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Factors Affecting the Quality and Efficacy of Compost Tea in Organic Agriculture

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Abstract: The water extract of compost termed "compost tea" retains all the beneficial soluble bioactive components, making it a potent source of plant stimulatory and defensive compounds. High quality compost refers to compost that is high in microbiological activity. Compost tea is made by two brewing methods; non-aerated method and aerated method. For both methods of compost tea production, microbial food may or may not be added. Numerous studies have demonstrated that composted materials and their resulting teas can provide manifold benefits as organic fertilizers in sustainable agriculture. Indeed, compost teas have been shown to suppress a wide range of soil-borne diseases when used as foliar sprays and soil drenches, thereby ultimately affecting plant growth and yield. The exact nature and extent of these features are, however, modified by composting system, feedstock quality, tea preparation and resultant use and management, including application dynamics of the compost tea. The purpose of this work is therefore to give an overview of the factors affecting the quality and efficacy of compost tea in organic agriculture. The objectives of this review are to identify the process, operational and environmental parameters that influence the quality and efficacy of compost tea, describe compost tea characteristics and quality assessment, and to summarize the current knowledge of compost tea application including; application methods, application rate and application time.、

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1. Introduction

Compost teas are brewed aqueous extracts containing soluble nutrients as well as useful compounds like metabolites and microorganisms such as bacteria, actinomycetes, filamentous fungi, yeasts and oomycetes, prepared by mixing compost in water in a specific ratio (Litterick *et al.*, 2004; Ingham, 2005). Producing and applying compost tea is a relatively new practice. It takes advantage of the high diversity of microorganisms and other valuable compounds found within compost. These substances and organisms have a synergistic effect on promoting plant growth and suppressing diseases. However, depending on the source material it is also possible that microorganisms pathogenic to plants, animals or humans can occur in the compost tea.

Compost teas are distinguished into aerated and non-aerated compost teas with respect to their method of production. Aerated compost teas (ACT) refer to products where the compost-water extract is actively aerated during the fermentation process while non-aerated compost teas (NCT) refer to products where the compost-water extract is not aerated, or receives minimal aeration only at the initial mixing stage of the fermentation process (Litterick *et al.*, 2004). Both methods involve fermenting well-characterized compost in water for a specific time period and require the use of a fermentation or brewing vessel, inoculum (compost), water, incubation and filtration prior to application. Nutrients may be added before or after brewing and additives or adjuvants may be added prior to application (Litterick *et al.*, 2004). NCT are generally produced by mixing one volume of compost with 4 to 10 volumes of water in an open container. The mixture is first stirred and then allowed to stand undisturbed, with no or minimal aeration, for at least three days at 15-20 ºC. Other authors have suggested stirring the NCT every two to three days during the fermentation process to facilitate the release of microorganisms from the compost particles (Allahyari *et al.*, 2015; Islam *et al.*, 2016).

Research has shown that nutrient efficiency of compost tea can be increased by microorganisms (Backer *et al.*, 2018; Beattie, 2015). Combining both the addition of organic material and highly active microbes led to improved soil fertility and plant growth (Antolín *et al.*, 2005; Loveland, 2003; El Sabagh *et al.*, 2015). The positive effect of compost tea on plant growth has been demonstrated in many studies (Bernal-Vicente *et al*., 2008; Fouda and Ali, 2016; El Sabagh *et al*., 2016; Siddiqui *et al*., 2008). On the other hand, there are reports with no or insufficient effect (Ghorbani *et al*., 2005; Vázquez Vázquez and Navarro Cortez, 2018; Wang *et al*., 2014). The combination of organic fertilizers and compost tea where shown to be particularly effective in minimizing nutrient losses and increasing nutrient efficiency (Hegazi and Algharib, 2014).

Aerated compost tea made with compost based on green waste increased fruit production, reduced the impact of the two soil borne pathogens *Rhizoctonia solani et Phytophthora capsici* and advanced flowering by one week of sweet pepper (González-Hernández *et al*., 2021). Consistent suppression of damping-off disease of cucumber seedlings caused by the soilborne pathogen *Pythium ultimum* was obtained with aerated compost tea (Scheuerell and Mahaffee, 2004). A critical component was the additives added during the brewing process, as the suppression was achieved only with a specific additive. In contrast, the type of compost used for the production of the compost tea had no influence. A suppressive effect on *Fusarium oxysporum f. sp. lycopersici* and *Rhizoctonia solani*, two soil borne pathogens of tomato, was achieved with an aerated compost tea and aerated vermin-compost tea (Morales-Corts et al., 2018). The first one had a stronger effect on *F. oxysporum f. sp. lycopersici* whereas the aerated vermin-compost tea was more suppressive on *R. solani*. The effect was only obtained when the teas were not diluted before their application. These three examples show that compost teas can be used to control certain soil borne diseases. But there are also studies showing that compost teas applications can result in no suppression of soil borne pathogens or that the control effect is not consistent.

