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Vermiculture: A Viable Solution for Sustainable Agriculture

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Abstract

Vermiculture is the cultivation of worms to produce compost. Worm farming for agricultural purposes uses specific worms that consume the organic waste in which they live and breed. Vermicomposting is biotechnology for the conversion of wastes into nutrient-rich agriculture amendments. The application of these amendments can improve the physical, biological, and chemical properties of the soil. Worm excrement enhances soil health, which improves plant health. When our plant and crop performance are enhanced, we see increased yields and improved quality. Vermicompost can boost crop production without the synthetic fertilizers that pollute our environment and decrease the health of people and plants.

Vermicompost production recycles food trash, paper sludge, livestock manure, and yard debris. This action reduces the expansion of landfills and returns the waste to the earth as a valuable fertilizer. Vermiculture has been referred to as the 'Second Green Revolution' by replacing harsh chemical inputs with organic matter. Other environmental benefits are the decreased use of water irrigation, improved pest resistance, and reduced weed growth. The biodiversity of increased microorganisms in our soils is supported by vermicompost. Vermiculture biotechnology expounds on the importance of environmental sustainability and economic stability.

Keywords: vermiculture, compost, sustainability, agriculture, biotechnology

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Introduction

Agriculture is one of the top industries in the world. It is also one of the most fragile. Our soils, farms, and crops have been overextended, overworked, and barely maintained. Current farming methods need to be overhauled and changed. Vermiculture can be the option to help remediate and heal our unhealthy farmlands. Sherman (2018) proposed multiple soil benefits from vermicast. Enhancing soil structure through microbial activities, polysaccharides, and the mucus secretions of worms cause aggregate stability by cementing soil particles together. Other advantages of utilizing vermicast include reducing soil compaction, improving soil aeration, breaking up clay soils, increasing the cation exchange capacity, and easing cultivation. All these issues are constant concerns for our farmers and their soil. Organic vermisystems can be used to answer the social, economic, and environmental concerns of farmers, including waste management, soil and plant health, and crop sustainability.

Vermiculture is the growth of earthworms in organic wastes. Vermicomposting is the processing of organic wastes (Edwards, 2004). Vermiculture can actively assist in rebuilding our food-producing systems through the regeneration of healthy soils with worm castings and vermicompost. Vermiculture has many favorable aspects to soil, crops, and production. Worm farming produces vermicasts and vermicompost to be usable for the farm. Vermiculture will also assist with waste management. Olle (2019) suggests that vermiculture will help recover natural products, combat disposal problems, and minimize pollution effects. Vermicomposting is the biotechnology for recycling industrial and home wastes into agronomical amendments for improving soil structure, plant fertility, and pest management. Chaudhary et al. (2004) concur with this assessment. Their studies promote the recycling of organic wastes not only for ecological purposes but for economic as well. Earthworms expedite the composting process significantly with a better-quality result.

Soil health is an alarming crisis. Not only do we lose approximately 70 billion tons of topsoil a year, what we do keep is constantly degraded by chemicals. But that can change. Vermiculture and vermicompost have soil healing properties. Chaudhary et al. (2004) reported increases in macronutrients and microbial activity in the earth with vermicompost. Soil remediation is enhanced with the presence of earthworms and their mechanical activity within the ground. Earthworms move through the soil, processing organic matter, releasing nutrients, and mixing compounds. Larger soil particles are broke-down to increase soil porosity and develop a strong soil structure. Earthworm burrows have increased attachments of compounds, while vermicasts assist with organic compound circulation. Oxygen and nutrient availability and microorganism activity are heightened with earthworm involvement. Soil that has become aged with entrapped contaminants renders the mineral and organic compounds inaccessible for microbial exchanges. These residues have the potential to be released through earthworm interaction (Gevao et al., 2001). Vermiculture practices can be used for land recovery, bioremediation, and advancements in soil fertility.

Sinha et al. (2010) focus on vermiculture's ability to rid chemical inputs from agriculture systems. Many agricultural practices are dependent on synthetic fertilizers and pesticides to maintain crop production. Unfortunately, it is a no-win situation with increased chemical amendments. Artificial additives degrade soil health and decrease plant quality with every application. Vermicompost is an organic contribution that Sinha et al. (2010) claim as growth promoters and protectors for crop plants. Hussaini (2013) addresses the hidden cost of environmental damage and repair needed due to increased chemical additions. He also mentions the possibility of a social price, as human health and quality of life decline as indirect casualties of the decreased condition of farm produce. The deterioration of our farmlands and the increasing expense of petroleum-based products has opened the door for an alternate, safer, healthier solution.

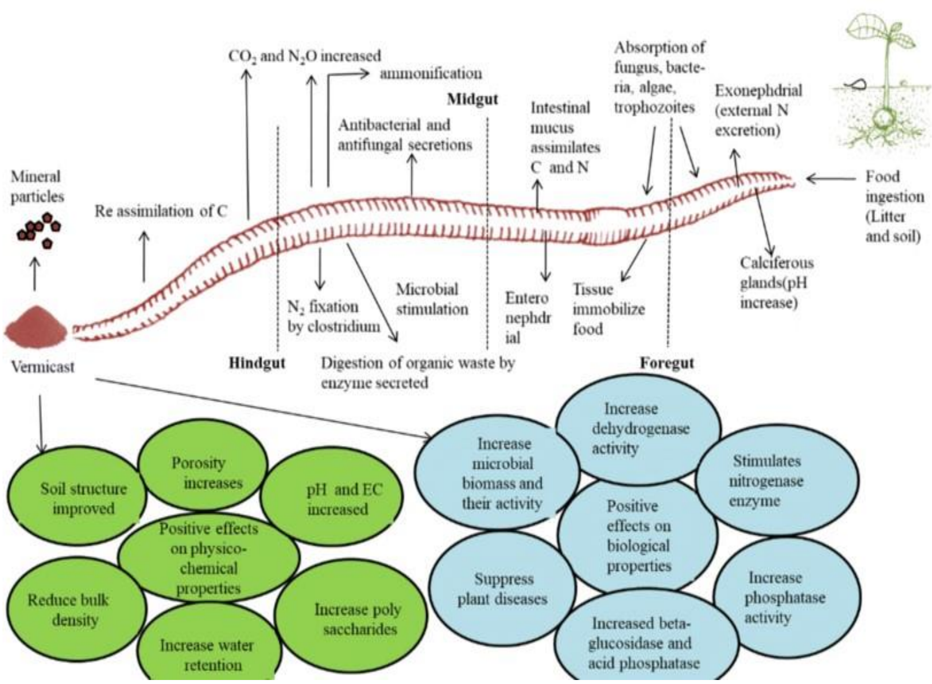
In addition to restoring our earth's farmland, earthworms can recycle many agricultural wastes instead of contributing to landfills. Hussaini (2013) claims that earthworms enhance the waste conversion process by quickly converting waste products into 'gold.' The vermicomposting process relies on earthworms and microorganisms to transform organic matter biologically, chemically, and physically into a valuable soil amendment (Sherman, 2018). Increased soil health leads to improved plant health. According to Olle (2019), vermicompost benefits plants by acceleration, increased fruits, more seeds, and faster seed germination. Sustainable agriculture is dependent on these individual concepts coming together.

Earthworms and their processes are not a new concept. Philosophers like Pascal and Thoreau have mentioned the role earthworms play in the soil. The ancient Egyptians recognized the benefits of earthworms and deemed them sacred. Cleopatra (69-30 B.C.) enacted laws citing the removal of earthworms as punishable by death in Egypt. Egyptian farmers feared offending Aphrodite, the God of Fertility, by even touching an earthworm. Ancient Greeks also regaled earthworms, acknowledging their part in improving the quality of the soil. Greek philosopher Aristotle (384-322 B.C.) referred to worms as the intestines of the earth (Medany, 2011). More recently, Sir Charles Darwin called earthworms the unheralded soldiers of humankind and friends of farmers. He also said that there might not be any other creature in the world that has played so important a role in the history of life on earth (Sinha et al.,2010). Gilbert White (1890), a pioneering naturalist, said, "Earthworms, though in appearance a small and despicable link in the chain of nature, yet if lost, would make a lamentable chasm."

Vermicomposting is the only pollution control bioprocess that has a multicellular animal as the core bioagent. Converting biodegradable organic waste into a valuable product is unique through the involvement of earthworms. Figure 1 shows an overview of the worm's processes and highlights the benefits of vermicast. Earthworms are the sole multicellular animal used in a reactor system to generate results other than reproduction (Abbasi et al., 2008). All other bioprocesses use enzymes, bacteria, or microfungi to create a beneficial amendment.

Figure 1

Earthworm Processes and Benefits



Note. Adapted from "Earthworms and vermicompost: an eco-friendly approach for repaying nature's debt." by Singh et al., 2020, *Environmental Geochemistry and Health.*

Vermiculture has many advantageous qualities to today's soil, crops, and production. Vermiculture will also assist with waste management. Olle (2019) suggests that vermiculture will help recover natural products, combat disposal problems, and minimize pollution effects. Vermicomposting is the biotechnology for recycling industrial and home wastes into agronomical amendments. Soil structure, plant fertility, and pest management improve with agronomical modifications. Chaudhary et al. (2004) concur with this assessment. Their studies promote the recycling of organic wastes not only for ecological purposes but for economic as well. Earthworms expedite the composting process significantly with a better-quality result. Waste management, soil health, plant vitality, and decreased chemical reliance are accomplished through vermiculture practices. Organic vermisystems can be used to answer the social, economic, and environmental concerns of farmers. This paper will review and elaborate on each contribution and how they will provide the necessary information to confirm vermiculture's role in sustainable agriculture.

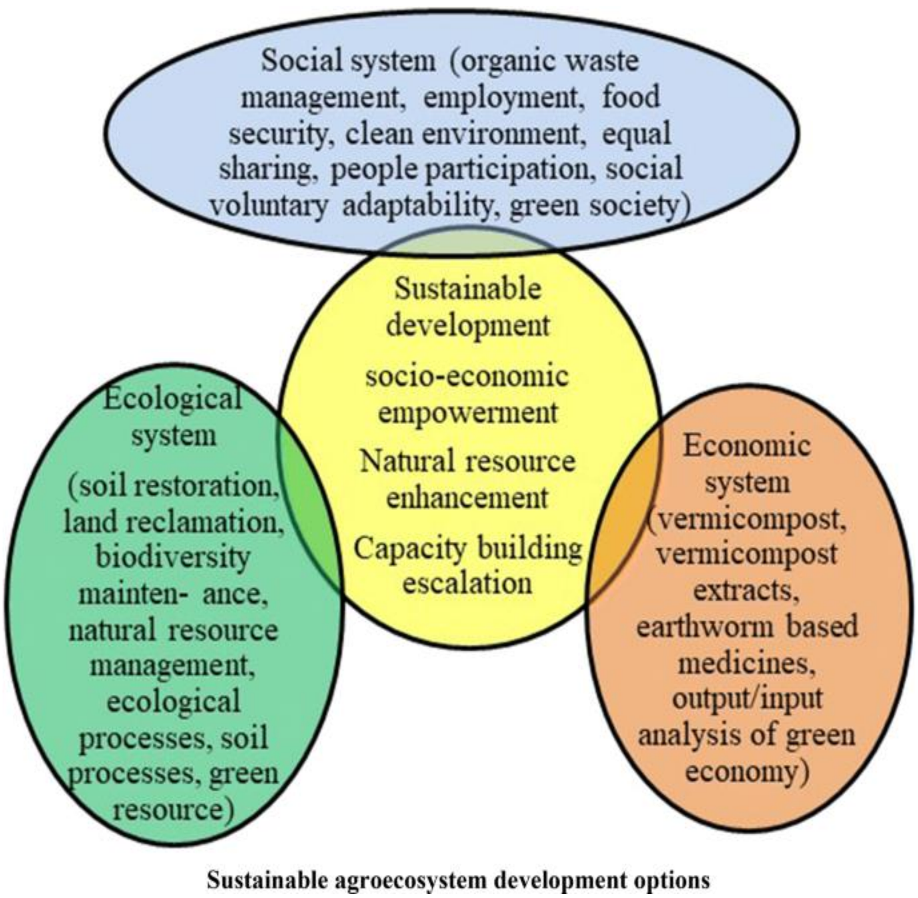
Sustainability through Vermiculture

Sustainable agriculture is designed to guard and enhance our soils, protect the environment, and preserve our natural resources. Vermiculture practices can manage the earth's waste issues, remediate our degraded lands, diminish our reliance on fossil fuels and keep expenditures low (Hussaini, 2013). Bogdanov (1996) states that sustainability can be achieved by enhancing crop productivity both in quantity and quality at significantly low economic costs than with expensive agrochemicals. Hussaini (2013) defines sustainable agriculture as a process of learning new and innovative methods developed by farmers and farm science and learning from their traditional knowledge and practices of the farmers and implementing what was good in them and relevant for present times. Vermiculture practices and vermicomposting would meet several requirements for genuinely sustainable agriculture. Hussaini (2013) suggests that a sustainable agriculture production system must ensure:

- Increased volume and stability of crops for the future
- preservation of crop diversity (biotopes)
- conservation of soil, water, and air quality in the farm ecosystem
- protection of the biodiversity of creatures, flora, and fauna in the farm ecosystem
- preservation of groundwater table
- preservation of good health for all
- reduction of water and energy use

Figure 2

Sustainable Development Branches



Note. Earthworms and vermicompost: an eco-friendly approach for repaying nature's debt. Singh et al. (2020). *Environmental Geochemistry and Health*

Vermicompost is rich in microbial diversity and can improve the moisture-holding capacity of the soil, reducing the water needed for irrigation. It can also increase the physical, biological, and chemical properties of the ground. Planning for sustainable agriculture can genuinely bring in 'economic prosperity for the farmers, 'ecological security for the farms, and 'food security for the people. This will require using earthworms to embark on a 'Vermiculture Revolution.' Economic viability and environmental sustainability will be preserved for our future through the utilization of earthworms and their bio-activity (Hussaini, 2013). Sustainable development rests on economic, environmental, and social achievements and their interactions. Figure 2 displays the interaction and relationship of these goals.

