineral content. They contain an excellent range of vitamins and are rich in niacin, which is a valuable component of animal feeds, and they are an unusual source of vitamin B_{12}. The overall nutrient spectrum of earthworm tissues shows them to have an excellent potential as a protein supplement to feed for fish, poultry, pigs, or domestic animals.

Table 3. Chemical composition of earthworms

•Protein	60-70%
•Fat	7-10%
•Carbohydrate	8-20%
•Minerals	2-3%

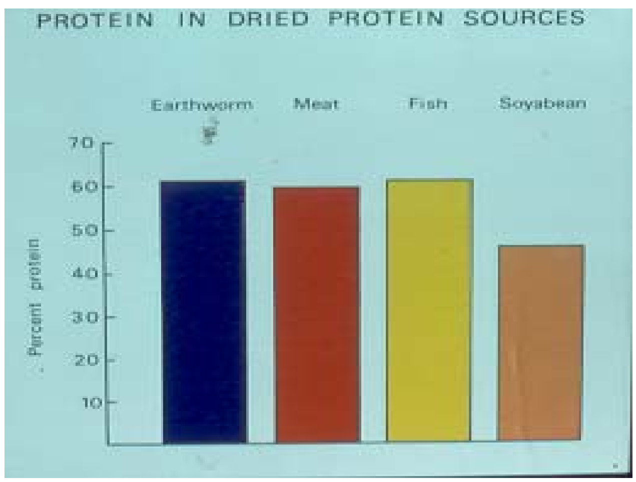


Figure 18. Amounts of protein in different organic resources

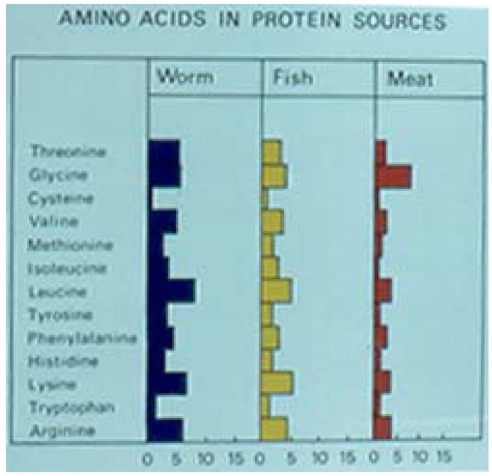


Figure 19. Amino acids in different protein sources

A range of different methods of processing the earthworms into materials suitable for animal feed has been developed (Edwards and Niederer 1988). Two of these methods produced a moist paste product, and the other four produced dry meals; all the products were acceptable formulations for particular types of animal feeds. The ultimate choice of a method of processing depends on (1) the species of animal to be fed, (2) the type of animal feed required, (3) minimal loss of dry matter allowed, (4) minimal loss of nutrient value allowed, and (5) the costs of production. The following were the processing methods developed:

1. Incorporation of earthworms with molasses
2. Ensiling earthworms with formic acid
3. Air-drying earthworms at room temperature
4. Freeze-drying earthworms
5. Oven-drying earthworms at 95˚C
6. Acetone immersion of earthworms followed by oven-drying at 95˚C

The type of processing method used affected the amounts of total and essential amino acids in the feeds very little; however, the lysine content was decreased slightly, by ensiling with molasses using formic acid and by freeze-drying, compared with the other methods. The dry weight matter yields differed only slightly among processing methods. Clearly, a stable protein feed can be produced by any of the methods listed, and the choice of method must depend mainly on the use to which the protein is to be put, the animal that is to be fed, and the cost of the processing method in relation to the feed value of the protein.