When compost tea is used to treat above-ground plant organs which are destined for direct human consumption, such as vegetables, fruits or herbs, then a microbial analysis of the source material is needed. If human pathogens are present, this source material cannot be used for the production of compost tea. The benefits of compost tea are:

i. Disease and pest suppression and/or resistance;
ii. Reduced use of pesticides;
iii. Increased numbers and diversity of microorganisms;
iv. To improve soil structure and water percolation that helps to improve plant growth (particularly on compacted soils such as bowling greens which are compacted by continuous machinery use);
v. Nutrient and carbon cycling, providing nutrients for plant uptake;
vi. Reduced fertilizer applications;
vii. Improved foliar biology that helps to improve plant vigour; and
viii. Improved yield.

From this point, the purpose of the present work is to review the factors affecting the quality and efficacy of compost tea in organic agriculture. The objectives of this review are to identify the process, operational and environmental parameters that influence the quality and efficacy of compost tea, describe compost tea characteristics and quality assessment, and to summarize the current knowledge of compost tea application including; application methods, application rate and application time.

2. Materials and Methods

A systematic screening search of relevant literature was conducted based on the core collection in the database which is considered to cover papers of high quality and in sufficient quantity for a systematic review (Li *et al*., 2020). The process of study selection and data extraction consists of three steps of results retrieval (Jia *et al*., 2020). First, search for articles based on a prioritized search strategy. Then, filter out irrelevant or unsuitable articles according to their titles and abstracts. Third, read the filtered articles in full text.

3. Factors Affecting the Quality and Efficacy of Compost Tea

The main reasons for compost tea use in agriculture are to suppress plant diseases and to supplement plant nutrition. This requires that the compost tea should contain high diversity of bacteria, fungi, protozoa and nematodes, as well as soluble nutrients extracted from the compost. This can be achieved by brewing a known quantity of compost of known properties in water for a defined period of time. A quality compost with high microbial diversity has the potential to make a good compost tea, if made properly. A poor compost will always make a poor compost tea. The transformation of compost into compost tea cannot improve on the original quality of the compost (Kelley, 2004; Ingham, 2005). Therefore compost quality is critical to maximize the number of beneficial species of each group of organisms (Figure 1) and should contain all the important groups of organisms that are typically found in the soil (Figure 2). The beneficial role attributed to each group of these organisms is as follows (Ingham, 2005):

i. Bacteria and fungi on the leaf surface compete with disease causing organisms for food, space, oxygen and water;

ii. Bacteria and fungi in the soil retain nutrients in their biomass, decompose plant and animal residues, and build soil aggregate structure;
iii. Protozoa eat bacteria thereby releasing nutrients for the growth of plants, bacteria and fungi; and
iv. Most nematodes (except plant feeders which are harmful as they consume root material and harm plant growth) in the soil feed on bacteria and fungi releasing nutrients; many nematodes also consume other pest nematodes thereby keep the population of beneficial and harmful nematodes under control because too many nematodes can reduce bacterial populations below the level needed to suppress disease, retain nutrients, decompose residues or build soil aggregates.

Compost tea brewing or fermentation process refers to the process of steeping compost in water at a constant temperature and for a defined period of time whereby nutrients and microorganisms from the compost source are extracted. Microorganisms convert insoluble nutrients into available nutrients during the brewing process. Soluble nutrients in turn promote growth of diverse community of organisms in the tea. There is little data in scientific literature that directly compares compost tea production processes. However, available data suggests that both aerated and non-aerated compost tea can be inconsistent from batch to batch. The inconsistency has been associated with to a number of factors that affect the nature of the compost tea. These factors include; compost grade, aeration, brewing time, nutrient supplements, microbial supplements, application process, compost to water ratio, environmental conditions, water source and mixing and extraction.