Compost vs Vermicompost

Abassi et al. (2008) observe that composting and vermicomposting are two distinct processes with similar end products. Both result in soil amendments with vermicomposting having additional microbial involvement. Identifying the two procedures includes separate control parameters, developmental conditions, process engineering, and the biological and chemical reactions. Operational strategies are separated by the biotic and abiotic factors that are involved. Composting and vermicomposting cannot be successful together in a single reactor. Composting is a batch process and is not done in a continual fashion. Composting also is dictated by temperature fluctuations to break down the substrate. Vermicomposting is the practice of adding earthworms to raw waste where they consume and excrete castings in a contiual manner. More foodstock is added as the worms consume the material, vermicasts are constantly being produced. This natural degradation routine occurs at ambient temperatures with no extreme highs or lows. There are several differences between conventional composting and vermicomposting that contribute to the end product. Figure 3 shows the various composting and vermicomposting characteristics contrasted and compared.

Figure 3

Composting vs Vermicomposting

	Composting	**Vermicomposting**
Depth	Can be any depth	Worms usually prefer to live in the top 6–12″ of the bedding (cannot be deep)
Convenience	Outdoors only with specialized buildings and equipment	outdoors or indoors
Speed	Hot composting takes 6–9 months to produce fertilizer	Much faster
Heat Levels	Hot as the aerobic breakdown of organic matter releases carbon dioxide and heat, resulting in piles than can top 70 °C	Cooler process with temperatures ranging between 10–32 °C
Microbial Populations	Dominated by thermophilic (or "heat-loving") microbes	Dominated by mesophilic microbes
Aeration	Turning is required	Turning is not required
Cost	Cheap	Needs care for worms protections
Financial Value	Cheap	Much greater financial value

Note. Adapted by "Innovative Processes and Technologies for Nutrient Recovery from Wastes: A Comprehensive Review of Sustainability," by Ahmed, Mukhtar & Ahmad, Shakeel & Qadir, Ghulam & Hayat, Rifat & Shaheen, Farid & Raza, Muhammad, 2019. *Sustainability, 11*(18), 4938

Fitzpatrick et al. (2005) describe the composting process with acacia leaf litter in windrows. The timeline and mechanization can vary depending on the substrate and the housing container, but the general steps and sequence remain the same. The end result should be available within 6-10 weeks.

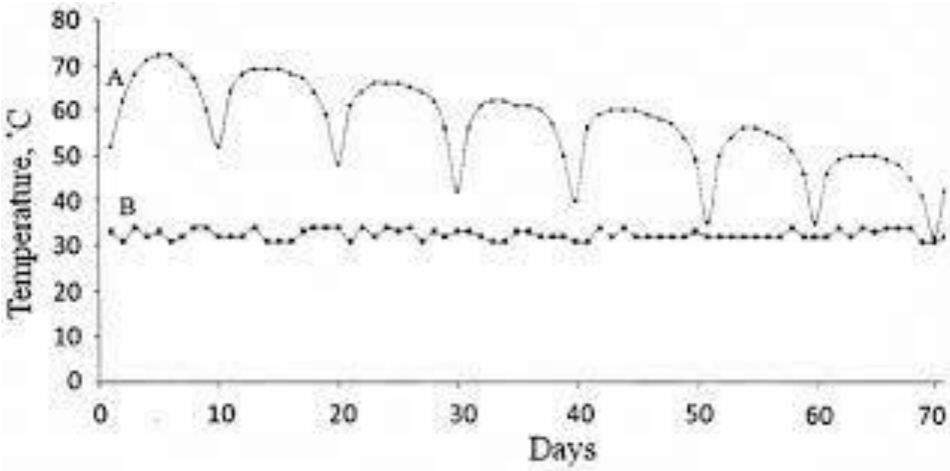
- The substrate is layered approximately 6 inches deep. It is then covered with approximately 1 inch of manure or sludge for microorganism activation.

- Moisture is added by sprinkler or irrigation. Passive or active aeration devices are installed to encourage airflow. Passive airflow consists of open-ended, perforated pipes randomly inserted into the windrow. Active airflow combines with a mechanism to force air into the composting pile.
- The composting pile is covered with plastic sheets or layers of clay. Aerobic decomposition begins as the temperature begins to rise to approximately 131°F (55°C). The availability of substrate and oxygen begins to decline, and the decomposition slows down. As the decomposition process slows, the temperature of the pile cools. Too much heat can kill off the microorganisms that assist with the breakdown. If the microorganisms disappear, composting is unfinished, and the outcome is unsatisfactory.
- The pile is stirred to revitalize the procedure to combine the microorganisms and air with untouched materials. Uncomposted items can be turned into a pile with shovels, pitchforks, or mechanical means. The composting heap is irrigated once more and covered. The exothermic process of aerobic decomposition begins again with temperatures rising then falling. These steps continue with successive temperature waves. As the substrate gets more stabilized, the peak temperature wave cools down. In approximately 50 to 70 days, the peak temperature of the pile is around 104°F (40°C), as depicted in Figure 4A.
- The repetition of the previous steps completes the microbial decomposition stage. The core temperature becomes constant as the substrate is now composted.
- The final phase lasts for 2-4 weeks while the compost pile is left untouched. This curing stage of composting permits the continued breakdown of organic matter,

inhibiting plant diseases and seed activity. As the temperature plateaus, microorganisms are re-established and encouraged to ripen the compost.

Figure 4

Temperature Waves of Composting and Vermicomposting



Note. (A) Temperature fluctuations of composting of acacia leaf litter. (B) Temperature fluctuations of vermicomposting of acacia leaf litter. Adapted from "Towards Modeling and Design of Vermicomposting Systems: Mechanisms of Composting/Vermicomposting and their Implications," by Abbasi et al., 2008, *Indian Journal of Biotechnology*, *8*

Separating composting from vermicomposting includes understanding the different aspects involved. Composting cannot be made with continuous substrate contributions. Once a composting pile has been initiated, no new material should be added. Any further materials would slow the processing activity. Turning the pile is necessary for all substrates to be completely composted. The heat generated in a pile is essential to destroy pathogens and seeds that can contaminate the end product.

Fitzpatrick et al. (2005) continue to compare composting and vermicomposting while elaborating on the vermicomposting process. Contrary to composting, vermicomposting can be accomplished in a continuous manner. In actuality, continuously adding organic matter for worm feedstock will persistently produce vermicasts for vermicompost. While composting takes an extended time, vermicompost is completed rather quickly as worms ingest, digest, and excrete. The following steps explain the vermicomposting process.

- Worms ingest the organic material within the bin.
- The size of the ingested materials is reduced by the worm's gizzard, located next to the mouth and portrayed in Figure 6.
- The substances are then digested as they move through the earthworm's body. The enzymes and microorganisms within the worm's gut assist with the breakdown of the particles.
- The fragments are then excreted from the anus. This process takes mere hours depending on the material to be composted and the size and species of the worm. Shorter worms take less time to manage their food movement. And epigeic earthworms process food faster than the endogeic or anecic species.

Significant factors for vermicomposting are the lack of exothermic temperature and aeration requirements. The vermicomposting process typically remains at a constant temperature with a variation of only 2-3 degrees, noticed in Figure 4B. Most worm species are unable to survive or thrive at temperatures over 104℉(40℃). Another contrasting issue is the lack of turning or mixing the pile, as noted in Figure 3. Earthworms naturally move and borrow, keeping the materials mixed in aerated. Composting can be a labor-intensive process, while vermicomposting is labored by the earthworms (Abbasi et al., 2008).

Although composting and vermicomposting cannot exist simultaneously in the same bin, pre-composting can complement vermicomposting. The microorganisms found in the 'curing' phase of composting are valuable for healthy soil and plants by killing the pathogenic organisms.

When pre-composted materials are introduced to the earthworms, they feed on the microorganisms and redistribute them into the vermicompost. The thermophilic action of composting removes weed seeds and stabilizes the swift biodegradation of various manures and other anaerobic wastes. Some rapidly biodegrading livestock and crop wastes can develop toxic acids that can be lethal to earthworms (Ganesh, 2007). Table 1 compares the nutrients and their values between conventional composting and vermicomposting.

Table 1

Nutrient Values of Composting vs. Vermicomposting

Parameters	Conventional Composting %	Vermicomposting %
Carbon (C)	9.34%	13.5%
Nitrogen (N)	1.05%	1.33%
Available Phosphorous (P)	0.32%	0.47%
Iron (Fe)	587.87	746.2
Zinc (Zn)	12.7	16.19
Manganese (Mn)	35.25	53.86
Copper (Cu)	4.42	5.16
Magnesium (Mg)	689.32	832.48

Note. Adapted by "Phytoremediation: The Application of Vermicompost to Remove Zinc, Cadmium, Copper, Nickel, and Lead by Sunflower Plant," by Jadia & Fulekar, 2008, *Environmental Engineering & Management Journal (EEMJ)*, *7*(5)

Earthworms can feed easier and quicker on pre-composted material due to the microbial action that breaks down matter into smaller fragments. Atiyeh et al. (2000) report that worms who feed on previously stabilized compost have a good reproduction and growth record. Precomposted materials digested by the earthworms gain enzymes and hormones valuable for plant growth and soil rejuvenation. Any substances not fully composted are processed during vermicomposting, creating a consistent product. Atiyeh et al. (2000) confirm the result of vermicomposting is a better outcome and amendment than composting alone.

Vermiculture is also unique through the function of a 'reactor within a reactor.' The explanation stems from the entire processing of organic materials that happens within the individual worm, yet through multiple worms in one housing container (Douglas, 2001). Each worm produces castings daily. However, the ratio of worms to food stock dictates the rate of bin production versus the raw organic material still available for consumption. The efficiency of the vermireactor is directly related to the earthworm's access to the feedstock. Food particles that are close by with no competition can be processed quicker. The more worms that are feeding simultaneously convert the substrate more competently. Yet, excessive earthworm population can increase food rivalry. The simplest balance is found with the surface-to-volume ratio concept. Vermireactors with a higher surface-to-volume ratio produced more vermicast than reactors with a lower surface-to-volume ratio. More shallow reactors reduce the need for vertical movement and decrease crowding with a broader surface to cover (Karthekeyan, 2008).

Worm Biology

There are approximately 9000 earthworm species in the world. All earthworms share some similarities. The front third of an earthworm's body contains all the vital organs. Earthworm bodies are divided into rings or segments. Each segment aids in movement by the use of muscles and setae. Earthworms are tubelike without appendages, and this allows them to move effortlessly through the soil. There are no eyes or ears but several nerves that sense light and vibrations. Their brain sends stimulation to the muscles that move in response to stimuli. Circulatory, muscular, nervous, digestive, and reproductive systems are all well developed in earthworms (Edwards 2004). The earthworm's head has a tongue-like lobe called a prostomium, and there is an anus at the posterior end. An earthworm's circulatory system consists of five pairs of aortic arches. Blood vessels carry the blood back and forth throughout the worm's body (Werner, 1990).

