Vermicomposting Biological, Environmental and Quality Parameters of Importance

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Vermicomposting is the low temperature (mesophilic) processing (composting) of fresh diverse organic matter by microorganisms and earthworms into a stable, uniform, nutrient rich soil amendment and nutrient source suitable for plant production. A goal of this presentation is to provide a foundation of knowledge helpful for further discussion about the design and operation of a wide range of vermicomposting systems and the use of vermicompost for maintaining soil and plant health (covered in separate documents). The principles presented here also apply to raising worms for sale.

My worm composting knowledge is primarily from a small scale and research perspective developed over the last four years so I am not an expert. When approaching vermicomposting I try to think like a farmer, livestock manager, biologist and horticulturalist. This introductory presentation is intended to: a) start at the beginning, b) find a balance between enough and not too much information, and c) develop a shared or common vocabulary and body of knowledge that improves communication of ideas.

Two main topic categories of information:

- Earthworm Taxonomy (type), Anatomy (appearance) and Biology (life cycle)
- Vermicomposting Environmental and Quality Parameters; importance and how to quantify

Worm Taxonomy (type), Anatomy, Morphology (appearance) and Biology (life cycle)

Taxonomy is the science of naming and classifying living organisms.

a. *Not just any earthworm will do.* While there are reportedly over 6000 species of earthworms, only 6 or 7 are used for vermicomposting. The type of worm used depends in part on the climate and temperature range. Worm selection varies from tropical (less than 23 degree latitude) to temperate climates.
b. *Eisenia fetida, Lumbricus rubellus, Eisenia hortensis,* and *Eudrilus eugeniae* are scientific names of worms commonly used for vermicomposting. These worms can also be used for bait worm production.
c. *E. fetida* can be used in a relative wide range of climates and is likely the most common worm used for composting. *E. fetida* is commonly called the composting worm, manure worm, red worm or red wigglers, which understandably leads to confusion.
d. *E. fetida* is an *epigeic* earthworm that is typically found in the litter or decaying organic matter near the soil surface, including animal manure on the soil surface. *E. fetida* are **not** permanent burrowing worms that make either vertical burrows (anecic) or horizontal burrows (endogeic) into the soil. That said, *E. fetida* can survive (although perhaps not thrive) in compost piles that are several feet deep.

Anatomy (internal structure and function) and Morphology (external appearance)

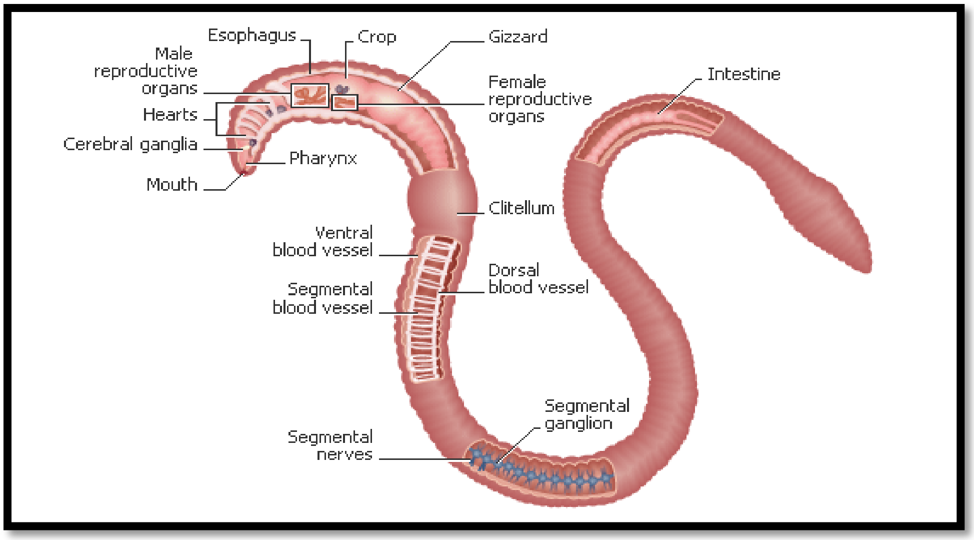

Diagram Source: http://www.reaps.org/compost/reproductive-system.html

a. Earthworms do not have lungs, instead oxygen is obtained through the body skin; therefore, water / moisture is important for gas exchange and active growth. A bedding moisture content of 60 to 90% is recommended. Worms can survive for several weeks in very wet or flooded systems if there is adequate oxygen.
b. The size of *E. fetida* will vary (small to large) depending on the food available and moisture content of the environment. A commonly provided figure is 1000 "average" size *E. fetitda* earthworms per pound with a range of from 500 large or 2000 small worms per pound. An *E. fetida* earthworm emerging from a cocoon will be 0.5 to 0.75 inch in length. The mature size can range from 2 to 6 inches with an average more like 3 to 4 inches.
c. The mouth opening or orifice is small and there are no teeth like structures to physically reduce the size of the material consumed. There is an internal "crop" or "gizzard" that aids in physical decomposition. The earthworms primarily consume decayed organic matter that has already been decomposed by microorganisms such as bacteria, fungi, protozoa, etc. Both living and dead microorganisms that are providing the decomposition are also consumed. So biological activity and a food web to provide decomposition are important to the success of the worms. The microorganisms are also influenced by moisture, temperature and oxygen availability. There is experimental evidence that the presence of earthworms increases the diversity of microorganisms present and biological decay.