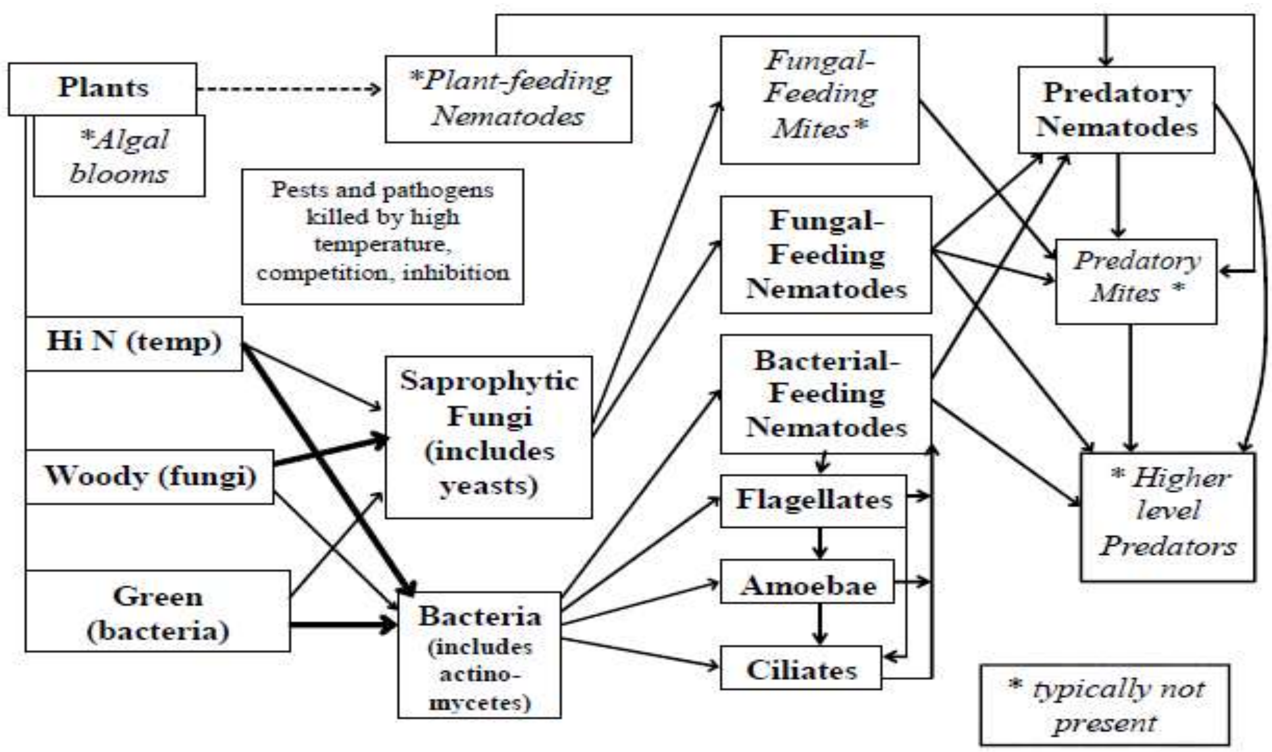

Figure 1: Typical Compost Organism Groups (Ingham, 2005)