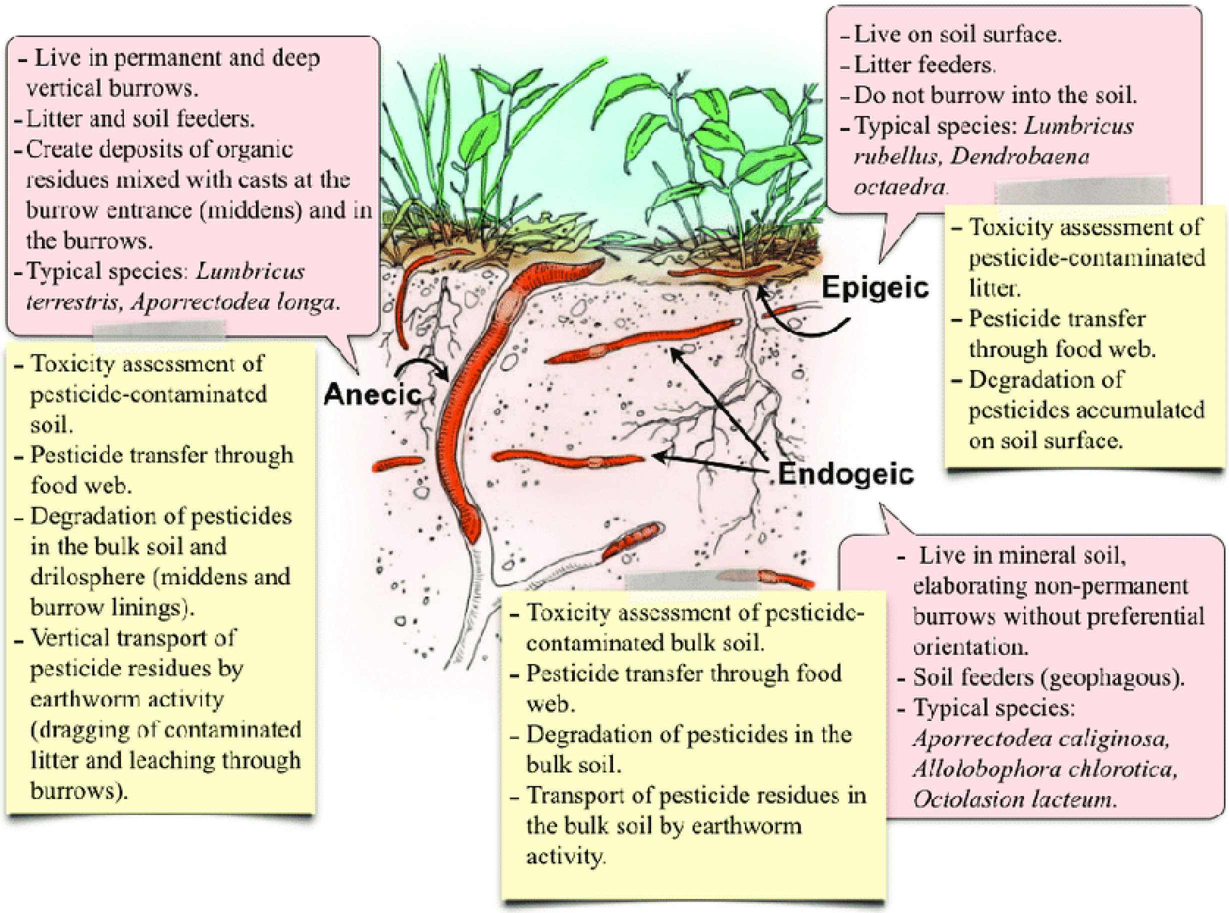
Farmers interested in worm husbandry need to be aware of the five basic traits of earthworms (Sherman, 2019):

- Earthworms are cold-blooded, meaning they are unable to regulate their body temperature. The environment dictates the temperature of the worms. Temperature extremes will cause earthworm activity and feeding to diminish.
- Earthworms are hermaphrodites. Both male and female reproductive organs are present in each worm. Earthworms still require contact with other earthworms to exchange fluids for reproduction.
- Earthworms do not have lungs. The exchange of oxygen and carbon dioxide occurs through their skin.
- Earthworms require moisture. This allows the passage of oxygen into their bloodstream. Earthworms create mucus that coats their skin; however, they still require a damp environment to survive.
- Earthworms are light-sensitive. They will retreat from bright light as it can induce paralysis. Too much light exposure can dry their skin and cause death. Studying earthworms should be done with a red light so as not to disturb them.

Earthworms are separated into three different groups based on their feeding and habitats; Endogeic, anecic, and epigeic. All worms are important to the soil food web, but one group, in particular, is a good composting worm. The endogeic and anecic groups are soil burrowing worms, while the epigeic is a litter-dwelling worm. Figure 5 portrays the ecological worm groups and their characteristics.

Figure 5

Ecological Worm Groups



Note. Adapted from "Bioremediation of Pesticide-Contaminated Soils by using Earthworms," by Sanchez-Hernandez, 2019, *Bioremediation of Agricultural Soils*, pp. 165-192, CRC Press

Endogeic worms thrive in the deeper soil layers around plant roots and feed on organic material and microorganisms. They create horizontal burrowing systems that aerate the soil and promote the movement of moisture and nutrients. Endogeic worms are pale, rarely come to the surface, and are not conducive for composting (Werner, 1990).

Anecic worms are vertical burrowers that build deep structures in the ground. These worms search for food at night on the soil surface. They eat soil, leaf litter and are known to pull their food into their burrows. Anecic worms aerate the soil for water retention, are primarily used for fishing bait, and are not composting worms.

Sherman (2018) speaks highly of epigeic worms. These are composting worms that feed only on the decay of organic material. They do not live in the ground due to their inability to burrow. They tend to live on the soil surface in loose litter or manure piles. They can withstand temperature and moisture fluctuations, making them ideal for worm farms. There are seven species of earthworms suitable for vermicomposting. Of the seven species, only four are temperate, while the other three are tropical species. *Eisenia fetida* (red wiggler), *Eisenia andrei* (red tiger), *Eisenia Hortensis* (European Nightcrawler), and *Lumbricus rubellus* (red earthworms) are the temperate species. Of these species, 80-90% of worm farms use *E. fetida*, red wigglers.

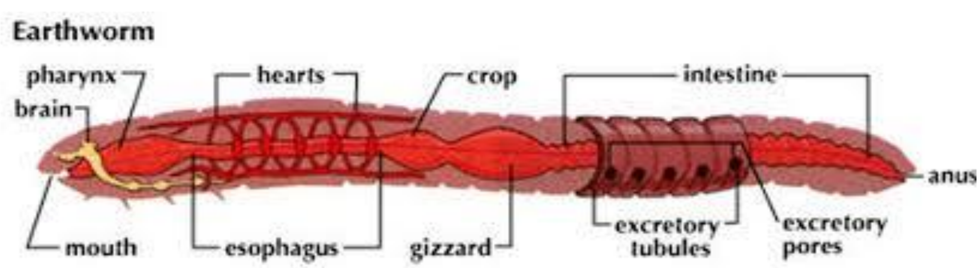
Red wigglers are adaptable to many environmental conditions. Red wigglers can withstand a wider range of temperatures than other worms. Temperature fluctuations can be between 40°F and 90°F, but worms will thrive between 55°F and 80°F. pH management for earthworms should be kept ideally between 6.8 and 7.2. However, they will grow within the pH range of 5 and 8. Moisture content for worm beds can be between 60% and 85%, with the target of 80% moisture. Moisture content over 90% will create low oxygen conditions, and worms can drown.

E. fetida feed as they move. They are known as an eco-biological engineer. The properties of contaminated soil are changed with earthworms. Soil is reclaimed from pesticide pollution and heavy metal contamination through earthworms (Sanchez-Hernandez, 2019). Land reclamation uses worms as bioindicators for the soil. Organic waste recycling and wastewater treatment are all performed by earthworms as they move and feed.

Worms have no teeth or stomachs; they depend on bacteria, fungi, nematodes, and other organisms to assist with the breakdown of food. The digestive tract of a worm extends the whole length of its body. Figure 6 traces the digestive process within the worm's body cavity. The worms prostomium guides the food into the mouth or moves bigger items out of the way. Instead of a stomach, the food moves through the crop, where it is stored and mixed, and continues to the gizzard. A worm's gizzard is similar to birds, where food is crushed and ground into tiny bits for further digestion. Food travels from there to the intestine, where most of the digestion and absorption takes place. This process is assisted by digestive enzymes that release amino acids, bacteria, fungi, nematodes, and other microorganisms. Only 5% to 10% of the food taken in by a worm is absorbed and used for cell production and energy. The rest of the processed foodstuff passes through the anus, resulting in the worm cast. Worm castings are packed with microorganisms that are the main ingredient in vermicompost. This digestive process takes approximately 2 1/2 hours (Edwards & Bohlen, 2006).

Figure 6

Basic Earthworm Digestive Anatomy



Note. Illustration from The Anatomy Project, 2021 (https://samirdossaanatomy.weebly.com/earthworm-anatomy.html)

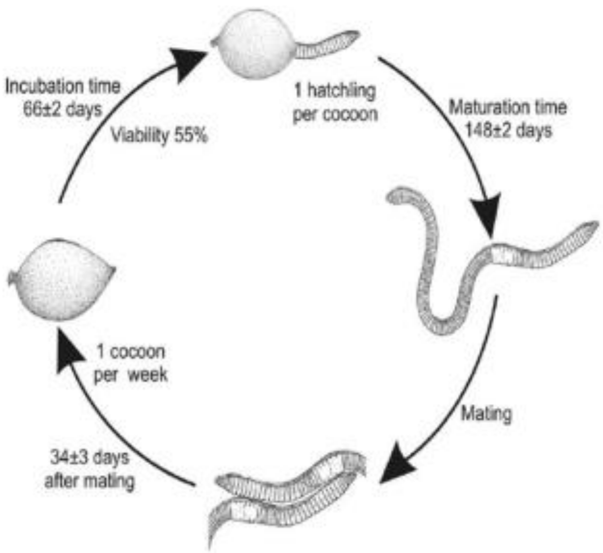
The nutrients, enzymes, and microorganisms produced in the earthworm gut are what create the valuable vermicompost. Worms are ravenous eaters. They can consume up to half their body weight in decaying organic matter per day (Minnich, 1977). One pound of *E. fetida* is approximately 1000 worms. Sherman (2018) advises that 1000 worms per square foot of surface area for composting systems. With these measurements, 1000 worms can consume half a pound of feedstock per day.

E. fetida are also a good choice of composting worms due to their reproductive rate (Sherman, 2019). Mature red wigglers can produce two to three cocoons per week. On average, three babies will hatch from each cocoon in about 30-75 days, depending on conditions. Due to the hermaphroditic nature of worms, each worm can produce offspring. The eggs and sperm of each earthworm are located in separate parts of the body to prevent self-fertilization. The worms lie with the undersides of their bodies touching, heads in opposite directions. Mucus is secreted from each worm, and sperm is transferred. The worms then disengage and collect the sperm and eggs into a mucus-created cocoon. This cocoon separates from the worms, and fertilization takes place. Red wiggler newborns appear as white thread less than 1/4 an inch long. Their color darkens within a few days to the typical reddish-brown (Minnich, J., 1977).

Minnich (1977) describes the maturity of earthworms and how quickly they can reproduce. Once the babies hatch, it takes approximately 8 to 10 weeks for them to be sexually mature and begin producing their cocoons. Figure 7 depicts the life cycle of *E. fetida* and is easily relatable to other species. Under the right conditions, with sufficient temperatures, space, food, and water available, red wigglers can double their population every 90 days. When conditions are less than ideal, cocoons will not mature and hatch. The cocoons become dormant and can stay viable for months or years. This allows the cocoons to survive for long periods until favorable conditions return. Worm populations are self-regulated. They will not reproduce until the environment is conducive to supporting the next generation.

Figure 7

Life Cycle of E. fetida



Note. Adapted from "*Eisenia fetida* Worm as an Alternative Source of Protein for Poultry: A Review," by Gunya, B., Masika, P.J., 2021, *International Journal of Tropical Insect Science*

Endogeic and anecic species of worms are typically not used for composting. However, they are valuable for sustainability. Their tunnels improve water filtration and increase nutrient access for plant roots. Their recycling of organic waste matter helps build soil aggregates for stability. They improve the biological soil characteristics by serving as a soil conditioner via nutrient and microbial enrichment. Karthikeyan et al. (2015) claim natural ecosystems are accountable for earthworm population proportions. Overdeveloped lands have decreased earthworm residents. Fallow or uncultivated areas have 8-10 times more earthworms than disrupted land. This evidence shows that the worm population declines with soil degradation (Briones et al., 2011).

Social Concerns

The world's population is expected to increase by two billion persons in the next 30 years, from 8 billion currently to almost 10 billion in 2050, according to a United Nations report.

This information has predicted consequences for achieving economic prosperity and social wellbeing while protecting the environment. According to the World Resources Institute, several concepts must be implemented to overcome the current and future food crisis. Creating a sustainable food future by 2050 is a must. Vermiculture addresses multiple issues plaguing today's agricultural processes. Searchinger et al. (2019) state that future yield growth in many crops will need to be higher than in the past to meet projected food demand on existing agricultural land.

Kale and Bano portray vermicompost as a natural growth promoter with nutrients four times more present than with conventional composts. They also state that vermicompost has shown a 30-40% yield increase in crops compared to chemical fertilizers (1986). This growth response of plants is associated with high levels of nutrients and humates in vermicompost. Humates are naturally occurring materials that are rich in organic matter and substances. Humic and fulvic acid made from prehistoric plant matter are various forms of carbon that are important for sustainable agriculture. Humates are the only substance that can attach to every nutrient in the soil. This increases nutrient absorbance in plant cell walls by up to 40%. Humates also contain a growth-promoting substance that enhances cell division and elongation. Humus is excreted by worms, which is what sets aside vermicompost from other organic fertilizers. The decomposition of soil organic matter forms humus, but it takes several years for that process (Sinha et al., 2010). Worms secrete humus in their excrement, which solidifies its value in sustainable agricultural practices.