Biology, Reproduction and Life Cycle

a. Earthworms are cold blooded meaning the body does not self regulate temperature and is typically the temperature of the surrounding media or environment. As for amphibians, low temperature means limited movement and activity (limited food consumption). Excessive heat is also damaging.
b. When environmental conditions are unfavorable or change rapidly, earthworms will migrate or "flee", even if the new "location" results in desiccation and death. Light is used to prevent migration.
c. *E. fetida* reproduces quickly when food and water are available and survives by leaving cocoons when food or water is not available. The cocoons can remain viable (alive) for months and years.
d. Earthworms are hermaphroditic, having both male and female organs, and exchange genetic material /sperm with a partner to reproduce. The "sperm" is stored and used to fertilize eggs over time.
e. Multiple eggs (2 to 4) are encased in a cocoon until the eggs hatch and the young worms emerge.
f. The presence of cocoons and newly emerged and young earthworms (variety of stages) during composting is an indication that the culture is healthy and the environment is favorable.
g. The presence of a band or clitella around the worm body indicates the ability to reproduce.
h. Reported time for cocoon to go from formation to hatching in favorable conditions: 4 to 6 weeks
i. Reported time that cocoon can provide protection in unfavorable conditions: months to years
j. Reported time to develop from emergence to maturity (producing young): 6 to 8 weeks
k. Reported time *E. fetida* will live, feed and reproduce in a favorable environment: 3-4 years
l. Reported that a mature earthworm can release up to 2 to 3 cocoons per week
m. Reported that in a worm bin the population can double about every 2 months.
n. Actual reproduction and population growth rates are typically much less than the maximum rates reported. A population has a form of reproductive regulation depending on environmental conditions.

http://northeastparkscience.wordpress.com/page/2/ http://www.vermica.com/articles/worm_birth.htm
(Left to right) 1. One pound of *E. fetida*; 2. Earthworms mating; 3. Cocoons of *E. fetida*, approximately 3-4mm diameter; 4. Earthworm emerging from a cocoon.

Environmental Factors to be Measured and Managed - Thinking like a biological farmer

As with any system of crop production or animal/livestock husbandry, a good place to start is learning about the variables that can be measured and managed to improve biological and physical conditions. Often farmers are given an "*optimum*" based on carefully controlled experimental environments and given the impression that they should strive for the "optimum". While knowing an optimum is helpful, what a famer also needs is a "*tolerable*" range and a "*target*" range that provides a high probability of experiencing economic success when environmental control is limited by minimal capital investment.

Descriptive Terms of Value:

- *Optimal* – usually a point or narrow range wherein "growth" or "productivity" is maximized.
- *Target* – a wider range where management options are considered to provide economic success.
- *Acceptable* – a slightly wider range with a focus still on increased input to get increased output.
- *Tolerable* – an even wider range that may be manageable if other input costs are reduced to account for a reduced rate of growth or productivity.
- *Unacceptable* – conditions unfavorable to worm development; worms are stressed and moving out.
- *Deadly* - the critical point, usually at both a low and a high extreme, that needs to be avoided.

Raising livestock often starts with the basics of providing Food, Air, and Water. From there, several other environmental criteria that can be measured and managed are identified and prioritized.

Vermicomposting occurs at low or mesophilic temperatures (60 to 90^{o}F). Thermophilic or hot composting occurs at higher or thermophilic temperatures (120-160^{o}F) due to the development of large populations of thermophilic bacteria. Many large scale commercial vermicompost producers support the proposal that the probability of success with vermicomposting is improved if one first develops experience and success with hot or thermophilic composting. The majority of the steps or processes have a similarity with both methods. However there are a few key differences that are critical to understanding successful vermicomposting and to the eventual differentiation and marketing of vermicompost compared to hot compost.

1. *Population Density* (What mass and how many earthworms?)
   a. Density is defined as a measure of the weight or mass of something per unit volume such as pounds per cubic foot (lbs/ft^3) or kilograms per cubic meter (kg/m^3). (1 lb/ft^3 = 27 lb/yd^3 = 16 kg/m^3)
   b. Livestock Density is usually reported as animals per unit area such as head per square feet or acre (43,560 square feet or about 208' x 208') or hectare (ha) (1 acre = 0.4 ha)
   c. Earthworm density can be expressed as either weight or number of organisms per unit of volume or area. It is most often described as pounds of organisms per square foot of bed surface area. The depth of the bed is often neglected or not reported and the worms are assumed to be in the upper 6 to 12 inches of material. However in less than ideal conditions and in loose, porous media, *E. fetida* can be found at depths of 12" or more.
   d. A commonly recommended minimum density for active composting is 1 pound of earthworms per square foot (ft^2) or ft^3. Very active vermicompost beds or systems may have 2 to 3 pounds of earthworms per square or cubic foot.
   e. A commonly provided estimate is 1000 "average" size *E. fetitda* earthworms per pound with a range of from 500 large or 2000 small worms per pound.

2. *Bedding and Feed - carbon, nitrogen, minerals, quantity*
   a. Vermicomposting *feedstocks*, particularly at the small scale and with use of bins, have been classified as either "bedding" (often newspaper) or "feed" (often food scraps). The earthworms are established in a large volume of bedding and feed is added routinely in small quantities. One reason for the gradual addition of feed is to prevent the heating (thermophilic composting) that can occur. For commercial production in larger scale systems, bedding and feed materials are often mixed at ratios that allow heating, and then allowed to cool before being supplied to the vermicomposting system. Regardless of the method, it is reasonable to consider most bedding materials as similar to "brown" or "carbon" materials used for hot composting and to consider most feed materials as similar to "green" or "nitrogen" materials for hot composting.

b. An operator/owner of a successful large scale flow through dairy manure vermicompost operation offered some good advice. He recommended that it was very important to not think of the worms as a waste disposal system that could survive on whatever was provided as feed. (Although they will likely survive.) Instead a key factor for long term success of raising bait worms or vermicomposting is to think of the earthworms as livestock that require a balanced diet. Like humans or livestock, worms can survive for an extended time with less than a balanced diet, but not forever. The more balanced the diet the better expectations for the worms and the worm compost. This is consistent with the view that the overall inputs made with bedding and feed must be balanced from a carbon to nitrogen perspective as with thermophilic composting. Providing complete mineral balance of all the essential nutrients is also important.