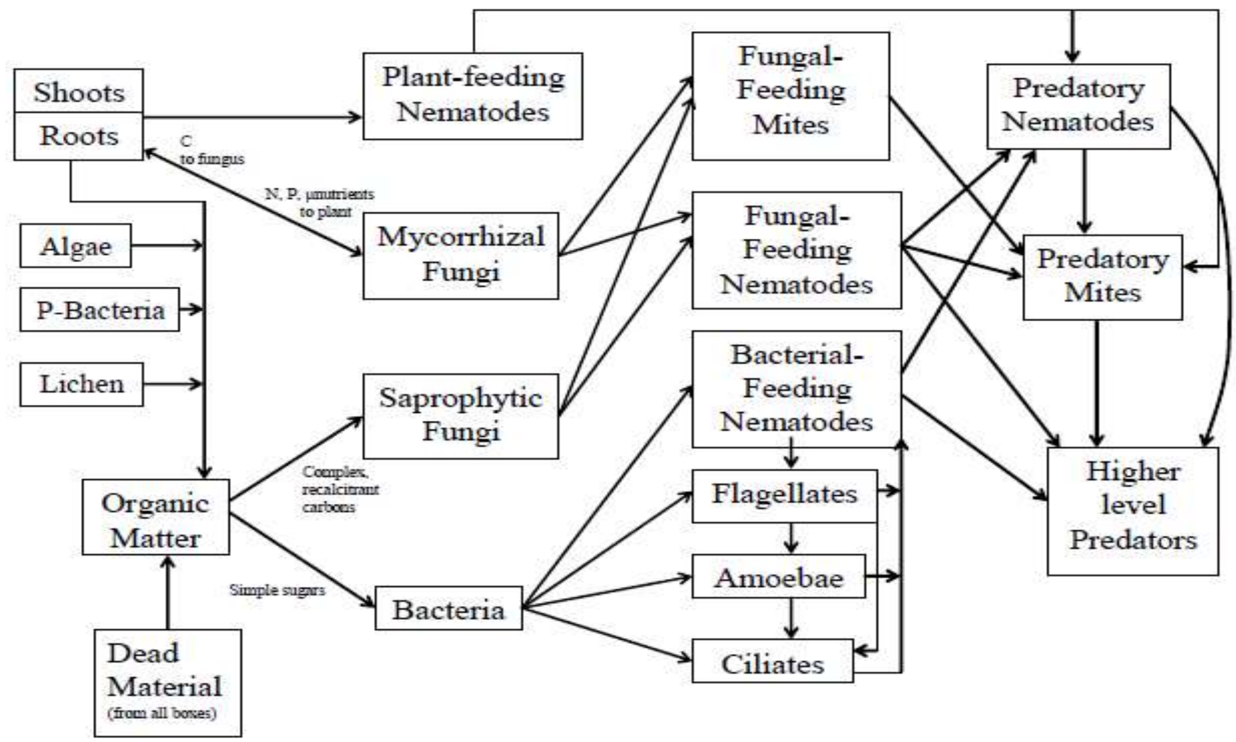

Figure 2: Typical Soil Organism Groups Needed to Grow Plants without Requiring Pesticides or Inorganic Fertilizers (Ingham, 2005)

3.1 Compost grade

The organic ingredients or feed stocks that make up the mature compost include animal manure, landscape and agricultural plant material, bio-solids and food waste. Each has characteristics that influence the quality of the mature compost (Ingham, 2005). Some research suggests composition of microorganisms in compost depends on the feedstock. For example, carbon rich feed stocks (e.g. dry leaves, sawdust, wood chips, and shredded newspaper), produce a compost with a higher fungal content while nitrogen rich feedstock (hay weeds, coffee grounds, herbaceous material and manures) produce compost with higher bacterial content. Similarly, vermi-compost is used as an ingredient in many compost tea recipes. This compost is typically the highest in available nutrients. Therefore selection of compost regardless of the production method depends on its intended use. Mature Compost should be stable and free of pathogens. Research at Wood Ends Laboratory indicated that many immature types of compost are available on the market, with little or no quality testing behind them (Ingham, 2005). The immature compost is less stable and may harbor pathogens. In California, commercial composters are required to meet specific regulatory requirements on the compost process itself that protect health and safety. The most important indicators of compost stability are the temperature cycles in composting process and the carbon to nitrogen content (C: N). The C: N ratio decreases as compost becomes more mature or stable (Allahyari *et al*., 2015).

Composting feed stocks influence the biological, chemical and physical character of finished compost, which in turn impacts the characteristics and efficacy of the derived compost tea. Early work on non-aerated compost teas (NCT's) indicated that the most disease suppressive tea was attained by using animal manure based composts, as opposed to compost made solely from vegetative materials. The advantage of animal manure compost was attributed to diversity in microbial populations (Scheuerell, 2003), or higher levels of available phosphorus, calcium and trace elements, compared to yard and lawn trimmings. However, other research projects have since determined that foliar applications of plant based composts were equally effective as manure based compost for making NCT that inhibited gray mould on foliage in greenhouse studies (Scheurell, 2004).

The selection of compost characteristics depends upon the type of compost tea that is required and the purpose of its use (Ingham, 2005). Trees and shrubs are reported to benefit preferably from fungal dominated soil (Touart, 2000; Ingham, 2005). Vegetables, turf and row crops are reported to benefit preferably from bacterially dominated soils (Touart, 2000) or need both bacteria and fungi (Ingham, 2005). Perennials require balance of fungal and bacterial dominated soil (Touart, 2000;

Ingham, 2005). Compost produced from high woody materials (resistant to rapid decay) with manure and green materials is considered likely to produce fungal dominated tea. Compost produced from a high proportion of green materials with manure and less woody materials is considered to produce bacterial dominated tea (Ingham, 2005). Highly aerobic compost, made from a mix of manure and plant material is favoured (Grobe, 2003). Aerobic compost is considered to maintain a habitat that allows beneficial organisms dominate and to out compete less beneficial and non-beneficial organisms that tend to populate more rapidly in reduced oxygen conditions (Ingham, 2005). The soluble nutrients and foods in aerobic compost also help organisms to grow in the tea brewing process.