Approximately 25% of all U.S. farms are certified organic as of 2019. All other farming methods depend on some variation of chemical inputs. Sinha et al. (2010) compare the chemical dependency of farming systems to that of a drug addict. Sinha et al. (2010) cite withdrawal symptoms as a vicious cycle requiring higher use of inputs for food productivity at the cost of declining soil fertility. With declining soil fertility comes a decline in viable produce for consumption. How does it make sense to continue to implement chemicals at an increasing rate that do not help to protect and improve soil quality? Food safety and security for the future can be through organic farming systems with the aid of compost. Compost made from the biodegradation of municipal solid wastes (MSW) is a good source of macro and micronutrients for the soil. MSW contains organic materials of approximately 70 to 80% and is being generated in huge amounts every day (Sinha et al., 2010).

Table 2

Earthworms, Vermicast, and Chemical Input Comparisons

Parameters Studied	CONTROL (No Input)	Treatment 1 EARTHWORMS Only (25 Nos.) (Without Feed)	Treatment 2 Soluble CHEMICAL FERTILIZERS	Treatment 3 EARTHWORMS + VERMICOMPOST (200 gm)
Seed Sowing	29th July 2007	Do	Do	Do
Seed Germination	9th Day	7th Day	7th Day	7th Day
Avg. Growth in 4 wks	31	40	43	43
Avg. Growth in 6 wks	44	47	61	58
App. Of Male Rep. Organ (In wk 12)	None	None	**Male Rep. Organ**	**Male Rep. Organ**
Avg. Growth in 12 wks	46	53	87	90
App. Of Female Rep. Organ (In wk 14)	None	None	None	**Female Rep. Organ**
Avg. Growth in15 wks	48	53 **(App. Of Male Rep. Organ)**	88	95
App. Of New Corn (In wk 16)	None	None	None	**New Corn**
Avg. Growth in 19 wks	53	56	92	105
Color & Texture of Leaves	Pale & thin leaves	Green & thin	Green & stout leaves	Green, stout & broad leaves

Source: Sinha *et al*. [27]

Note. Average growth in cm. Adapted from "The Wonders of Earthworms and its Vermicompost in Farm Production: Charles Darwin's 'Friends of Farmers' with Potential to Replace Destructive Chemical Fertilizers from Agriculture," by Sinha et al., 2010, *Agricultural Sciences Journal.1 (2)*, 76-94

Other research studies show an improvement in the yield and weight of marketable strawberries grown with vermicompost amendments compared to inorganic inputs. Similarly, farm soils showed a significant increase in microbial biomass with vermicompost than soils with inorganic applications (Arancon et al., 2004). Sinha et al. (2009) performed a study that was conducted on corn crops with vermicompost versus chemical fertilizers, with results reflected in Table 2. Plants with the chemical inputs showed limited growth, while the vermicompost plot grew significantly in the same time frame. Other benefits found in this study were faster maturation of plants and a decrease of necessary irrigation. Sinha et al. (2009) designed a comparable study of wheat crops. This experiment presented an 18% greater yield with vermicompost over the synthetic inputs. And the need for watering was decreased by 30 -40%. Another advantage was the significant reduction of nearly 75% of pest and disease infections on crops grown with vermicompost.

Vermiculture is rich in plant growth hormones. Growth responses of plants from vermicompost are associated with high levels of nutrients, humic acids, and humates. Vermicompost use further stimulates plant growth, improves seed germination, enhances seedling growth and development, and increases plant productivity. Vermicompost contains the growth-promoting hormone auxins, cytokinins, and gibberellins, all secreted by earthworms (Atiyeh et al., 2007). This allows for increased production yield without increased farmland use. Soil fertility is improved by earthworms and helps to increase crop production by the use of vermicast. Worm activity provides beneficial soil microbes and other compounds into the soil. Soil fragmentation and aeration are improved in farmlands through vermiculture and earthworm movement. A U.S. study promotes the use of worms by comparing the equal benefits of 10,000 worms versus three farmers, working 8 hours a day, for a year, with 10 tons of manure (Sinha et al., 2010).

Global use of vermiculture is growing. India, China, the Philippines, Mexico, Brazil, and Japan utilize vermicompost to reduce solid wastes and convert them to organic fertilizer for crops (Sinha et al., 2010). This vermiculture movement show success of community waste management and an economical option for replacing synthetic fertilizers and producing healthier food for impoverished villages. This process has dual benefits of reducing waste disposal costs and providing revenue from the sale of worms and compost. Vermicompost sales to farmers in the U.S. have been doubling every year since 1991.

Cuba is recognized as a global leader in organic farming development. In 1989, with the demise of the Soviet Union, Cuba suffered an imports void. Mayling & Roach (2008) state that Cuba lacked 80% of its chemical fertilizer imports, 50% oil, and 53% of food imports. This shortage led to food deficiencies and rationing of supplies. During this time, the average Cuban lost 20 lbs. due to a lack of sustenance (Sinclair & Thompson, 2001). Before this, the priority crop was sugar cane, with not much emphasis on food products. The Cubans used twice as many synthetic inputs as the USA on their sugar cane fields. Rosset & Benjamin (1994) found the results to be highly degraded soils with erosion, compaction, salinization, and environmental pollution.

Immediate necessity led the government to execute changes to Cuba's agricultural system. Over 170 vermicomposting systems were implemented, efficiently replacing 40 tons/H.A. of livestock waste with four tons/H.A. Aggressive urban agriculture was born, providing food to city dwellers without using scarce fossil fuels for transportation. Havana has 7,718 HA in crop production, with 90,000 people participating in agricultural practices. Cuba is an example of a realistic conversion to organic, sustainable practices from an intense, energy-consuming system (Koont, 2011).

Farmers in India are using vermicompost on a large scale with outstanding profits. Multiple villages have been designated as 'bio-villages' where many farmers have stopped using chemicals to become organic farmers with vermicompost. Sinha et al. (2010) report these farmers have described the benefits of vermicompost in India's agricultural methods:

- Decreased need for irrigation water
- Pest attacks reduced by at least 75% with vermiwash, a spray created with vermicompost liquid
- A decrease in weed growth
- Increases in seed germination, seedling growth, and plant development
- More fruit per plant, with heavier produce in quantity and quality
- 30- 50% increase in flower production, blooms were more significant and more vibrant.

In the 1960s, agrochemicals were introduced, showing an increase in crops, fruits, and flowers. Unfortunately, that era of chemicals and synthetics used in agriculture killed the beneficial soil organisms and destroyed soil natural fertility. Yields are now more susceptible to pests and diseases due to the overuse of chemical inputs. Chemically grown produce has also taken its toll on human health. Residual pesticides have continued to contaminate our food, making it unsuitable for human consumption (Hussaini, 2013). Vegetable samples were contaminated 100% with Hexachlorocyclohexane (HCH) and 50% with Dichlorodiphenyltrichloroethane (DDT) (Hussaini, 2013). Pest residue has also been found on chemically treated produce (UNEP, 1992). Agrochemicals in the agricultural ecosystem have had adverse effects on the health of farmers, producers, and consumers. According to the World Health Organization (WHO), this epidemic is evident all over the world. Nearly 3 million people suffer from acute pesticide poisoning, and 10 to 20,000 people in developing countries die every year. In the United States, approximately 20,000 people die annually from cancers related to low residual pesticides. This significant challenge addresses the quality of food being produced. Organic inputs can replace chemical inputs to produce a safer, non-toxic option for healthier food choices (Sinha et al., 2013).

Worms are also capable of bioaccumulation of endocrine disrupting chemicals (EDC). Human health can have adverse outcomes when exposed to EDC. Many different hormones can be disrupted by EDC's. Human fertility, sex organ abnormalities, altered nervous system functions, respiratory problems, and certain cancers are linked to EDC. Markman et al. (2007) studied *E. fetida* in sewage beds and garden soils and found high levels of EDC's in their tissues. EDC found in soil and water environments can be removed with vermiremediation and diminish this threat to social wellbeing.

Economic Concerns

The USDA classifies farms into three separate groups: rural farms, intermediate farms, and commercial farms. The number of U.S. farms has decreased, while the average size and production per farm have increased. The average U.S. farm size is 420 acres. Part-time farmers and ranchers account for half of the U.S. total of farms. But they only produce approximately 13% of the agricultural sales. Most American farms are run by family units that are concerned with financial security and longevity. Many farmers employ the business strategy of high volume, low margin production. The increased demand for generic feed grains, produce, and food products pressure farmers to emphasize quantity over quality. Unfortunately, this strategy degrades the soil by overuse in constant chemical inputs. This degradation puts farmers on a continuous cycle of additional chemicals to offset the unhealthy ground that has been created.

Soil rejuvenation plays a lead role in plant health. Plant health, in turn, creates healthier fruit packed with better nutrition and quality. Sherman (2018) goes on to explain the effects of vermicast on plant growth. Growth hormones and humic acids, located in vermicast, have a significant impact on seed germination and the speed of seedling growth. Olle's (2019) studies also praise vermicompost performance on crops. The application of vermicompost increases chlorophyll content, carbohydrate, and protein content and improves the quality of fruits and seeds. Increased yields are a welcome crop benefit in a vermicompost system with a 30-40% increase over chemical fertilizers (Sinha et al.,2010). Olle (2019) continues her observation with plant protection. Disease resistance is also common in vermicompost practices. Various pests and diseases are either suppressed or repelled by inducing biological resistance in the plants through vermicompost additions. Hussaini (2013) reports that only a 10-20% application of vermicompost is needed for optimal results in all growth trials. Sinha et al. (2010) contribute that the most significant advantage of food produced with vermicompost is entirely organic, safe, and chemical-free food. Vermicompost enhances the size, color, smell, and flavor of produce. Earthworms increase the bioavailability of essential organic and inorganic elements to plants. Soil properties with vermicompost have increased amounts of beneficial compounds, including Nitrogen, Phosphorous, and Potash availability compared to chemically treated soils. Synthetic inputs are more difficult to break down, making them increasingly inaccessible to plants for absorption, whereas vermicompost minerals are accessible and operational as needed. Due to the concentrated supply of nutrients the plants benefit from the timely slow-release conveyances. Table 3 portrays the immediate benefits of vermicompost and worm castings for plants and soil.

Table 3

Worm Castings Benefits

DIRECT USE	The only fresh manure that does not scorch plants. Direct sow of seeds into 100% castings.
HEALTHY PLANT DEVELOPMENT	earthworms excrete calcium carbonate necessary for the production of strong plant cell walls and nitrogen absorption
SLOW RELEASE	plant requirements vary throughout the growing season, and the concentrated nutrient base releases substances as needed
MOISTURE RETENTION	vermicast retains up to 50% moisture defending against drought or excess rainfalls
OPTIMAL GROWTH	Auxins, cytokines, and growth hormones are provided by vermicast, encouraging elongated root systems and healthy plant growth
DISEASE CONTROL	beneficial fungus eating nematodes
PEST CONTROL	high levels of chitinase, a natural insect repellent
HIGHLY CONCENTRATED	full of beneficial soluble minerals, 10 to 20% vermicast suggested for plant mediums
SOIL STRUCTURE IMPROVEMENT	worm castings aid in soil porosity, decreasing compaction, assisting with air and water movement.

Note. Adapted from "Vermicomposting: The Future of Sustainable Agriculture and Organic Waste Management," by DelaVega, 2016, *Winston Churchill Memorial Trust Fellow*

Vermicompost contains humus. Humus takes several years to be created in the soil, but earthworms secrete it. Humus is valuable to plants by stimulating root growth, helping the plant extract nutrients from the soil, and overcoming plant stress. Humus has also been found to elongate plant roots and facilitate lateral root establishments. According to Sinha et al. (2010), antibiotics and actinomycetes, found in vermicompost, are significant in creating resistance among crop plants against pests and diseases. The same studies explain that high levels of beneficial microbial populations in vermicompost protect the various plants by outcompeting plant pathogens for available food and blocking their access to plant roots. Vermicompost applications also suppress mites, nematodes, and aphids. Physiological plant changes of faster reproduction and faster maturity are also the result of vermicompost. This action reduces the life cycle time frame and quickens the harvesting schedule.

Chaudhary, Bhandari & Shukla (2004) discuss the economic cost of increased use of chemical fertilizers, combined with the deleterious effect on the soil environment. Soil degradation and declining crop yields are the main concern with synthetic inputs. Year after year, more chemicals are required to maintain stabilized crop production. Vermicomposting is an appropriate technique for replacing chemical use. This practice contributes to cost-effectiveness and efficient recycling of animal wastes and agricultural residues using low energy processes. The rehabilitation cycle of worms solves the problems of deteriorated soil conditions, meeting soil nutrient needs while disposing of raw materials at low energy consumptions and low material costs. Sustainability is determined by the vital processes that benefit the soil and are equal to or greater than the overall adverse effects of degradative practices.