c. Categories of classification of bedding and feed materials:
    i. Carbon forms: sugar, starch, (*Feed/ available) or* cellulose, lignin (*Bedding/slow*)
    ii. Nitrogen forms: nitrate, amino acids DNA, protein (*Feed*); nitrogen is often a limiting factor for growth of biological systems. It also varies greatly in compost feedstocks. The amount of nitrogen present in the final vermicompost will likely have the largest impact on how the vermicompost is used for growing plants.
    iii. Carbon to Nitrogen Ratio (C:N):
        1. All organic materials will have both carbon and nitrogen, just in different amounts.
        2. C:N ranges from 10-15:1 in stable finished compost to 25-50:1 as recommended starting point for compost.
        3. Nitrogen rich hay can be from 15-20:1 C:N which will release nitrogen during decomposition and is referred to as a “green” feedstock.
        4. Straw can be 60-100:1 C:N which will require nitrogen for rapid decomposition to occur and is referred to as a “brown” feedstock.
        5. A general recommendation is that materials with a C:N of less than 30:1 will be able to release nitrogen (greens) and with more than 30:1 will require or remove nitrogen for decomposition (brown).
        6. The mixing of browns and greens, often at a ratio of 2 or 3 browns to 1 green by weight (or volume if the density is similar), is used to attain the desire C:N ratio.
    iv. Minerals – 13 to 18 essential minerals with a wide range of concentrations

d. Compost and Plant Tissue Testing Methods are important to characterize C, N and minerals.
    i. Total nutrient analysis – a dried sample of the compost is combusted resulting in ash that is dissolved in dilute acid and then analyzed. Same method used to analyze plant tissue.
    ii. Soluble nutrient analysis – a moist sample of the compost is mixed with water to form a slurry. The pH is measured in the slurry and then the solution is extracted and tested for soluble salts (EC) and specific ions. (Saturated media extract or SME)
    iii. Kjeldahl nitrogen – a sample of the compost is digested in sulfuric acid and all the nitrogen is captured and the concentration determined.
    iv. Organic matter and carbon – a sample of the compost is combusted and the weight of the resulting ash is determined and used to estimate the amount of organic matter. The organic matter is assumed to be a certain percent carbon and carbon is calculated.

e. *Carbon (generally Bedding)* – Humans and most animals digest sugars, starch and protein (these are food sources of carbon) but not cellulose and lignin also known as “fiber” (these are usually bedding sources of carbon). Ruminants (cows, sheep, goats, llamas) have multiple stomachs and bacteria in the digestion systems which digest cellulose and lignin. There are also free living organisms including fungi that decompose cellulose and lignin which often leads to the production of humus (long term stable soil organic matter).
    i. To provide favorable conditions for the earthworms and microorganisms, the bedding provides a source of carbon for the decomposition process, as well as structure for holding water and allowing gas exchange.
    ii. Examples of bedding materials suitable for on-farm worm composting include:
        1. aged leaf mold; ground or shredded leaves from a lawn mower
        2. shredded office paper or news paper; shredded cardboard; paper towel
        3. straw (wheat, oat, spelt, rice, etc), chopped if possible; rice or spelt husks
        4. stable high carbon compost that is not high in soluble salts (less than 1.5 (1:2) or 3.0 (SME) mS.

        5. Coconut coir and peat moss also provide valuable structure if available and economically justified; which is the case if the compost is sold for $1 per pound or more. However, they are better considered as neither a carbon or a nitrogen since the breakdown would be very slow. The cost of peat or coir is perhaps more justified when raising worms for bait than when producing compost.
        6. horse manure works very well, both as a bedding (carbon) and as a feed source (Nitrogen). C:N is about 30:1 if urine is not mixed with the manure.
    - iii. When worms are moved from one type of bedding to another type of bedding, there is usually an adjustment period to the new environment. Take steps to avoid drastic changes in short time periods. If possible allow the worms to move gradually.

f. *Soluble carbon and Nitrogen (Feed)* – The microorganisms in the bedding and vermicompost will use sugars, starch and protein as quickly available feed sources. Protein will also provide nitrogen, which is the mineral or element normally required in the largest quantity for active plant/biological systems. Nitrogen is supplied by the protein of decomposable organic matter or urine in manure, which are comparable to the "greens" of hot composting.
    - i. An important factor is not adding too much feed and not adding it in a way that will cause thermophilic composting or heating that can kill the worms. Heating is more of a concern in small containers or piles where the worms cannot move away from the heat.
    - ii. The *size* of the pieces of feed will also impact the rated of decomposition with smaller breaking down faster. Pineapple and melon skins as cut off will decompose much slower than if put through a garbage disposal or pulper first. The same for garden or farm organic matter that has been chopped or ground first. An example that has been used is how a tree will take decades to decompose, the tree ground to chips will take less than a decade to decompose, and a tree made into saw dust might decompose in a few years.
    - iii. Examples of feed materials include:
        - (a) Specifically prepared earthworm feed particularly for bait worms will contain ground corn, oats, wheat and other grains or bran similar to a layer or chicken feed. Prepared worm feeds are not recommended for routine vermicompost production. (See NCAT/ATTRA publication Worms for Bait or Processing, pg 6).
        - (b) farm manure without urine (dairy, beef, pork, horse, sheep, llama, alpaca); dairy manure from cement floors with combined feces and urine have more nitrogen, poultry manure in small quantities due to the high nitrogen content since the feces and urine are combined;
        - (c) hay, leafy green matter, vegetable and fruit scraps from food processing facilities or homes, institutions, restaurants or grocery stores; uncooked preconsumer kitchen preparation scraps.
        - (d) Unused prepared foods or post consumer food waste such as plate scrapings may contain cooked food, animal products (meat, fat, bones, etc) and or dairy products, which contain more protein and may be more difficult to compost.
        - (e) either purchased or expired/spoiled grain, animal feed or seeds including beans, wheat, oats, corn, rice, etc (whole or ground – rate influenced by size)
        - (f) brewery waste – spent grain / seeds, good nitrogen source; allow for dissipation of alcohol which is detrimental to earthworms.
        - (g) coffee grounds – ground up coffee seeds, good nitrogen source