Compost must be effectively pasteurized to destroy pathogens, requiring the temperature of compost to reach 57 °C continuously for 3 entire days throughout the entire pile (Ingham, 2005). Then the outside material must be turned to inside and the temperature maintained. Well-made compost will be dominated by beneficial bacteria or fungi (Ingham, 2005). If vermi-compost is used, the raw materials must be adequately processed, to destroy human and plant pathogens. The biomass, diversity and growth (or activity of microorganisms) can be enhanced in compost by adding organisms and different kinds of foods, or nutrients to improve conditions for beneficial bacterial and fungal growth (Ingham, 2005).

It is claimed that compost teas made from compost that have decayed past the sugar stage and have ample humic acid content, are considered disease suppressive. The less disturbed a compost is, especially in the maturation phase of composting (if bacteria and fungi have gone through growth burst in the early composting process), then, the greater the likelihood that compost will not reheat and will contain a higher biomass of fungi and predators (that will help compost maturation), such as beneficial nematodes, protozoa and micro-arthropods (Ingham, 2005). It is prudent to use compost that is free of human pathogens. A good aerobic compost should not contain weed seeds, human pathogens and plant pathogens (Ingham, 2005).

Scheuerell (2003) cites German work claiming that composts should be cured for 2 to 6 months after processing for use in compost tea production. However, it is not clear whether the shifting microbial community or the reduction in microbial food was the main factor in relation to compost age. The compost made of only plant material such as leaves, yard trimmings and straw is not useful after aging for 3 months, while horse and dairy manure compost can be used until 9 to 12 months of age (Scheurell, 2003). For control of cucumber downy mildew using NCT, 6 months old horse manure compost was significantly more effective than one year old compost (Scheurell, 2003).

3.2 Aeration

Aeration systems should provide the proper amount of water agitation. A sufficient oxygen supply is crucial to supply the beneficial microbiology in compost tea. The dissolved oxygen content should be above 6 mg/l throughout the brewing process to prevent the growth of harmful microbes. When compost tea is not adequately agitated, oxygen can become depleted, reducing aerobic microbial growth, favoring anaerobic conditions, and resulting in poor extraction of materials from the compost. The quantity and quality of the compost used, the additives and the temperature influence the oxygen consumption during the brewing process. The air pump used for compost tea brewers should have an airflow of at least 0.4 - 0.6 litres per minute per litre. Thus, for example, if a brewing system with a volume of 100 litres is used, the air flow should be 40 to 60 litres per minute. It is considered that aerobic conditions maintain the presence and growth of beneficial organisms. Plant and human pathogens tend to require reduced oxygen conditions in order to be highly competitive, whereas, most beneficial organisms require fully aerobic conditions. If oxygen becomes limited, human and plant pathogen populations will increase under anaerobic conditions (Ingham, 2005; Scheuerell, 2003). Brief anaerobic periods for few minutes, hours or sometimes days may not be undesirable, if the aerobic organisms are not destroyed or become inactive (Ingham, 2005). In fact brief anaerobic periods may increase diversity of microorganisms. However prolonged anaerobic conditions may make many beneficial microorganisms inactive or kill them (Ingham, 2005).

Over the years there has been continuous debate about the benefits of aeration during the process of producing compost teas. Specifically, some advantages have been identified in relation to ACT processes, including shorter brewing times, greater microbial diversity, lower phytotoxicity and less potential for regrowth of human pathogens (Ingham and Alms, 2003). Aerobic or aerated compost tea (ACT) requires aeration in the production process, which adds to the cost and effort. A significant advantage with ACT is that this method can produce tea in 2 to 3 days, as opposed to NCT which requires up to 2 weeks fermentation (Kelley, 2004; Scheuerell, 2003). The shorter timeframe for ACT production is a significant advantage that enables growers to respond more quickly to weather forecasts or other indications of disease outbreak (Kelley, 2004). Aerated compost tea production creates fewer odours than NCT, and ACT reduces the risk of contamination by human pathogens. However, one of advantage of NCT is attributed to the accumulation of antibiotics due to the longer fermentation times (Scheuerell, 2003). Such antibiotics are considered to activate natural plant defence responses and help in disease suppression.