Chemical pesticides have become necessary for high-yielding crops that are susceptible to pests and diseases. Repeated use of chemicals created a biological resistance in many crops. When the use of chemical pesticides is reduced, costs are minimized, and profits are increased. Vermicompost can protect plants from various pests and diseases by suppressing or repelling them, inducing a biological resistance through pesticide action (Suhane, 2007). The cost of production with vermicompost is far less than with chemical inputs. Vermiculture can lower costs by more than 60 to 70%, and the food produced will be chemical-free. Consumers and farmers reap the benefits from this action. Vermicompost also speeds up crop maturity and shortens harvesting time. This reduction in production time also adds to the economy of the farmer. Multiple crops can be planted and harvested within the growing seasons (Sinha et al., 2010).

A study performed on cherries in Australia for three consecutive years found a higher yield with a single application of vermicompost. Vermicompost was added to the trees at 5 mm and 20 mm plus mulch. The first harvest yielded cherries at the value of A.U. $63.92 and A.U. $70.42, respectively. In the third harvest, the yield was A.U. $110.73 and A.U. $142.21 respectively for the 5 mm and 20 mm of vermicompost with mulch (Webster, 2005). Webster also performed a study on grapes and vineyards. Treated vines produced 23% more grapes, and this additional yield was worth approximately A.U. $3400 per hectare.

Many farms can set up a vermiculture practice with ease. Each farm will base its setup on several factors, including size, crop, climate, feedstock, and space available. There are many different approaches to choose from based on needs. The most used systems are bins, trenches, pits, towers, windrows, wedges, and continuous flow-through (CFT) bins. Each system utilizes the same basic concept of a container, bedding, worms, feedstock, and moisture. Litter-dwelling worms are responsible for composting. These particular worms consume the bedding and the feedstock and convert it into an organic product we call vermicompost.

The container houses the worms. The worms eat, breed, and produce castings in the same container. Composting worms prefer the temperature between 55°F- 75°F inside the bin. Worms do not thrive in temperatures below 34°F or over 90°F. The container also protects them from weather and predators. Most containers have a moisture outlet, so the worm bin does not become too wet. Bins are harvested to remove the vermicompost. The harvesting process varies per container. Generally, the harvesting process is initiated once the feedstock is consumed and the castings are most of the container. The vermicompost is removed, the worms are given new bedding and feedstock, and the vermicomposting process begins again.

Worms prefer aerobic conditions for composting. Aerobic refers to oxygen content, while anaerobic is without oxygen. Trench or pit compost piles behave in anaerobic conditions and attract bacteria and other microbes to break down the material. This process is very stinky. Unpleasant-smelling gases are released, including methane. Aerobic systems encourage bacterial growth that is odorless. This bacterium assists the breakdown of food for earthworms. If the vermis system is too moist, the oxygen will decrease, and the anaerobic bacteria will move in and create foul-smelling compost (Abbasi et al., 2009).

Earthworms release valuable nutrients back to the soil while converting the residue. Chaudhary et al. (2004) also claim that earthworms harbor several microorganisms, enzymes, and hormones that influence soil regeneration. According to Sinha et al. (2010), the soil's natural fertility is reinforced by the essential nutrients and beneficial soil microbes that reside in vermicompost. In addition, vermicompost neutralizes soil pH, an increase in soil porosity. Vermicompost also acts as a 'slow-release fertilizer,' allowing for nitrogen and phosphorus to plant roots when needed. Studies have found that potassium, sulfur, and magnesium are significantly increased in the soil by adding vermicompost. Sinha et al. (2010) also compared thermophilic compost to vermicompost with an increase of 6% Nitrogen, Phosphorous, Potassium (NPK) in vermicompost versus only 3% NPK in thermophilic compost within the same soil grid. Olle (2019) describes the biochemical degradation of organic matter, with earthworms being the crucial drivers. Earthworms act as mechanical blenders, fragmenting and conditioning the substrate. As organic matter is modified, the C:N (carbon to nitrogen) ratio is reduced, increasing the area exposed to microorganisms and promoting microbial activity and further decomposition. Table 4 is a breakdown of the most common agricultural wastes and their C:N ratio.

Table 4

Carbon: Nitrogen (C: N) Ratio of Agriculture Waste

Material (*Browns*)	**C:N ratio**	**Material (*Greens*)**	**C:N Ratio**
Cardboard	350:1	Alfalfa	12:1
Wood Chips	400:1	Vegetable Scraps	25:1
Corn Stalks	75:1	Clover	23:1
Fruit Waste	35:1	Coffee Grounds	20:1
Dry Leaves	60:1	Food Scraps	20:1
Shredded Newspaper	175:1	Garden Waste	30:1
Peanut Shells	35:1	Manures	15:1
Straw	75:1	Weeds	30:1

Note. Adapted from "The Worm Farmers Handbook," by Rhonda Sherman, 2018*, White River Junction, VT. Chelsea Green Publishing*

Many farming budgets include the expenditure of waste removal. Composting worms reduce that expenditure by consuming multiple forms of waste. Feedstock for worms is based on the target C:N ratio of 30:1 (Sherman, 2018). This ratio is the correct proportion of carbon for energy and nitrogen for protein production. Carbons are typically referred to as browns, where nitrogen is referred to as greens. Browns are higher in carbohydrates and lower in moisture content. Carbons take longer to decompose. The greens have higher proteins and moisture content. Elevated proteins and increased moisture provides cell structure building, and they break down quickly and create heat. Vermiculture feedstock will fall in one of these two categories. Farmers and ranchers can implement a vermiculture practice that will consume the agricultural waste and produce organic amendments safe for all crops. Recycling agricultural wastes can save the farmer money and effort. This procedure will also continue to regenerate the soil, which will, in turn, reduce costs for the future.

Vermiculture technology, including vermicomposting, vermiremediation, vermicast production, and bio-indication, is a high-value addition practice. Vermiculture is a low or no energy, zero-waste technology that is simple to create, manage, and maintain. Vermiculture involves approximately 100 - 1000 times less investment than other biological technologies. Purchasing earthworms can be a one-time expense for vermiculture needs. Earthworms reproduce quickly, creating a multitude of worms to continue and promote productivity (Sinha and Sinha, 2007). Mechanical excavation and removal of contaminated soil can cost $10,000 - $15,000 per ha, compared to vermiremediation at $500 to $1000 per ha. The indirect value is the reuse and recycling of organic wastes otherwise destined for landfills. A greater benefit is the enhanced quality of the degraded land, not just a basic clean-up of hazardous waste. Vermiremediation conditions the soil to become lighter and more porous. The return of biodiversity and an increase in biological activities modifies soil quality for the future. Vermiculture practice can begin with the initial investment of 1000 worms for the U.S. $30 (Sinha et al., 2008).

Environmental Concerns

Overcropping and excessive deforestation have had degradative consequences on our soil health. The environment has suffered habitat destruction and loss of biodiversity. Physical, biological, and chemical degradation is destroying our lands. Almost 75 billion tons of topsoil are lost to land cultivation around the globe. Pimental & Burgess (2013) state that some significant reasons for environmental alterations are industrialization and urbanization. These ecological changes decrease land available for use in farming. Table 5 provides information about the causes and processes of land degradation. The lack of good farmland causes insufficient quantities of healthy food to feed the 820 million malnourished in the world (Searchinger et al., 2019). As the population grows, an increase in livestock and crops will be needed to fulfill the heightened food demand.

Table 5

Land Degradations

Type	Causes (not one to one along row)	Degradation process	Impact on soil processes
Physical	Deforestation	Breakdown of soil structure, aggregation and porosity	Reduction in infiltration capacity Changes in soil water-retention characteristics
	Biomass burning	Crusting and surface sealing	Increase in runoff rate and amount
	Tillage up and down slope, excessive animal, human, and machine traffic, overgrazing	Compaction of surface and subsoil, reduction in proportion and strength/stability of aggregates	Accelerated erosion by water and wind Increase in bulk density leading to reduction in porosity Water logging and anaerobiosis
Chemical	Irrigation with poor quality water, inadequate drainage	Salinization, alkalinization	Accumulation of base-forming cations
	Little to no use of fertilizers	Nutrient depletion	Decreased levels of macronutrients on exchange sites, soil organic matter, and in soil solution
	Excess use of fertilizers	Acidification, eutrophication	Leaching and runoff of nutrients to water sources
	Application of industrial, urban wastes	Toxification, contamination with heavy metals, pollution	Excessive build up of some elements (e.g., Al, Mn, Fe) and heavy metals (e.g., lead and mercury); increase in soilborne pathogens
Biological	Removal of or burning residues	Depletion of soil organic carbon	Reduction in N mineralization, soil aggregation, and related properties
	Little or no use of organic inputs	Decline in diversity and abundance of soil biota	Shift in species composition and diversity of favorable soil organisms
	Monoculture, excessive tillage	Loss of soil structure	Reduction in porosity and infiltration, reduction in activity of soil biota

[a]Modified from Reference 104.

Note. Adapted from "Soils: A Contemporary Perspective," by Palm, C., Sanchez, P., Ahamed, S., & Awiti, A., 2007, *Annual Review of Environment and Resources, 32*, 99-129

Chemical agriculture has taken a toll on our farmland and our environment. In 1918 Fritz Haber and Carl Bosch won the Nobel Prize for developing a synthetic fertilizer, NPK, that doubled crop productions. Nitrogen, phosphorus, and potassium are the core ingredients for this chemical concoction. Phosphate mining to create NPK is an expensive process that is about to run out. Cordell et al. (2009) claim that peak phosphate extraction in 2030 will soon cause depletion of this resource. Between 2007 and 2008, the price of synthetic fertilizer increased by 800%.

Along with that, the cost of phosphate has doubled since 2006 (Tomlinson, 2010). China and the USA no longer export phosphate due to imminent depletion. At this point, Morocco holds 80% of the earth's total phosphate resources (Brown, 2011). In the 1980s, agricultural advancements were made to produce more food, resulting in poor soil quality, especially in irrigated regions, due to the excess use of fertilizers (Sinha & Herat, 2012).

Even though synthetic inputs increased the quantity of our food, they dramatically decreased the nutritional quality. Soil fertility has also reduced, requiring additional chemical inputs every year to maintain the current food productivity. From 1950 to 1984 there was a 3% annual rise of fertilizers used in farmlands. We have now reached a plateau where the land is not responding to synthetic inputs. Biological droughts are becoming more prevalent in the world where heavy use of agrochemicals is being used. Beneficial soil microbes and earthworms are diminishing due to the overuse of chemicals. Biological resistance is developing in many crops where pests and diseases are now immune to chemical pesticides (Hussaini, 2012). Chemical dependency can be lessened, if not eradicated, using vermiculture and vermicompost.

Vermicompost can also replace chemical pesticides. Biological resistance is induced in plants to fight various pests and diseases. This pesticidal action repels and suppresses plant predators. Earthworms produce actinomycetes fungus that kills the parasitic fungi *Pythium* and *Fusarium* (Edwards et al., 2004). Yardim et al. (2006) confirmed that cucumber beetles, larval hornworms, and cucumber larva were restricted in their damage with the presence of vermicompost. Chemical pesticide sprays are decreased approximately 75% where vermicompost has been applied. The antibiotics and actinomycetes in vermicompost increase natural resistance in crops (Suhane, 2007).

Edwards et al. (2004) refer to the evidence of vermicastings repelling hard-bodied pests. Many arthropods, including aphids, buds, mealybugs, and spider mites, have diminished populations with vermicompost applications. The noticeable decrease in plant damage of tomatoes, peppers, and cabbages was studied with trials of 20% and 40% vermicompost addition. Munroe (2007) attributes this reaction to the worm's production of the enzyme chitinase, which breaks down the chitin in the exoskeleton of beetle-type insects.

Plant-parasitic nematodes and soil-borne diseases are suppressed with the use of vermicompost. Edward et al. (2004) studied peppers, tomatoes, strawberries, and grapes and found significant disease resistance with the application of vermicompost. This concept is explained by the increased levels of agronomically beneficial microbial population in vermicompost. Plant pathogens are starved of available food resources by blocking their access to plant roots and occupying all available sites. On an additional note, sterilized vermicompost cannot control diseases, suggesting that microbial antagonism is the biological mechanism at work (Sinha et al., 2009).

Chemical use in our crops also takes a toll on our water systems. Studies indicate that an application of 100 kilograms of nitrogen does not all benefit the farm soil. Only 20 to 25 kilograms are available to plants, while another 20 to 25 kilograms of nitrogen leeches underground pollute the groundwater (Sinha et al., 2010). Eroded soils carry fertilizers, pesticides, and pollutants to water bodies through runoff after rains. Agriculture runoff causes eutrophication in U.S. lakes. Nitrogen-rich fertilizer compounds cause oxygen deficiency in rivers, lakes, and coastal zones (Van Grinsven et al., 2012).

Sedimentation due to runoff affects water quality. Pollutants like pesticides and phosphorus are transported and accumulated due to sedimentation. Sediment particles, including agriculture chemicals, also attach to fish gills; fish cannot respire and die. Many sediments carry dangerous chemicals, including petroleum products, to various bodies of water, causing additional pollution (Letchinger, 2000).