g. Premixed Bedding & Feed Systems
    - i. Starting vermicomposting with small home bin systems leads to thinking of separate bedding and feed approach. However, in many cases for larger scale systems a mixed precomposted material that serves the function of both bedding and feed is more practical to manage in larger quantities.
    - ii. Flow through or angled wedge composting systems are routinely supplied with a mixture of materials that provide both the function of bedding and feed; for example precomposted dairy manure that has been mixed with straw bedding or low quality hay.
    - iii. Another example of a mixed system are batch systems with a pile or windrow of feedstock that is inoculated with worms and then not fed again

h. Mineral Elements necessary for microbes, plants and animals
    - i. Measured as the percent (%) or the parts per million (ppm) present in a mixture. For conversion purposes, a 1% concentration is equal to 10,000 ppm.

   ii. Specific minerals needed for vermicomposting are similar as for any other living organism:
      1. Nitrogen (N_2, NO_3^-, NH_4^+, NH_3(gas))
      2. Phosphorus ($H_2PO_4^-$) (rock phosphate or brown rock phosphate)
      3. Sulfur (S, SO_4^{--}) (elemental or potassium sulfate or calcium sulfate)
      4. Potassium (K^+) (potassium sulfate)
      5. Calcium (Ca^{++}) (lime or calcium sulfate)
      6. Magnesium (Mg^{++}) (dolomitic lime, potassium magnesium sulfate)
      7. Iron, Manganese, Zinc, Copper (divalent cations – positive charge) (Azomite as a source of micronutrients- “A to Z of Minerals Including Trace Elements”)
      8. Boron, Molybdenum, Chloride (anions – negative charge)
      9. Silicon, Nickel, others
   iii. Minerals can be measured or quantified from at least 4 perspectives
      1. Intensity - ppm or soluble salts immediately available
      2. Capacity – insoluble, reserve, buffering or cation exchange capacity of the medium or soil that can hold nutrients not in solution
      3. Balance – relationship or ratio to other minerals, for example, 60-85% Ca, 10-25% Mg, and 5 to 15% K
      4. Availability – as influenced by pH and solubility in water

i. How is the amount of feed determined or measured?
   i. Overfeeding is cited as a common error of new worm farmers.
   ii. Traditionally feed is quantified in weight of food per unit weight of worms or weight per square foot of surface area if the population density can be estimated or measured.
   iii. Recommended feeding rates range from 30% to 100% of the weight of the worms present added per day. However, as noted below there are several variables that affect the rate.
   iv. Recent recommendations are for only 30 to 40% of the weight of the worms present.
   v. While rates are given in weight per day, feeding is usually not done daily. Feeding is done when the previous feeding has been decomposed and consumed, usually after 2 to 4 days in flow through systems and perhaps after 1 to 2 weeks in angled wedge or bed systems.
   vi. There are a variety of feeding methods:
      1. Some feeding systems provide a given weight of fresh feed to an existing bed of “bedding” at a regular time interval or based on appearance of previous food;
      2. Some systems provide a dose of mixed “food/bedding” at a regular time interval;
      3. Some start with a batch of mixed “food/bedding” and compost it for a certain period of time with no additions of food or bedding.
      4. For organic certification, feeding or vermicomposting must occur for a specified time (from 2 to 6 months based on system) with no additional fresh food added.
      5. All methods recommend a thin (1 to 2”) or light feeding more frequently as opposed to a larger feeding at less frequent intervals. Most recommend feeding only a portion of the bed so worms can move away from the added feed.
   vii. ***Moisture Content as a commonly uncontrolled variable*** – current recommendations do not appear to take into consideration the moisture content of the feed. For example, 100 lbs of feed at 50% moisture (50 lbs dry feed) is twice the amount of food as 100 lbs of feed at 75% moisture (25 lbs dry feed). The energy or caloric value of the feed is also quite different from fruit and vegetable preparation scraps compared to grains such as corn or oats.
   viii. ***Particle size of the feed material is another often uncontrolled variable.*** Large pieces will decompose much smaller than something that has been powdered (floured) or pureed. Some worm farmers focused on bait production may use flour rather than grain and puree rather than fruit and vegetable scraps. The small particles decompose much faster and can potentially be directly ingested as opposed to requiring initial decomposition by bacteria. Grinding will speed up composting, but adds cost of both labor and usually fossil fuel energy. Precomposting reduces the size of the feedstock, and reduces the food value for the worms.
   ix. Nitrogen and mineral content is another uncontrolled variable - the protein and food value of 100 pounds of fruit and vegetable processing scraps that are 90% water will likely be much different than 100 pounds of dairy manure and definitely different than 100 lbs of grain or seed based food such as rice. The resulting compost will also be quite different in regards to the effect on plant growth and the acceptable use rate. When being sold commercially,

vermicompost needs to be labeled / characterized by the feedstock, for example dairy manure vermicompost, or food scrap vermicompost.

j. Precomposting (hot composting) is not necessary for many dry or stable feeds, but for animal manure and pre or post consumer food scraps, precomposting is an effective way to stabilize moisture, minimize possible undesired biology such as seeds, insects, plant pathogens or human health related pathogens, and to minimize potential odors.
k. For vermicompost production intended for organic production, manure or other feedstocks with possible human pathogens must be precomposted according to NOP requirements or the vermicompost can only be used as fresh manure.