It has been suggested that aeration or oxygenation during ACT brewing process encourages growth and propagation of diverse group of good microbes extracted from the compost, while limited or lack of oxygen during NCT brewing process may support growth of human and plant pathogens (Ingham, 2005; Naidu *et al*., 2010; Hatam *et al*., 2015). However, there is no available scientific data that support the popular claim that only low oxygen conditions are ideal for most pathogens to grow or only aerobic condition encourages growth of beneficial microbes. Early studies with non-aerated compost teas (NCTs) indicated that brewing conditions that favor a brief period of low oxygen may in fact increase diversity of active microorganisms and disease suppressive properties of NCT while sterilization of NCT eliminates the microbial population and disease suppression observed in the laboratory studies (Ingham, 2005)**.**

In general, production of NCT is favoured over production of ACT because the method is simpler and requires less energy consumption, as specialized aeration equipment is not needed to produce the teas (St. Martin and Brathwaite, 2012). Moreover, several studies have shown that the methods used to produce NCT can be as effective as those used to produce ACT, in relation to suppression of phytopathogens and plant diseases (Welke, 2004; Scheuerell and Mahaffee, 2006; Koné *et al.*, 2010; St. Martin *et al.*, 2012; Marín *et al.*, 2013). For NCT, foul odor has been reported only under conditions where nutrient additives were added during the fermentation process. It remains unclear whether it is necessary to aerate during compost tea production. It should be noted that aerated compost tea or oxygenated tea in practice becomes non-aerated if not used immediately. The producers and users of ACT must take into consideration the added cost of the brewing process (Allahyari *et al.*, 2015). Ingham (2005) considers that the presence of anaerobic organisms in compost is not a concern, as long as they are not increasing in total population. The main reason for concern over anaerobic organisms is the production of volatile organic acids (VOAs), alcohols, ammonia, and phenols produced by anaerobic bacteria and yeast. These compounds are toxic to the roots of plants, even very small quantities are phytotoxic (Ingham, 2005). Aeration of the brew helps to maintain aerobic conditions, and the by-products of anaerobic conditions such as VOA and alcohols are consumed by aerobic microorganisms.

3.3 Brewing time

The optimum brewing time is when most of the soluble nutrients and organisms have been absorbed into the liquid or extracted from the compost. A long brewing time will enable greater amounts of soluble material and organisms to be extracted from the compost and into the liquid. The greater the amount of soluble material in the tea, the more food resources there are to grow beneficial bacteria and fungi, and the more nutrients will be available for plants (Ingham, 2005). However, a long brewing time does not always produce good quality compost tea. For example, if the supply of oxygen is not adequate for a long brewing time, anaerobic organisms will grow in the tea and can produce phytotoxic compounds in the tea. A shorter brewing time is less likely to develop anaerobic bio-films (Ingham, 2005). Therefore the optimum brewing time is the time that allows a balance between the extraction of nutrients and the growth of organisms, depending on the brewing conditions.

Several studies on disease suppression properties of NCT have indicated that NCT brewing time of 8-16 days is optimal fermentation time for any level of disease control. The longer fermentation time has been reported to promote greater amount of nutrients to be extracted from the compost and enable accumulation of antibiotics in the NCT which are claimed to activate natural plant defense responses and help in disease suppression (Scheuerell, 2003). A significant advantage reported by the manufacturers and the users of ACT is the short brewing time of 18 hrs to 3 days, depending on the temperature and also the microbes to be promoted, which makes the tea readily available. Shorter brewing times promote a bacterial dominated compost tea, which is often used for leaf application and disease prevention. The longer the brewing time, the more fungi and protozoa are multiplied, that can promote nutrient mobilization in soils. Using a sophisticated micro-brewing system, it is possible to produce good-quality compost tea in 18 to 24 hours. It has been proposed that that optimal brew time of 18-24 hours coincides with maximum activity of microbial population in the tea (Ingham, 2005.