The EPA estimated that in 2018 almost 103 million tons of wasted food were generated in the industrial, residential, commercial, and institutional sectors. EPA (2018) estimates that more food reaches landfills than any other material, making up approximately 24% of all items sent to the dump. When food is wasted, it also wastes land, water, energy, and labor resources. Wasted food is a growing problem but also an opportunity.

Various items have been composted with worms. Chaudhary et al. (2004) found that coffee pulp reported an increase of macronutrients and increased nitrogen content when vermicomposted. Paper waste sludge was experimented with and found to have a rise of 25% of extractable phosphorus through vermicompost. Earthworms will fragment and mix plant residues, livestock manure, rural and urban wastes. Many nutrients are augmented during the vermicomposting process, and the C:N ratio is averaged out. Microbial activity and humidification are considerably higher with vermicomposting as compared to thermophilic composting. According to Sherman (2018), food waste is the primary material recycled by worms. Yard debris, biosolids, animal bedding, food processing wastes, paper and cardboard, crop residue, and rice hulls can all be regenerated through worms as a valuable crop amendment. Recycling waste products through worms reduces landfill waste.

Vermicompost production is a process that reduces wastes and saves landfill space. Composting worms convert a harmful waste product into a nutrient-laden amendment for farm enhancement. Raw waste materials are plentiful, while petroleum-based inputs are vanishing resources. The utilization of vermicompost holds multiple benefits for the environment and the economy. Landfills are an expensive endeavor for any country. Construction of landfills costs approximately $20 to $25 million before waste is even added. The expenditure on landfill disposal waste has doubled over the last five years. Kitchen and food wastes are high contributors to greenhouse gases (GHG). GHG methanes from food waste can be up to 300 times stronger than carbon dioxide (DeLaVega et al., 2016). Vermicomposting reduces the amount of waste taken to landfills, consequently reducing the use of fossil fuels required to transport it. According to government mandates all landfills must be monitored for at least 30 years for immersion emissions of GHG and other toxic gases due to the excessive amounts accrued (Hussaini, 2013).

In developing nations where there are no landfills, the dumping of waste produces toxic environmental concerns. Municipal solid wastes (MSW) have been increasing rapidly in developing countries. MSW is a nonliquid waste that is discarded by persons, households, businesses, or institutions. These can consist of packaging, foods, yard debris, clothing, newspapers and paper products, and other general trash or garbage. Globally, MSW is generated at approximately 1.3 billion tons a year and is expected to increase annually (Hoornweg & Bhada-Tada, 2012).

The EPA (2018) estimates that more than 500 million tons of animal manure are produced annually from animal feeding operations. Manure management is a challenge many farmers face. A vermicomposting system for processing livestock waste can contribute to the economic and environmental benefits of the farm. Due to the expansive resource availability, farm producers can use vermicomposting to their advantage within their manure handling systems. Crop residues can be contributed and used as bedding and feedstock. Cattle manure and swine manure are the most common livestock additives. Chicken manure has a high content of nitrogen that can be toxic to worms in large amounts. Manure requires a mixture of carbons, such as leaves or other crop residues. The bio humus has a more homogeneous and structured porosity surface than thermophilic compost. Plus, organic content was increased. Metals from the manure were accumulated in the earthworms; therefore, the bio humus was purified from pollutants (Kovshov & Skamyin, 2017).

Table 6

Remediation Study

for 24 hours without earthworm and 120 hours with earthworm

Petroleum Hydrocarbon	24 hours without earthworm	120 hours with earthworm	% reduction (remediation level)
Tridecane	3.73	2.40	35.66
Tetradecane	5.61	3.52	37.25
Pentadecane	6.89	5.70	17.27
Octadecane	18.44	6.03	67.30
Hexadecane, 2,6,10, tetradecane	4.77	2.75	42.34
Eicosane	8.17	4.66	42.96
Heneicosane	10.48	8.64	17.56
Tetracosane	3.52	1.75	50.28
Pentadecane, 2,6,10, trimethyl	1.80	0	100
Dodecane, 2,6,10, trimethyl	3.57	0.75	78.99

Note. Adapted from "*Eisenia fetida* Increased Removal of Polycyclic Aromatic Hydrocarbons from the Soil," by Contreras-Ramos, 2006, *Environmental Pollution*

Many land areas have been contaminated with industrial pollutants. Earthworms play an essential part in land reclamation. Vermi-remediation is used to remove toxic chemicals and hydrocarbons from soils. Contaminants can infiltrate our air, food, and water. Sinha and Herat (2012) have studied several species of earthworms, including *E fetida*, and their ability to remove toxic compounds, pesticides, and organic compounds like polycyclic aromatic hydrocarbon (PAH) from many soils. PAH are naturally occurring chemicals from coal and crude oil. They are also produced by burning items such as garbage, wood, tobacco, and gas. The released chemicals form small fragments or join with other air-born particles. Humans are exposed to

PAH regularly by inhaling contaminated air. Cigarette smoke, vehicle exhaust fumes, wood smoke, and asphalt gases. In a study performed by Contreras-Ramos et al. (2006), several industrially polluted sites were detoxified by earthworms. Table 6 gives the results of a chemical study with and without earthworms. The PAHs have been divided apart in only 11 weeks with a ratio of 50 worms per one kilogram of soil. Contreras-Ramos et al. referred to the thermodynamic tendencies and the polarity contribution of vermicompost and its role in the deterioration of PAHs. Vermicompost has an elevated electric charge reducing the thermodynamic tendency by absorbing the organic chemicals involved.

Sinha et al. (2008) assert that developing countries have a high rate of chemical contamination in their farmland. Mine activities, industrial disposals, oil and gas drilling are all responsible for the toxic inputs in developing nations. Persistent pesticides are common in the farmland of developing countries. Aldrin, chlordane, endrin, heptachlor, mirex, toxaphene are synthetic compounds that are hazardous to the soil and infect growing crops. Abandoned mining sites and closed landfills are included as areas that are detrimental to farmland. Most of these sites contain heavy metals such as cadmium, lead, mercury, zinc, and even chlorinated compounds like Dichlorodiphenylthrichlorophane (DDT) and Polychlorinated Biphenyl (PCB). These polluted sites run the risk of contaminating groundwater by leaching with heavy rains. The expense of mechanically excavating and disposing of these poisoned sites is an excess of billions of dollars. Underdeveloped and developed nations or unable to fund such an endeavor. Even established nations have their share of contaminated sites:

Australia - 80,000 sites

United States- 40,000 sites

Europe - 55,000 sites

New Zealand – 7,800 sites

Asia-Pacific – 3 million sites

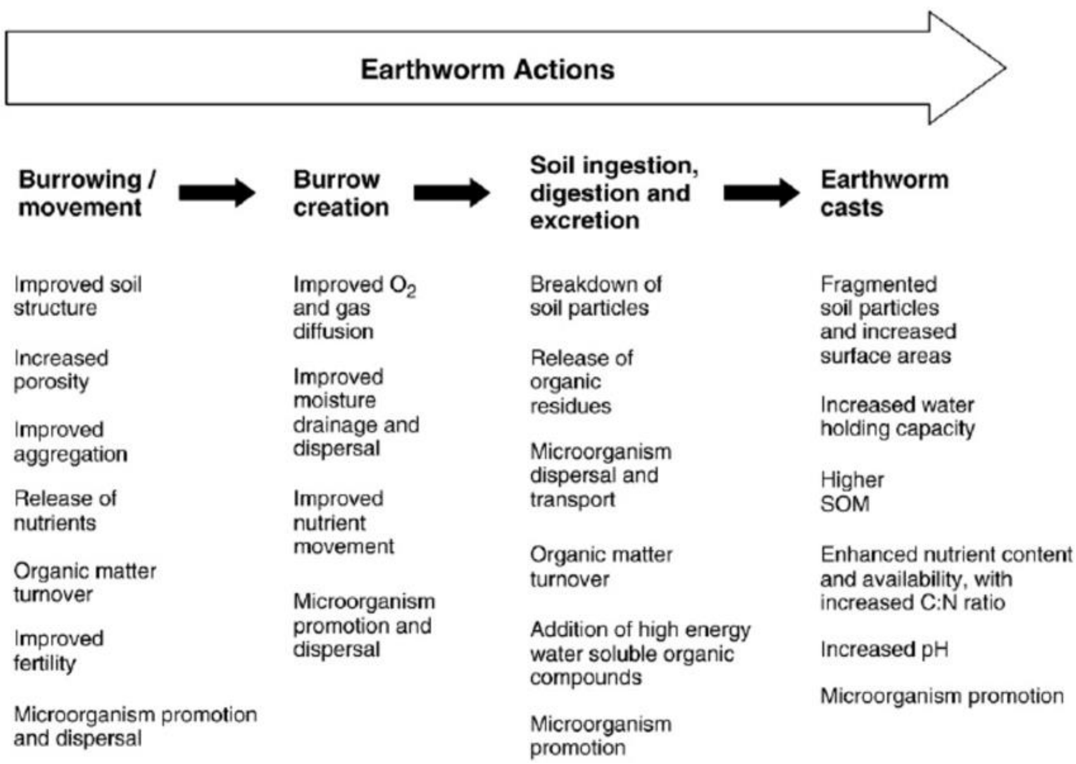
According to Shi et al. (2019), soil pollution can be indicated by earthworm casts. The casting is used to assess contamination levels. Vermicasts can bioaccumulate toxic compounds to decrease soil pollution. Some species of earthworms bioaccumulate cadmium, lead, and mercury in their tissues (Sinha and Herat, 2012). Microbes in vermicompost reduce the number of heavy metals and herbicides in soils. Vermicompost is known to decompose chemicals that are used for agricultural purposes. Organization for Cooperation and Development(OECD) assessed for different soil contaminants on *Eisenia fetida* earthworms. Multiple reports indicate that *E. fetida* can tolerate 1.5% of crude oil (Safwat et al., 2002). Earthworms inhibit many soil-borne pathogens as they work as a detoxifying agent for tainted soils (Buschmann, 2013). Safwat et al. (2002) reported a 30% reduction of *Salmonella* in earthworm populated soils.

Soil organic matter goes through the process of humification in the worm's intestine. The large organic particles digested through worms are converted into humus. This substance becomes a slow-release fertilizer for the soil. Organic additives, such as vermicompost enhance the nutrient supply capacity for soil and shield topsoil from contaminated inputs. Another advantage of vermicompost is the contribution of worm cocoons. As worms hatch, they continue to improve soil fertility requiring diminished amounts of vermicompost additions for the future. A decreased need for vermicompost inputs contrasts with the need for increased amounts of chemical fertilizers to maintain productivity levels (Sinha et al., 2010). Bhawalkar and Bhawalkar (1994) claim that, on average, 18t of soil per year is rotated by earthworms ingesting 12t/ha/year of organic matter. As wasteland begins the transformation to fertile land, it may contain approximately 50,000 worms per ha. An experiment by Bhawalkar and Bhawalkar concluded that within 3 months, up to a million worms/ha can be re-established on contaminated land as it progresses.

Worms are considered as a 'biological indicator' of suitable, healthy soil. The absence of worms confirms a degraded, unhealthy medium requiring remediation before cultivation. Earthworm castings contain enzymes that break down soil organic matter and distribute nutrients to plant roots. Worms act as a bioreactor, secreting enzymes proteases, lipases, amylases, and cellulases that quickly bring about a biochemical reaction that converts organic waste materials (Sinha et al., 2010). Ammonium in the soil is bio-transformed into nitrates. The earthworms recycle nitrogen quickly, ranging from 20 to 200kg N/ha/year (Sinha et al., 2008). The physical, chemical, and biological transformation of soil by earthworms improves fertility. Figure 8 includes the earthworm's action and effect within the soil environment.