3. *Aeration: Oxygen and Carbon Dioxide*
   a. Oxygen (O_2) concentration in air or water is reported as the percent (%) of O_2. O_2 in the atmosphere is near 21%. Levels as low as 20 to 19.5% can be dangerous for humans. O_2 in the air of an active compost pile can be as low as 2% which is considered *anaerobic*. *Acceptable* levels are 5 to 10% and >10% is considered *optimal*. A key reason for shallow beds for vermicomposting is to facilitate oxygen diffusion.
   b. For composting, oxygen availability is often determined by the depth of the bedding and the amount of moisture and feed. Too deep (>15-18"), too wet (>90% moisture) can be a problem due to slowed diffusion of the gas from the bedding. Too much decomposing food in a closed space can lead to low oxygen because of depletion of oxygen and production of carbon dioxide.
   c. The particle size and arrangement of the bedding and feed will also impact oxygen availability. Larger particles that prevent compaction allow for greater oxygen movement, particularly during the early rapid period of decomposition. Wood chips or straw can reduce compaction.
   d. In a closed container or environment with no mixing of air, carbon dioxide is heavier than air and may settle and be at a higher concentration at the bottom.
   e. Conditions that favor decomposition of organic matter – warm and moist – also favor biological activity of microorganisms that are generally using oxygen. If the oxygen gets low, some microorganisms can still survive without oxygen, but earthworms cannot.
   f. Oxygen measuring or monitoring equipment is not readily available or affordable nor is it easy to use. The Woods End Laboratory provides the Solvita compost testing system which quantifies the amount of carbon dioxide developing from a compost sample. Reduced carbon dioxide emission is used as an indicator of compost maturity and reduced biological activity.
   g. The solubility of oxygen in water decreases as the temperature of the water increases, which is contrary to what happens with the solubility of salts in water. High temperature water has less oxygen and high temperature can make the effect of low oxygen worse.
   h. Providing for gas diffusion or movement is an important part of system design. Carbon dioxide is heavier than air and can settle in low spaces if there is no air movement or mixing.

4. *Moisture (water)*
   a. Moisture content is reported as the percent (%) water weight as a fraction of the total wet weight of the bedding. For example, if 100 pounds of moist/wet bedding is dried, and the dry weight is 50 pounds, the moisture content is (100 lbs wet – 50 lbs dry) divided by 100 lbs wet or 50%.
   b. One gallon of water is 8.3 pounds (a pint is a pound the world around). (8 pints per gallon).
   c. *Acceptable* bedding moisture for earthworms is 60 to 90% with a *target* range of 70 to 80%. High moisture also impacts the biological activity of microorganisms such as bacteria and fungi.
   d. Worms can be submerged in water for some time (days) if there is enough oxygen in the water.
   e. 80% moisture corresponds to 100 lbs of wet bedding drying down to only 20 lbs of dry weight.
   f. From a different perspective, if you have 10 lbs of very dry material, such as paper, leaves or grain, the amount of water to moisten to around 80% would be around 40 pounds, 4 times the weight of the dry material. That would be close to 5 gallons of water. The absorption of an additional 40 lbs of water would be necessary to increase the moisture content from 80 to 90%.
   g. In general soak dry material in water and then allow draining before adding to the bed or mixture. Add dry material if the moisture content is already too high and absorbing excess is needed.
   h. Fresh kitchen preparation food scraps are typically 80 to 90% moisture so can be combined with drier materials.

i. In general excess water or “leachate” should not drain from beds or bins. The leachate would carry away valuable minerals and soluble organic matter.
j. A method of estimating moisture content in compost is to use a “squeeze test”. The bedding and or composting material should be moist enough (60 to 80%) so that some free water can be squeezed out as if squeezing water from a sponge. If moist bedding is squeezed in a fist and the material holds together but no water drips out, the moisture content is likely in the 50 to 60% range. If the moist bedding is squeezed and when opening the hand the material falls apart, the moisture content is likely in the 30 to 45% range.
k. Inexpensive moisture meters are generally of limited value. Test the meter by placing the probe in purified or distilled or reverse osmosis water. It is likely that the meter will read 0% moisture. Soluble salts (see below) influence the meter reading.
l. Water quality or the amount of dissolved minerals and alkalinity in the water can possibly impact the vermicomposting process. Chlorinated water is not likely a concern. Softened water will be replacing desirable Ca and Mg in hard water with sodium (Na) so is not recommended. The bicarbonate alkalinity common in the Midwestern US with limestone aquifers will gradually contribute to an increasing pH but is not anticipated to be concern. Rain water is often mentioned as an acceptable alternative when there are concerns.
m. Suggested moisture content for holding or storing finished vermicompost with no earthworms is 30 to 50% moisture content. Moisture content is an important consideration if selling worm compost by the pound. Since moisture content and therefore weight can be variable and hard to maintain, some choose to sell by volume and not weight.