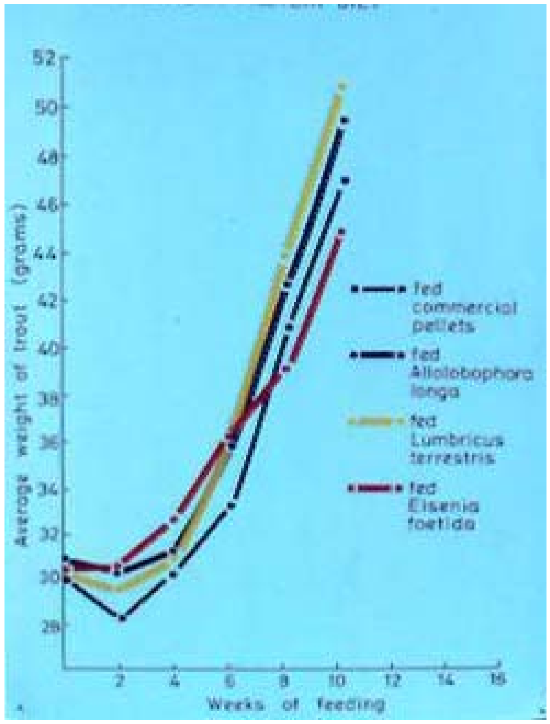


Figure 20. Growth of trout on earthworm proteins

Table 4. Growth of chickens on protein from earthworms

.	Level of earthworm meal in diet of chicken			
Amount of earthworm Meal (g/kg)	0	72*	144	215
Initial live weight (g)	203	201	198	201
Final live weight (g)	735	725	677	674
Gain/food per unit of food	0.669	0.628	0.619	0.608
N-retention (g/g diet N)	0.588	0.573	0.569	0.599

*** Recommended rate**

Table 4. Growth of suckling pigs on earthworm diet

Starter Period (38-50 days)	***Earthworm protein***	***Meat protein***	***Commercial diet***
Mean weight gain (kg)	4.36	3.65	4.26
Mean rate of growth (kg/day)	0.31	0.26	0.30
Growth Period (84-95 days)			
Mean weight gain (kg)	6.54	6.80	6.60
Mean rate of growth (kg/day)	0.47	0.49	0.46

Constraints on the use of earthworms as animal feed protein

The only constraints on the commercial adoption of earthworm protein for animal feed are economic ones. Eartthworm production is economically feasible with high technology rearing methods. However, current methods of separating earthworms from organic wastes are labor-intensive on the scales that have been tested. Hence, earthworms as a source of protein has not yet been adopted commercially in developed countries but they could well be an economic option as an associated process to vermicomposting, or if improved separate equipment is developed. In countries such as China, the Philippines, India, or Indonesia where labor costs are lower the use of earthworm protein is much more feasible.

Clearly, earthworms are an excellent source of protein, rich in essential amino acids and vitamins. Large numbers of earthworms can be bred in a range of organic wastes, with a conversion ratio for waste to earthworm biomass of about 10%. They can be separated from the wastes mechanically and processed into dry or wet animal feed supplements that can be used in the diets of fish, poultry and pigs as 15% protein supplements. Earthworms can outperform other protein sources, such as waste fish or soybeans, in terms of animal weight gain, growth and nitrogen retention by fish, poultry and pigs. Further discussion is given by Dr. Rafael Guerrero.

VI. **THE USE OF EARTHWORMS IN SOIL POLLUTANT BIOREMEDIATION**

In recent years evidence has accumulated from our laboratory and elsewhere that vermicomposts and aqueous extracts of vermicomposts (teas) have considerable potential in removing organic pollutants and heavy metals from polluted air.

a) <u>Heavy metals</u>

Heavy metals are virtually indestructible chemicals in soils. The only way to remove them from polluted soils is to take them up into the tissues of organisms such as plants (phytoremediation) or invertebrates such as earthworms (vermiremediation).

Additionally they can be bound up in processed organic wastes such as vermicomposts by stable humates which makes them unavailable to plants.