Figure 8

Biological, Chemical, and Physical Effects of Earthworms

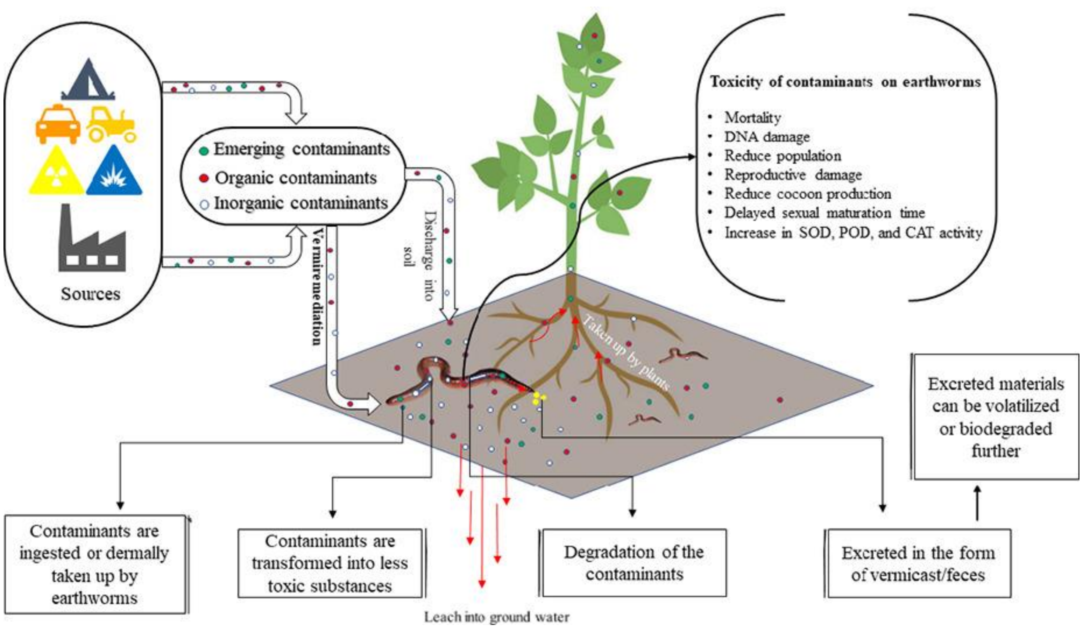


Note. Adapted from "Earthworm Assisted Bioremediation of Organic Contaminants," by Hickman & Reid, 2008, *Environment International, 34*

Soil salinity and pH levels in India affect the sugarcane crop. Saline soils are irrigated by saline groundwater, inhibiting plant growth by hindering plant roots access to beneficial hydration. Farmers combined live earthworms with the sugar cane crop and increased the yield to 125t/ha. Soil chemistry also showed marked improvement. Bhawalkar and Bhawalkar (1994) continued to acknowledge a 37% increase in nitrogen, 66% more phosphates, and 10% more potash within the year. The soil's chloride content was reduced to less than 46%. Grape production was also evaluated in India with a 5 t/ha application of vermicast. Though the harvest was typical in quantity, it demonstrated improvements to taste, quality, and shelf life. The soil was analyzed and found the pH was reduced from 8.3 to 6.9 within a year, and potash levels increased from 62.5 to 800 kg/ha. Figure 9 depicts the contaminant cycle through earthworms.

Figure 9

Vermiremediation of Soil Contaminants



Note. Adapted from "Insights into the Mechanisms Underlying the Remediation Potential of Earthworms in Contaminated Soil: A Critical Review of Research Progress and Prospects," by Zeb et al., 2020, *Science of the Total Environment*

Vermiremediation recycles polluted soils into a usable plant-growth medium by utilizing the earthworm's enzymes and processes. Chemical uptake can be done by way of passive absorption through their skin. Intestinal uptake is accomplished as particles move through the gastrointestinal tract. Earthworms consume half their body weight of material a day, including soil microbes and other organic matter. A significant amount of chemicals, heavy metals, and contaminants are immobilized and excreted regularly. Many contaminants are either bio-transformed or bio-degraded in the worm gut and are rendered harmless within the worm tissues. Other contaminants are metabolized or sequestered in tissues or vacuoles (Sinha et al., 2008). The earthworm continues to contribute multiple positive physical impacts through vermiremediation.

Findings

Vermiculture is a viable alternative for sustainable agriculture. Reducing chemical inputs by utilizing vermicompost can contribute to restoring soil health. Topsoil has been eroded and degraded over the years by continuous use. Constant output of crops has depleted soils of vital nutrients. Excess synthetic fertilizers have damaged our crops' response to pests and diseases. Our plants and soil have become dependent on outside involvement to remain successful. Each year they demand more synthetic inputs to combat new weeds, diseases, and pests.

Vermicompost is essential for soil health. Vermicompost brings the soil to life by promoting microbial activity. Microbes and humus protect and empower the plant to repel pests, thwart diseases, and suppress weeds. Vermicasts are rich in growth hormones and enzymes that enhance seedling growth and seed germination. Vermicompost can increase potential yield without contributing to environmental pollution. Vermiculture works to promote and protect the soil. Vermiculture can be the change needed to maintain soil health, produce healthy, chemical-free food, manage waste, and provide a future for sustainable agriculture.

Sustainability can be practiced through vermiculture in various settings. Small, mid-size, and large vermicomposting systems can be developed to promote waste management, healthy soil, and food production worldwide. The global success of vermiremediation, vermicomposting, and vermiculture is represented in several scenarios (DelaVega, 2016).

The Monroe Correctional Facility in Monroe, WA. participates in the 'Sustainability in Prisons Project.' They have developed a vermiculture system dubbed 'The Worm Farm.' They are an example of institutional vermicomposting. They freely provide education, worm distribution, and wormeries to other prisons, schools, and organizations.

The program began as a method to reduce the expenses of waste removal. The system was created in 2010 with 200 worms and now saves the facility approximately $100,000 a month by feeding 10 tons of food waste to approximately 9 million worms. The 13,000 sq ft facility houses worm bins made from recycled materials, and the worms are managed by the inmates. The Worm Farm contributes to the area by supplying 5000 gallons of worm castings tea to replace chemical inputs in public spaces. Inmates also create floral hanging baskets using the vermicast in the soil medium and donate them to the local government beautification plan. This program demonstrates awareness of climate change, topsoil depletion while introducing a new skill set for inmates. The Worm Farm encourages imitation from other prisons while providing social, economic, and environmental benefits for the community DelaVega, 2016).

The Portland Community College in Portland, OR. began a vermicomposting system in 2015. The school purchased a food macerator and a continuous flow-through bin (CFB). This on-site system processed 13,615 lbs. of food waste in 2016. The vermicompost is used to amend the soil at the 3.4-acre Portland Community College Learning Garden. The garden supplies the college cafeteria with 1200 lbs. of fresh produce and has begun an education program for elementary students. The success of this program determined the hiring of four laborers to continue and grow the worm farm and learning garden (DelaVega, 2016).

The Worm Farm in Durham, CA., is a family-run vermiculture enterprise selling worms and worm castings globally. Because of the temperate climate, this worm farm has outdoor windrows covering their 5 acres. Each worm windrow is fed 450lbs dairy cattle manure every two weeks. This family farm sells 120 lbs. of worms a week in the off-season, reaching 500 lbs. a week in the spring, at $28.50 per pound. Vermicastings are also sold regularly. A typical sales week is 520 yards of vermicast at $200 a yard, with most of their castings going to organic medical marijuana farms. The farm also conducts farming workshops for businesses and educational tours for schools (Sherman, 2018).

Havana is home to the second-largest organic farming producer in Cuba, Vivero Alamar Organoponico. This 7-acre food production facility provides 625 tons of fresh fruits and vegetables annually to local businesses and consumers. Vermicomposting is an integral part of their process. The on-site system uses six windrows, and each windrow is 45 square meters and houses 200,000 worms a meter. This method produces 300 tons of vermicastings each year. Worms are fed livestock manure from the horses and bulls on the farm (Sherman, 2018). Organic farming in Cuba is now a resource-saving venture. The previous expense of $40 a ton of chemical inputs has dropped to $0.55 for locally produced organic inputs (Koont, 2011).

Sherman (2018) describes a vermicomposting operation in Mexico that was born in 2005. The goal was sustainability using organic materials to provide food security and the remediation of their country's soils. Several families came together to form Grupo Aldea Verde (GAV). This company produces vermicasts, offers vermicomposting consulting, worm production facilities, and land remediation services. They are continually expanding through more communities and more partners. By 2018 the company and its partners were processing greater than 5000 tons of organic matter a day throughout Mexico. A few of GAV successful sustainability projects:

- 300 tons of agave bagasse composted per day from a tequila producer
- A palm oil plant is producing 4000 tons of vermicast a year
- Meat processing plant processing 500 tons of livestock manure and litter per day
- Berry grower and packer is vermicomposting 10 tons a day of packing debris and creating over 27,000 gallons of vermicast tea a week
- A 7,413-acre vegetable and fruit farm recycles 50 tons of crop waste a day through vermiculture. The castings are used in their fields, and production has increased by 30%.
- A Cancun hotel processes the kitchen and hotel waste and reuses the casting in the hotel kitchen garden.
- Pineapple and Papaya farm manages the crop wastes to be used to improve fruiting, reduce expenses, and decrease chemical dependence.

Many facilities, industrial and agricultural, are utilizing vermiculture to promote sustainability throughout the globe. Small, mid-size, and large worm farming systems can be adapted to improve soil health, dispose of waste, and create safe, organic inputs for quality crops.

Conclusion

Vermiculture practices are an appropriate alternative to promote social, environmental, and economic sustainability in agriculture. Sustainable agriculture is the future of feeding the growing global population. Direct and indirect earthworm actions will promote healthy soil, productive crops and increase biodiversity without pollution for a safe environment.

Sustainable agriculture will meet today's food and textile needs while being mindful of the future. This mindfulness protects and promotes the environment and ecosystems for tomorrow's generations and their needs. Crop yields need to increase without compromise of quality or nutrition. Vermicomposting processes address those needs with indisputable success.

International farming planning using vermiculture methods has proven records of growth increases without excess chemical inputs. Vermicompost produces a growth response in plants due to high levels of humate and nutrients. Research studies of fruits, vegetables, and flowers showed an improvement in the yield and weight of marketable produce. The decreased need for irrigation coincides with increased soil porosity and microbial biomass with the vermicompost additions. Vermicompost stimulates seed germination and growth development in plant productivity. Soil fertility is enhanced with vermicompost improving quality and quantity of production without added farmland use. This aspect of vermiculture helps meet the need for our growing global population's food crisis.

Agrochemicals, introduced in the 1960s, have degraded our soils and food quality. These synthetic inputs were created to dissuade pests and diseases. Overuse of chemicals has created resistance in several pathogens triggering additional chemical additives in a never-ending cycle. This abuse has caused soil and plant health to decline. Vermicompost can alleviate chemical dependency on our farms. Vermicompost in farming soil adds worm cocoons that eventually contribute to the earthworm population, developing beneficial soil properties and fertility. Vermicompost is an organic amendment that acts as a natural herbicide and pesticide. Soils with vermicompost amendments tend to have a natural resistance to blight, wilt, mildew, and other pathogenic attacks. As the soil returns to its natural state, less vermicompost is required for productivity maintenance. India has shown success with 'bio-villages' becoming organic farmers with vermicompost, ceasing their need for agrochemicals.

Increased pesticide use coincided with human health decline. Residual pesticides contaminate food, making it hazardous for human consumption. Pesticide poisoning is a significant illness with increased fatalities. Cancers, skin lesions, respiratory issues are all common in farmers and consumers of affected produce. Replacing chemically grown crops with organic, vermicomposted produce is a safer, healthier option. Fruits and vegetables grown with vermicompost have a higher nutrient count with elevated proteins, minerals, and vitamins. Increased nutrition and healthier food products provide proper energy for immunity, digestive, and cardio systems within the human body.

Farmers succumbing to the constant use of chemical inputs are also partnering with an elevated expense. Vermicompost is optimized at a 10 -20% application, which is a lower amount of contribution than chemical inputs. The humus produced by vermicompost help stimulate root growth and creates resistance against pests and diseases. These plant changes create faster maturity and quicken the harvesting time, allowing more crops to be planted with higher yield content. The most significant advantage of food produced with vermicompost is a safer, organic product with enhanced size, smell, and flavor.

A vermicomposting system is an appropriate replacement for chemical amendments on the farm. Animal wastes and farm debris can be recycled through earthworms to create vermicompost. This activity is efficient and cost-effective, controlling expenditures of waste management and soil degradation. Vermiculture technology can be implemented on-site with minor investments compared to chemically dependent systems. The savings accrued does not stop with the immediate financial rewards but continue with the bioremediation of the soil with consistent vermicompost inputs. Vermiculture practices used in agricultural campaigns are economically feasible, reducing expenses for the farmer and the consumer.

Environmental concerns are an aspect of sustainability that relates to water, air, and land pollution. Chemicals invade our water systems by runoff and leaching into our groundwater systems. Soil erosion carries synthetic particles into our waterways, polluting them and affecting our aquatic ecosystems. In our lakes, streams, and rivers, oxygen deficiency is caused by nitrogen fertilizers from runoffs on farmlands contaminated with excess chemical inputs. Sedimentation contributes to the accumulation of toxins that attach to aquatic wildlife, causing diseases and death. These chemicals could be replaced by organic vermicompost creating a safer habitat throughout our waterways.

Landfills are overrun with wasted food that could be recycled through earthworms to reduce the footprint caused by excess litter. Wasted food abuses our land, water, energy, and labor resources. Greenhouse gases are created by kitchen and agricultural wastes. GHG pollutes our air and our environment. Landfill constructions, waste transportation, and disposal costs are constantly increasing while depleting our fossil fuels. Vermiculture systems would reduce the amount of waste taken to the landfill, reducing pollution of our environment. Other agricultural and livestock waste can also be managed through vermiculture practices. Cattle manure, bedding, and crop residue can all be returned to the farm as a soil-boosting amendment by way of vermicomposting.

Vermiculture practices include vermi-remediation that is used to remove toxins and poisons from our contaminated soils. Many toxic compounds, pesticides, and organic compounds such as PAH cause pollution and airborne contaminations. Many farmlands have chemical contaminations that can be corrected through earthworm populations and activities. Closed landfills, abandoned mines, former industries, and old hospital sites contain heavy metals in their grounds and property. Vermicasts and associated microbes bioaccumulate and decompose chemicals and other soil-borne pathogens when introduced into the contaminated area. Soils are recycled into a usable medium for plant growth and renewed biodiversity.