5. *Temperature*
   a. Temperature is measured in degree Fahrenheit (^oF) or Celsius (^oC).
   b. To date a graph or curve of earthworm biological activity with a change in temperature has not been identified or found in the literature. Many biological organisms show a doubling in metabolic activity as the temperature increases 20^{o}F or 10^{o}C. For example, a doubling may occur when the temperature increases from 50^{o}F to 70^{o}F. Minimum and maximum temperatures also need to be identified.
   c. *E. fetida tolerate* 40 to 90^{o}F; with a reported *acceptable* temperature range of 60 to 80^{o}F and a *target* range of 65^{o}F to 75^{o}F. Low composting activity is expected at 40 to 50^{o}F. Many authors report heat stress at 80 to 90^{o}F but others have reported high activity at 95^{o}F. The tolerable high temperature is likely influenced by the amount of moisture and oxygen present. High temperature can increase activity of bacteria that may also influence earthworm survival.
   d. As a cold blooded organism, worms are generally the temperature of the surrounding environment. In cold conditions worms will move towards a warmer space. With excessive heat worms will also move away as long as there is a place to move to. *Providing room for worms to move away from high temperature is an important method of minimizing risk. It is recommended to feed only along one side or part of a bed so earthworms can move into the feed when the temperature is right. Earthworms fed with a top layer should be able to move down if necessary.*
   e. High temperature (greater than 90^{o}F) can also reduce the solubility of oxygen in water and therefore aeration. The low oxygen may be a key part of high temperature stress.
   f. The worms and or the cocoons appear to survive some freezing conditions. Gradually lowering temperatures allow for adaptation or *acclimatization* and therefore a greater chance of survival. *E. fetida* also appear to cluster together in bedding near freezing temperature. We have seen worms moving about in bedding with ice crystals. Information is available for how to help composting worms survive in outdoor systems by providing insulation or heat from composting.

6. *Light*
   a. Light intensity for human eye sight is commonly measured in foot candles *(fc)* with full summer sun mid day about 10,000 fc, winter cloudy weather about 2000 fc, bright indoor lighting about 500 fc, bar room light less than 100 fc and bright moonlight less than 2 fc.
   b. Bright light (greater than 2000 fc?) reportedly can induce a paralyzed state so exposure to bright light must be minimized. If your hand casts a shadow, the light is intense for the worms. This is more of an issue working in a greenhouse or outside then working in a building or under a roof.

   c. Light can carefully be used to drive worms lower into the bedding or compost as a method of removing them from the compost.
   d. Low intensity light (10 to 50 footcandles?) can also be used to help keep worms from moving out of the bedding when not desired.
   e. Shade can help to decrease bedding temperature, for example a cardboard or loose hay cover.
   f. While enclosed buildings or structures are normally recommended because darkness is preferred, our research at MSU is in an unheated greenhouse to test the lower cost structure as an option. We use shade fabric and tarps to reduce light and heat in the summer and clear covers to increase light and heat in the winter.

7. *Bedding and Feed pH*
   a. pH is often defined as the acidic or basic condition of a solution or soil that influences nutrient availability / solubility.
   b. More importantly, pH is a measure of positive (H^+) or negative (OH^-) ions in the water (H_2O) that influence what minerals and gasses will or will not dissolve in the water. Only a very small amount of the water exists as H^+ or OH^- (0.0000001 molar H^+ at pH of 7 compared to 55 molar H_20). Under low pH or acidic conditions (pH 4 to 6) there is an excess of H^+ and under high pH or basic condition (pH 7.5 to 9) there is an excess of OH^-.
   c. The pH is measured either using a colorimetric system such as *litmus paper* or using a *pH meter* and electrode. An alternative is to send a sample to a lab for analysis. A pH meter can be purchased from www.specmeters.com .
   d. Red worms seem to *tolerate* pH 4 to 5 (acidic- more H^+) to pH 8-8.5 (basic- more OH^-), at least for short periods of time; the *target* range provided in the literature is pH 6 to 7.
   e. Bedding pH can be lowered by adding sphagnum peatmoss (acts immediately) or finely ground powdered (or prilled) elemental sulfur (acts over weeks in warm soil or months if soil is cold).
   f. Bedding pH can be raised by adding lime (calcium carbonate) or much smaller amounts of wood ashes which are very reactive and are better if first mixed with water or bedding components and allowed to stand for several days before using.
   g. Certain feedstocks are often reported to be acidic or acid forming, such as leaves or coffee grounds or citrus, but evidence to support these claims is not readily available and often such claims are not reliable or true in all cases.
   h. The pH of irrigation water is not very important for farming systems. What is important is that water can geographically vary dramatically in the amount of dissolved lime or bicarbonate (alkalinity) and the amount of calcium and magnesium (hardness). Water from limestone aquifers (Midwest) has high alkalinity and hardness and water from granite aquifers (east coast) has low amounts of alkalinity. The alkalinity in water can act like lime when applied to soil or plant growing media.
   i. The initial phase of hot composting often results in an increase in pH to 8 or 8.5. As compost matures the pH declines, but the change typically takes weeks to months.
   j. Most of the food scrap vermicomposts made at MSU are high pH (7.5-8.3) when we extract the earthworms. The pH generally declines while the moist vermicompost is stored.
   k. Managing pH is important for managing ammonia as described in the next section.
   l. The initial stages of thermophilic (hot) composting often result in an increase in pH that can be in the 8.0 to 8.9 range resulting in release of gaseous ammonia.