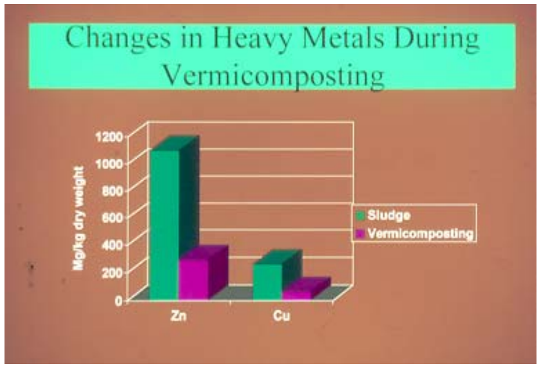


Figure 21. Changes in heavy metals during vermicomposting

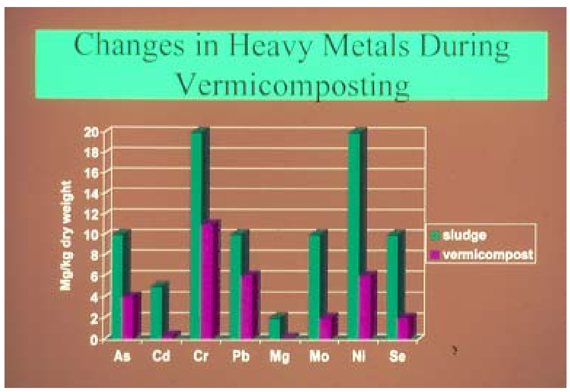


Figure 22. Changes in heavy metals during vermicomposting

b) **Organic pollutants**

Organic compounds that can be eliminated by vermicomposts include:

- •Polychlorinated biphenyls (PCBs)
- •Chlorinated hydrocarbon insecticides
- •Petroleum derivatives e.g.
  - -polycyclic aromatic hydrocarbons
  - -phenolic compounds
  - -benzene compounds

Many of these are very persistent in soils and can also be taken up by plants and animals. They can also be immobilized in humic matter.

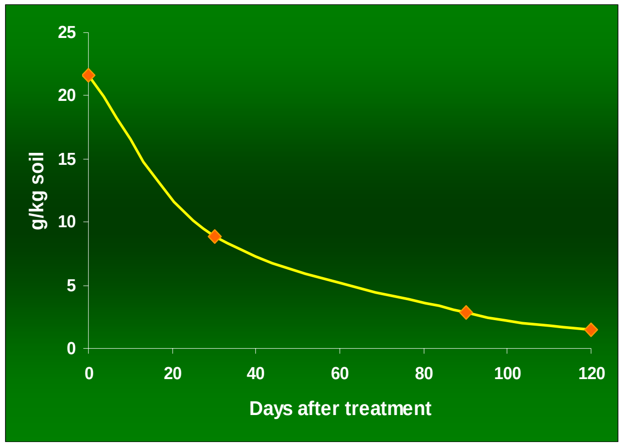


Figure 23. Breakdown of polycyclic aromatic hydrocarbons after a polluted soil treatment with cattle vermicompost (61.9m³/ha) and vermicompost teas (9.23l/ha)

This is a rapidly developing field that seems to hold a great deal of potential for reclaiming polluted sites and returning them to crop production.

VI. **Earthworm products as pharmaceuticals in treatment of human diseases**

There have been many reports of cellular immunity in earthworms ranging from phagocytosis to cell-mediated immunodefense responses. These have been related to both human cellular and humoral immunities, that include: neuroendocrin-immunology, immunotoxicology and potential cancer therapy. There are also reports of earthworms producing anti-bacterial materials. There are many reports of earthworms and earthworm extracts being used to treat a range of human diseases in China and other parts of Asia. These include arthritis, male sterility, cardiovascular diseases, bronchial asthma, leg ulcers, eczema and tissue inflammation and for general health improvement. A number of active compounds, with pharmaceutical properties, have been isolated from earthworms. Most research reports are in Chinese scientific journals and will be discussed in more detail by other speakers, particularly Dr. Sun Zhenjun.

References

Edwards, C.A., 1988. Breakdown of animal, vegetable and industrial organic wastes by earthworms. In: *Earthworms in Waste and Environmental Management.* C.A. Edwards and E.F. Neuhauser (Eds.) SPB Academic Publ. Co., The Hague, Netherlands, 21-31.

Edwards, C.A. Ed. 2004. Earthworm Ecology (2nd Edition). CRC Press, Boca Raton, FL, London, New York, Washington. 448 pp.

Edwards, C.A. and Bohlen, P.J. 1996. *The Biology and Ecology of Earthworms* (3rd

Edition). Publ. Chapman & Hall, London, 426 pp.

Edwards, C.A. and Niedere, A. 1988. The production and processing of earthworm protein. In: *Earthworm in Waste and Environmental Management.* C.A. Edwards and E.F. Neuhauser (Eds.) SPB Academic Publ. Co., The Hague, Netherlands, 211-220.

Edwards, C.A. and Neuhauser, E.F. (Eds.) 1988. *Earthworms in Waste and Environmental Management.* SPB Academic Publ. Co., The Hague, Netherlands, 391 pp.