3.4 Nutrient supplements

Certain stimulatory additives can be included during brewing to increase the quantity of microbes derived from the compost in order to improve the final quality of the compost tea. These include materials such as kelp, rock dust, molasses, humic and/or fulvic acids, and commercially available microbial spore suspensions. Solid materials, like rock dust, must be added to the compost in the tea bag, while soluble materials like molasses should be added to the water. By introducing additives to the brewing process, it is possible to alter the microbial community in the compost tea (Deepthi and Reddy, 2013; Naidu *et al*., 2010). Simple sugars tend to promote a bacterial dominated compost tea while more complex compounds promote a more diverse microbiology including protozoa and fungi. Nutrients such as kelp, fish hydrolysate, molasses, and humic acid are added as catalysts or microbial starter (Naidu *et al*., 2010) during brewing process to promote selective enrichment of microorganisms.

For both ACT and NCT, fermentation nutrients have the ability to inhibit or increase growth rates for different types of organisms (Scheurell, 2003). Increasing microbial populations by introducing nutrients can improve biological control, but nutrients must be used with extreme caution (Ingham, 2005; Scheuerell, 2003). In an aerobic environment, excess bacterial and fungal growth resulting from the addition of nutrients can cause higher oxygen consumption that is detrimental to maintaining aerobic conditions, and the liquid may become anaerobic (Ingham, 2005). If compost tea fermentation is terminated at the maximum metabolic activity level, it is likely to leave unfermented nutrients available to all organisms, potentially stimulating pathogens that have an efficient saprophytic phase (when microorganisms grow and derive their nourishment from host and/or dead or decaying organic matter) which is linked to negating the suppressive effects of the compost tea.

Amending compost tea with molasses has been found to favour the regrowth of human pathogenic bacteria (Duffy *et al*., 2004), and to assist the loss of disease suppressive characteristics of compost tea (Scheuerell, 2003). Simple sugars and molasses also have potential to result in increased *E. coli* and *Salmonella* in compost tea brews, if the compost used to brew the tea contains these organisms (Scheuerell, 2003). For example, a Salmonella population increased from 0 to 1000 CFUml^{-1} in dairy manure compost tea that was amended with 1% molasses and 0 to 350,000 CFU ml^{-1} in chicken manure compost tea over a 72 hour period. *E. coli* populations increased from 0 to 1000 CFUml^{-1} in both dairy and chicken manure teas over a 72 hr period (Duffy *et al*., 2004). This raises a concern for public health and the potential for contamination of treated crops, particularly produce intended for fresh consumption. However, others researchers consider that a diversity of food resources and nutrients will improve as more kinds of plant materials are used in the composting process and the addition of molasses to compost tea will not favour regrowth of human pathogens if they are not present in compost to begin with (Ingham, 2005).

3.5 Microbial supplements

It is well established that compost contains a diverse group of organisms dominated by bacteria and fungi participating in decomposition of organic matter (Naidu *et al*., 2010). Bacteria can grow and multiply in both oxygen rich (aerobic) and low or no oxygen (anaerobic) environments. There is considerable interest among growers, producers and scientific community in manipulating the brewing processes to obtain optimum composition of beneficial microbes that include both aerobic and facultative anaerobic groups (Hatam *et al*., 2015). Commercial suppliers advertise prepackaged microbial inoculums that can be brewed on its own, added to the compost source or to ACT following the brewing process. One of the popular microbial inoculums is “Effective Microorganisms” (EM). Effective Microorganisms (EM) is a mixture of live cultures of microorganisms isolated from fertile soils in nature and useful for crop production. EM preparations generally contain *Lactobacillus*, photosynthetic bacteria, yeasts and other beneficial microorganisms which increase the crop growth. Other microbial formulations include Fungi in the genus Trichoderma that have been known since at least the 1920s for their ability to act as biocontrol agents (a term coined for beneficial organisms with ability to suppress pathogens) with successful results in maize (Kim *et al*., 2015). Trichoderma species grow naturally around the plant roots and feed or parasitize on pathogenic fungi. However, if pathogenic fungi are not present in the soil, addition of Trichoderma can have little or no benefits as they will die-off without feeding on pathogens (Ingham, 2005). Increasing the microbial diversity without understanding the role of each species in the context of the plant’s natural environment can be risky, but is a power concept that needs to be explored further under controlled scientific experiments in the field.