8. *Ammonia*
   a. Ammonia (NH_3) is a gas that is toxic to living organisms at low concentrations. Anhydrous ammonia has been injected into the soil as a fertilizer but doing so is clearly not considered a good idea for biological or ecological farming (including for the worms in soil if present).
   b. Measured or reported in parts per million (ppm)(1 ppm= 1 milligram per liter) (1% concentration equals 10,000 ppm). As little as 5 ppm (5 milligram per kilogram) can be smelled by the human nose. It is not clear what concentration is toxic to worms but the recommended level is less than 0.5 ppm. Electrode type equipment to measure ammonia is not relatively available or affordable. ***If your nose can detect it, the level is too high.*** Woods End Laboratory provides the Solvita soil health and compost maturity test to quantify ammonia from compost samples. The method is simple and affordable ($10-15 / sample) if ammonia needs to be quantified. (http://woodsend.org/)

   c. NH_3 gas usually results when ammonium (NH_4^+) ions in solution are present as a form of nitrogen resulting from the breakdown of proteins and amino acids and the pH is above 8.0. The ammonium is taken up by plants or converted to nitrate (NO_3^-) and is not nearly as toxic or a concern as the ammonia. Prevent ammonia by lowering the bedding pH with peat or sulfur.
   d. Ammonium is common in fresh manure or animal urine. If the ammonium is present at high concentrations and the pH of the bedding/ medium/ compost is high (greater than 7.5), ammonia gas can form. In general the higher the pH above 8, the more ammonia. Reducing ammonia is a key reason for precomposting manure or high protein materials.
   e. Ammonia gas can dissipate or disperse and not be toxic to earthworms. The concern is greatest when containers are closed or air movement is restricted.

9. *Soluble Salts (electrical conductivity – EC)*
   a. Salts are made up of cations (positively charged atoms or molecules) and anions (negatively charged). For example sodium chloride is composed of Na^+ cations and Cl^- anions.
   b. Soluble salts are usually measured by testing the electrical conductivity (EC) of the bedding or medium and the units of measure are usually mS/cm or millimhos/cm. The higher the salts the more electricity conducted. If there are no salts as in purified water or rain water the electrical conductivity is zero. The reported mean conductivity of sea water is 3.27 mS/cm
   c. Soluble salts may also be reported in ppm or %. A general rule is that a 1% solution (concentration) is equal to 10,000 ppm. So if a literature reference states a limit of 0.5% soluble salts, that would suggest 5000 ppm which would be an EC of approximately 7 to 10 mS/cm (SME) depending on the salts present.
   d. An electrical conductivity meter can purchased from www.specmeters.com . Expect to invest a minimum of $100 for a basic meter and up to $300+ for a good meter. A direct read probe has some advantages but readings with direct read can be variable depending on moisture content.
   e. The EC of the bedding can be measured directly if enough moisture is present but typically is measured in a saturated medium extract (SME) (close to a 1:1 dilution of dry medium with purified water), or 1 part media to either 2 parts water or 5 parts water. The same media measured with the four methods might have an approximate EC of: Direct: 5.0 mS; SME 3.0 mS, 1:2 dilution 2.0 mS and 1:5 dilution 1.0 mS. Know what method was used.
   f. To help provide some perspective, I dissolved commercial sea salt in purified water and got the following results: ¼ tsp per quart – 3.1 mS; ½ tsp – 6.2 mS; ¾ tsp – 9.35 mS, 1 tsp – 12.1 mS. A 1000 ppm (mg/liter) or 0.1% solution of sodium chloride has an EC of 2 mS/cm.
   g. When there is an excess of soluble ions present, living organisms are unable to remain hydrated with adequate water.
   h. Soluble salts usually accumulate over time if there is no rainfall to wash them away.
   i. It is not clear just how high an EC earthworms can tolerate. A starting recommendation is to have the EC below 5 mS/cm with a saturated medium extract or below 2.5 with a 1 medium to 2 water (1:2) dilution. Some of our finished worm composts have had EC in the range of 5 to 10 with the highest at 10 to 12 mS/cm (SME method). However, the EC continued to increase after the worms were removed due to biological maturation of the compost.
   j. In parts per million (ppm) the critical salt concentration may be around 2500-5000 ppm. The critical level will depend on the salts present with Na^+ or Cl^- being more toxic than K^+ (potassium), Ca^{++} (calcium), Mg^{++} (maganesium) or $H_2PO_4^-$ (phosphate).
   k. Cooked or prepared food waste may be (often is) higher in Na and Cl which will impact the EC and likely the worms. Our experience is with preconsumer kitchen preparation scraps salt is not an issue.
   l. A flow through or angled wedge system where the worms are moving into fresh material will have few problems with excessive EC compared to a bin or batch system where the EC will accumulate overtime and likely limit the growth of earthworms not continually moving into fresh bedding.

10. Bulk density (BD) of bedding or compost
    a. BD is the weight per unit volume (pounds per ft^3; pounds per yd^3 (27 ft^3) or grams per cubic centimeter (g/cc); 1 gram per cubic centimeter (g/cc) equals 62.43 lbs/ft^3 or 1685.6 lbs/yd^3.
    b. BD of feedstocks and bedding will give an indication of how earthworms will be able to move and oxygen will be able to diffuse through the bedding. Lower BD is better.

c. Bulk density of finished vermicompost can be used as in indicator of the amount of organic matter and or mineral soil that is in the compost. A range of 8 to 16 lbs/5 gal (0.2 to 0.4 g/cc) dry or 16 to 32 lbs at 50% moist is a starting range. Buyers paying per lb of vermicompost do not want to pay for sand or soil in place of compost.
d. The volume of a yd^3 (cubic yard) is equal to 40, 5 gallon buckets. The weight of a 5 gallon bucket of compost can be multiplied by 40 to estimate the weight of a yd^3 of the same material.
e. Dry peat based potting media typically have a bulk density of 0.13 to 0.15 g/cc or 8.1 to 9.4 lbs per cubic foot or 219 to 253 lbs per cubic yard. Dry mineral field soil is typically reported as a bulk density of 1.33 g/cc or 83 lbs per cubic foot or 2242 lbs per cubic yard. Compost is typically reported as a bulk density of 0.59 g/cc or 37 lbs per cubic foot or 1000 lbs per cubic yard at 40 to 50% moisture. The dry BD would then be about 0.3 g/cc or 400 to 500 lbs /yd^3.
f. The addition of soil at 10% by volume to compost can increase the BD by 50%.
g. Nutrients are reported in some soil tests as part per million. If the material is twice as heavy per unit volume, the amount of nitrogen on a percent basis is half as much but the difference on a volume basis is negligible. ***This is very important for evaluating the nutrient value of compost.***