A sustainable agricultural future can be produced through vermiculture practices. Higher yields, nutrient-rich crops, waste management strategies, and decreased chemical reliance can bring economic prosperity for the farmers. Vermiculture strategies can address the hunger crisis of the growing population through increased food production on current farmland. Quicker harvest, improved quality, bigger fruits will provide food security for the people. Vermiremediation, soil health, contaminant reduction, and recycled agricultural waste increase the physical, biological, and chemical properties of the land. The microbial activity and biodiversity contributed to farmland through vermiculture and vermicompost create ecological security for the farm. Many social, economic, and environmental concerns can all be answered by vermiculture practices for a sustainable agricultural system.

References

Abbasi, T., Gajalakshmi, S., & Abbasi, S. A. (2009). Towards modeling and design of vermicomposting systems: mechanisms of composting/vermicomposting and their implications. *Indian Journal of Biotechnology*, *8*, 177-182

Ahmed, M., Ahmad, S., Qadir, G., Hayat, R., Shaheen, F. A., & Raza, M. A. (2019). Innovative processes and technologies for nutrient recovery from wastes: a comprehensive review. *Sustainability*, *11*(18), 4938

Arancon, N. Q., Edwards, C. A., Bierman, P., Welch, C., & Metzger, J. D. (2004). Influences of vermicomposts on field strawberries: 1. Effects on growth and yields. *Bioresource Technology*, *93*(2), 145-153.

Arancon, N. Q., Edwards, C. A., Lee, S. S., & Yardim, E. (2002, November). Management of plant parasitic nematode populations by use of vermicomposts. In *Brighton crop protection conference pests and diseases, Vol. 2*, 705-710.

Atiyeh, R, Lee S., Edwards, C.A., Bachman, G, Shuster, W. (2000). Effects of vermicompost and composts on plant growth in horticulture container media and soil. *Pedobiologia 44*, 579-590.

Atiyeh, R. M., Edwards, C. A., Subler, S., & Metzger, J. D. (2000). Earthworm-processed organic wastes as components of horticultural potting media for growing marigold and vegetable seedlings. *Compost Science & Utilization*, *8*(3), 215-223.

Bhawalkar, V., Bhawalkar, U. (1994). Vermiculture Biotechnology. Bhawalkar Earthworm Research Institute (BERI) Pune, India

Bellemare, M. F., Çakir, M., Peterson, H. H., Novak, L., & Rudi, J. (2017). On the measurement of food waste. *American journal of agricultural economics*, *99*(5), 1148-1158.

Bogdanov, P. (1996) *Commercial Vermiculture: How to Build a Thriving Business in Redworms.* Oregon. VermiCo Press.

Briones, M. J. I., Barreal, M. E., Harrison, A. C., & Gallego, P. P. (2011). Earthworms and nitrogen applications to improve soil health in an intensively cultivated kiwifruit orchard. *Applied Soil Ecology*, *49*, 158-166.

Buschmann, J. (2013). The OECD guidelines for the testing of chemicals and pesticides. *Teratogenicity testing*, 37-56.

Chan, M. L., & Roach, E. F. F. (2013). *Unfinished puzzle: Cuban agriculture: The challenges, lessons & opportunities*. Food First Books.

Chaudhary, D.R., Bhandari, S.C., Shukla, L.M. (2004). Role of vermicompost in sustainable agriculture. *Agriculture Review 25(1)*, 29-39.

Contreras-Ramos, S. M., Alvarez-Bernal, D., & Dendooven, L. (2006). *Eisenia fetida* increased removal of polycyclic aromatic hydrocarbons from soil. *Environmental Pollution*, *141*(3), 396-401.

Cordell, D., Drangert, J. O., & White, S. (2009). The story of phosphorus: global food security and food for thought. *Global environmental change*, *19*(2), 292-305.

DelaVega, A. (2016). Vermicomposting: The Future of Sustainable Agriculture and Organic Waste Management. *Winston Churchill Memorial Trust Fellow*.

Douglas, F. (2001). The worm that earned. *New Scientist*, *15*. 32-34

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

Edwards, C. A., & Bohlen, P. J. (1996). *Biology and ecology of earthworms* (Vol. 3). Springer Science & Business Media.

Edwards, C. A., Dominguez, J., & Arancon, N. Q. (2004). The influence of vermicomposts on plant growth and pest incidence. *Department of Entomology, 18*

Fitzpatrick, G. E., Worden, E. C., & Vendrame, W. A. (2005). Historical development of composting technology during the 20th century. *HortTechnology*, *15*(1), 48-51.

Ganesh, P.S. (2007). Some applications of bioprocess engineering in solid waste management. *PhD Thesis*. Pondicherry University. Pondicherry

Garg, V.K., Gupta, R. (2009). Vermicomposting of agro-industrial processing waste. *Biotechnology for Agro-Industrial Residues,* 431-456.

Gevao, B., Mordaunt, C., Semple, K. T., Piearce, T. G., & Jones, K. C. (2001). Bioavailability of nonextractable (bound) pesticide residues to earthworms. *Environmental science & technology*, *35*(3), 501-507.

Gunya, B., Masika, P.J. (2021). *Eisenia fetida* worm as an alternative source of protein for poultry: a review. *International Journal of Tropical Insect Science.*

Hay, J. C., & Kuchenrither, R. D. (1990). Fundamentals and application of windrow composting. *Journal of Environmental Engineering*, *116*(4), 746-763.

Hickman, Z. A., & Reid, B. J. (2008). Earthworm assisted bioremediation of organic contaminants. *Environment International*, *34*(7), 1072-1081.

Hoornweg, D., & Bhada-Tata, P. (2012). What a waste: a global review of solid waste management.

Hussaini, A. (2013). Vermiculture bio-technology: An effective tool for economic and environmental sustainability. *African Journal of Environmental Science and Technology, 7(2),* 56-60.

Jadia, C. D., & Fulekar, M. H. (2008). Phytoremediation: The application of vermicompost to remove zinc, cadmium, copper, nickel and lead by sunflower plant. *Environmental Engineering & Management Journal (EEMJ)*, *7*(5).

Kale, R. D., & Bano, K. (1986). Field trials with vermicompost-an organic fertilizer. In *Proc. Of National Seminar on 'Organic Waste Utilization by Vermicomposting'; GKVK Agricultural University, Bangalore, India*.

Kale, R. D., & Karmegam, N. (2010). The role of earthworms in tropics with emphasis on Indian ecosystems. *Applied and Environmental Soil Science*, *2010*.

Karthikeyan, P., Sathiya, G., & Kavitha, D. (2015). An ecobiotechnological approach for recycling of different solid organic wastes into useful products-A comparative study. *International Journal of Modern Research and Reviews*, *3*(3), 622-626.

Karthikeyan, M. (2008). Studies on vermireactor efficiency as a function of geometry. *M Phil Thesis*. Pondicherry University, Pondicherry.

Koont, S. (2011). Sustainable urban agriculture in Cuba. *Sustainable urban agriculture in Cuba*.

Kovshov, S. V., & Skamyin, A. N. (2017). Treatment of agricultural wastes with biogas–vermitechnology. *Environmental Earth Sciences*, *76*(19), 1-7.

Letchinger, M. (2000). Pollution and water quality, neighbourhood water quality assessment. *Project Oceanography*.

Markman, S., Guschina, I. A., Barnsley, S., Buchanan, K. L., Pascoe, D., & Müller, C. T. (2007). Endocrine disrupting chemicals accumulate in earthworms exposed to sewage effluent. *Chemosphere*, *70*(1), 119-125.

Medany, M. (2011). Vermiculture in Egypt: Current Development and Future Potential. *Food and Agriculture Organization of the United Nations Regional Office for the Near East Cairo, Egypt,* 1-20.

Minnich, J. (1977). *The Earthworm Book, How to Raise and Use Earthworms for Your Farm and Garden*. Emmaus, Pennsylvania.

Munroe, G. (2007). Manual of on-farm vermicomposting and vermiculture. *Organic Agriculture Centre of Canada*, *39*, 40.

Olle, M. (2019). Vermicompost, its importance and benefit in agriculture. *Journal of Agriculture Science 2,* 93-98.

Palm, C., Sanchez, P., Ahamed, S., & Awiti, A. (2007). Soils: A contemporary perspective. *Annual Review of Environment and Resources 32*, 99-129.

Pimentel, D., & Burgess, M. (2013). Soil erosion threatens food production. *Agriculture*, *3*(3), 443-463.

Rosset, P., & Benjamin, M. (1994). Cuba's nationwide conversion to organic agriculture. *Capitalism Nature Socialism*, *5*(3), 79-97.

Safwat, H., Shakir, H., & Weaver, R. W. (2002). Earthworm survival in oil contaminated soil. *Plant and soil*, *240*(1), 127-132.

Sanchez-Hernandez, J. C. (2019). Bioremediation of pesticide-contaminated soils by using earthworms. *Bioremediation of Agricultural Soils* (pp. 165-192). CRC Press.

Searchinger, T., Waite, R., Hanson, C. & Ranganathan, J. (2019). Creating a sustainable food future. *World Resources Report.*

Sherman, R. (2018). *The Worm Farmers Handbook.* White River Junction, VT. Chelsea Green Publishing.

Shi, Z., Tang, Z., & Wang, C. (2019). Effect of phenanthrene on the physicochemical properties of earthworm casts in soil. *Ecotoxicology and environmental safety*, *168*, 348-355.

Singh, A., Karmegam, N., Singh, G. S., Bhadauria, T., Chang, S. W., Awasthi, M. K., & Ravindran, B. (2020). Earthworms and vermicompost: an eco-friendly approach for repaying nature's debt. *Environmental Geochemistry and Health*, 1-26.

Singh, R.D. (1993) Harnessing the earthworm for sustainable agriculture. *Institute of National Organic Agriculture* 1-16.

Sinha, R.K., Agarwal, S., Chauhan, K., Chandran, V., Soni, B.K. (2010). Vermiculture technology: Reviving the dreams of Sir Charles Darwin for scientific use of earthworms in sustainable development programs. *Technology and Investment. 1 (2),* 155-172.

Sinha, R. K, Agarwal, S., Chauhan, K., Valani, D. (2010). The wonders of earthworms and its vermicompost in farm production: Charles Darwin's 'friends of farmers' with potential to replace destructive chemical fertilizers from agriculture. *Agricultural Sciences Journal.1 (2).* 76-94

Sinha, R. K., Bharambe, G., & Ryan, D. (2008). Converting wasteland into wonderland by earthworms—a low-cost nature's technology for soil remediation: a case study of vermiremediation of PAHs contaminated soil. *The Environmentalist*, *28*(4), 466-475.

Sinha, R. K., & Herat, S. (2012). Organic farming: producing chemical-free, nutritive and protective food for the society while also protecting the farm soil by earthworms and vermicompost–reviving the dreams of sir Charles Darwin. *Agricultural Science Research Journal*, *2*(5), 217-239.

Sinha, R. K., Herat, S., Chauhan, K., & Valani, D. (2009). Vermiculture & sustainable agriculture. *American-Eurasian Journal of Agricultural and Environmental Science*, *5*(S).

Sinha, R. K., Soni, B. K., Agarwal, S., Shankar, B., & Hahn, G. (2013). Vermiculture for organic horticulture: Producing chemical-free, nutritive & health protective foods by earthworms. *Agricultural Science*, *1*(1), 17-44.

Suhane, R. K. (2007). Vermicompost. *Publication of Rajendra Agriculture University, Pusa,* 88

Tomlinson, I. (2010). A rock and a hard place: Peak phosphorus and the threat to our food security. *London Soil Association*

United Nations Environment Program (UNEP). (1992). The contamination of food. *UNEP/GEMS Environment Library, No. 5.*

Van Grinsven, H. J. M., Ten Berge, H. F. M., Dalgaard, T., Fraters, B., Durand, P., Hart, A., & Willems, W. J. (2012). Management, regulation and environmental impacts of nitrogen fertilization in northwestern Europe under the Nitrates Directive; a benchmark study. *Biogeosciences*, *9*(12), 5143-5160.

Webster, K. A. (2005). Vermicompost increases yield of cherries for three years after a single application. *EcoResearch, South Australia*.

Werner, M. R. (1990). Earthworm ecology and sustaining agriculture. *University of California Sustainable Agriculture Research & Education Program*.

White, G. (1890). *The natural history of Selborne* (Vol. 24). Gibbings.

Yardim, E. N., Arancon, N. Q., Edwards, C. A., Oliver, T. J., & Byrne, R. J. (2006). Suppression of tomato hornworm (Manduca quinquemaculata) and cucumber beetles (Acalymma vittatum and Diabotrica undecimpunctata) populations and damage by vermicomposts. *Pedobiologia*, *50*(1), 23-29.

Zeb, A., Li, S., Wu, J., Lian, J., Liu, W., & Sun, Y. (2020). Insights into the mechanisms underlying the remediation potential of earthworms in contaminated soil: A critical review of research progress and prospects. *Science of the Total Environment*, *740*, 140-145.