11. Microbial Activity and Diversity
   a. The rate of microbial activity is measured by the amount of carbon dioxide (CO_2) that is produced by or lost by a sample of compost or vermicompost. More CO_2 shows more activity. CO_2 evolution can be measured using the Solvita compost quality test from Woods End Laboratory.
   b. Temperature can also be a measure of microbial activity, but the temperature of a pile is influenced by the size of the pile and the amount of insulation that prevents cooling. In vermicomposting the pile is kept small / thin so heating due to bacteria does not occur.
   c. Determining the diversity, type and density of microorganisms present is a valuable aspect of characterizing compost. However, tests are costly and not readily available. Most compost and or vermicompost producers do not characterize microbiology during composting or in finished product.
   d. Desired characteristics: balanced diversity of bacteria, fungi, nematodes and actinomycetes.
   e. One option is using a microscope but equipment is high cost and method requires training.
   f. Another option is to send samples to a lab. The cost can be as much as $100 per sample. An example lab is Woods End Laboratory or The Soil Food Web Lab.
   g. Researchers can use an assay that estimates what organisms are present based on what food sources are digested. The cost for this analysis is in the range of $10 per sample in a laboratory setting. The test takes several days to complete.
   h. In one research report, the diversity of organisms increased during vermicomposting due to the effect of the worms, and then decreased soon after the worms were removed. In comparison, the microbial diversity of hot compost decreases during composting then increases after.

12. Time: Compost Maturity and Quality
   a. Hot compost is considered *stable* when the temperature drops below 100^oF and carbon dioxide evolution decreases. Is there a similar measure or term for vermicomposting?
   b. Maturity is a measure of reduced carbon dioxide and increased biological diversity that usually is associated with a falling pH and increasing nitrate and soluble salts. While stable compost can be produced in a week or up to several months depending on the amount of turning and management, maturity cannot be rushed or hurried and takes additional weeks or months.
   c. Maturity is important when compost is used for starting seeds and growing container plants. A seed germination “bioassay” is an easy way to test compost maturity and quality.
   d. The length of time from start to finish (days or months) is generally cited as less or shorter for vermicomposting compared to hot composting. A primary reason cited for the difference is that vermicompost can be used immediately after harvesting. While it can clearly be added to growing plants or used to make compost water extracts, can it be used to germinate seeds immediately after harvest? I do not have an answer to that question yet. All our vermicomposts have been stored for several months before sale or use.
   e. How long does vermicomposting take? One example is that a well managed flow through system takes approximately 60 days depending on the rate of vermicompost extraction.

f. For organic certification, vermicomposting time minimums are provided: indoor flow through – 2 months; indoor container or angled wedge systems – 4 months; outdoor windrows – 12 months. The assumption is that this is the time from the last addition of feed.

g. The rate of vermicomposting is dependent on the population density and most of the other factors covered previously. ***The organic certification rules or recommendations do not specify worm density which is a major flaw in the rule that needs to be corrected.***

Summary and Conclusions

- Vermicomposting does not have to be this detailed, "scientific" or exact to be successful. However, quantifying and measuring variables can help take the guess work out of farming and can reduce the risk of monetary loss (increase the probability of success). It can also increase the probability of producing a high quality consistent product from year to year.
- Worms can be treated as other farm animals in an integrated biological system that require specific conditions to thrive and can tolerate a wide range of conditions to survive.
- Understanding and practicing hot composting will likely improve efforts focused on vermicomposting.
- *Not all compost is the same*. A key concern about all farming and gardening practices concerning the use of compost and or vermicompost is that *often all compost is considered the same*. The mineral and organic matter content of compost and vermicompost can vary dramatically and thus the effect on soil microorganisms and plant growth will vary as well. To sell a high cost product you need a high value consistent, uniform, reproducible quality product.
- Composting influences mineral availability, but cannot create minerals that are not initially present in the feedstocks. Dairy manure vermicompost is not the same as food waste vermicompost.
- The biological organisms and complex organic compounds (such as humic acid) that develop during worm composting are very important to the value of the worm compost. Characterizing and quantifying them is an important topic for future presentations.
- Using the information presented here to design and manage vermicomposting systems is the topic of a separate companion publication.

A work in progress - keep it simple and integrated.

Parameter	Tolerable	Acceptable	Target
Population Density	?	0.5 to 3 lbs/ft^2 ?	1. to 2 lbs/ft^2
Food (lb/lb/day)	?	0.2 to 1.0 ?	0.3 to 0.5
Oxygen (%)	?	? %	> 15 %
Moisture (% wet)	50 to 95 % ?	60 to 90 %	70 to 80 %
Temperature (^{o}F)	40 to 90	60 to 80	65-75
Light (footcandles)	1000 ?	?	Dark
Bedding pH	4 to 9	5 .5 to 8	6 to 7
Ammonia (ppm)	< 0.5 ppm	less?	none?
Soluble Salts (mS)	< 8 ms (SME	< 6 mS (SME)	< 4.0 ms (SME)
Bulk Density (Dry)	8-16 lbs/5gal	?	?
Minerals (% - ppm)	?	?	Balanced
Microbiology	?	?	High/Active

Every attempt has been made to provide accurate information. However, this document in still a work under development and has not been professionally reviewed for accuracy.
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Vermicomposting Learning Based Groups or Opportunities:

- www.vermicomposters.org
- Linkedin vermicompost group
- http://www.redwormcomposting.com

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