3.6 Application process

Filtration and dilution are often necessary when compost tea is applied through irrigation system or sprayers to avoid clogging the nozzle. Compost tea is usually filtered before application, particularly when applied via sprayers or irrigation systems by using a fine mesh strainer to prevent the clogging of sprayer nozzles and irrigation systems. Irrigation filters, particularly in drip systems, also remove suspended particles that can contain part of the microbial diversity found in compost tea. Filtration does not let a sufficient amount of particulate matter pass through in tea. Some types of microorganisms like to live attached to particulate matter as a result finely filtered teas tend not to contain significant population of such microorganisms. That means beneficial fungi and actinomycetes, prominently active in suitable composts, may be poorly represented because of the necessity to strain out particulate matter that they would normally be attached to due to the functional requirements of irrigation system equipment or various sprayers (Bess, 2000; Ingham, 2005).

Similarly, dilution of the tea prior to foliar application may reduce the nutrients and microbial population. For soil application, is has been recommended to use a volume sufficient to reach the root area. Soil application is thought to protect the roots from potential colonization of root pathogens and promote healthier plants. For foliar application, compost tea is diluted 1: 4 or 1: 6 with water prior to application (Hatam *et al*., 2015). It has been proposed that maximum coverage of leaf surface area may necessary for the beneficial microbes in the tea to outcompete colonization by plant pathogens, however, frequent and repeated applications are needed to maintain the surface coverage (Ingham, 2005).

Compost tea can be applied undiluted or up to a 1:10 dilution with water using conventional application devices. If the compost tea is diluted, it is recommended to apply compost tea more frequently. The application should ideally take place in the evening or under overcast skies. Do not apply foliar sprays if rain is forecast within 24 hours. It is best to apply after heavy rainfall. If the compost tea is applied with a field sprayer, the following points must be considered:

i. With the field sprayer, a sieve must be used to avoid clogging. Make sure that the sieve and nozzles are not smaller than 0.4 mm. With a smaller sieve size, some beneficial microbes do not reach the leaf and soil.
ii. The optimum working pressure of the field sprayer is a maximum of 2 bars. Sensitive microorganisms are killed at a higher application pressures.
iii. If crop protection products were applied with the same field sprayer, the field sprayer must be thoroughly washed with water before filling with compost tea.

3.7 Compost to water ratio

Optimum ratio of compost to water tends to vary, depending upon the brewing process and equipment used. For NCT, the majority of studies use a 1:3 **-** 1:10 ratios (Allahyari *et al.*, 2015). For ACT, the ratio depends on type of equipment and is usually suggested by the compost tea equipment suppliers. For making a compost tea, the compost to water ratios reported in the literature varied from 2-3 kg of compost in 75 litres of water to 9-10 kg of compost in 200 to 400 litres of water for the final product **(**Ingham, 2005). Too little compost will result in dilute tea with few nutrients or organisms and will not provide maximum benefits. Too much compost means not everything is extracted that could be extracted resulting to excess of nutrients for bacteria, which can lead to oxygen depletion and anaerobic conditions. It may also be possible to overload some of the compost tea making equipment, so that water cannot flow through the compost and extraction efficiency will be low (Ingham, 2005).

3.8 Environmental conditions

Temperature, humidity, evaporation and other abiotic conditions influence the growth rate of microorganisms. High temperatures inhibit microorganisms, volatilize nutrients and causes evaporation that will concentrate salts, while low temperatures reduce nutrients extraction and slow microorganism growth. It is hard to change the ambient weather, so it is suggested to place tea making equipment inside a greenhouse or shed. In hot weather, cover tea making units to prevent evaporation and concentration of salts (Ingham, 2005).

Temperature has a great influence on the brewing time. The compost tea should preferably be brewed at room temperature (18-24 °C). The brewing process is shortened at warmer temperatures. Temperatures above 30 °C are to be avoided. Low temperatures result in longer brewing times. If the night temperatures fall below 10 °C, a heater is recommended (Ingham, 2005).

3.9 Water source

It is important to use water that is as pure and as uncontaminated as possible for making compost tea or any dilution thereof regardless of the production method. Water containing high levels of salts, heavy metals, nitrates, pesticides, chlorine or pathogens should not be used. These will affect the survival and reproduction of beneficial organisms from the compost and may also adversely affect the plants on which the compost tea is applied. Chlorine or chloramines are added to potable water as a sanitizing agent(s); when present in the water, these chemicals can inhibit growth and propagation of microorganisms during the brewing process (Ingham, 2005). Where present, removal of contaminants becomes a priority before using the water. Both chlorine and sulfur can be removed by aeration. Carbonates can be removed by precipitating them with additives, and then de-gassing those additives.

3.10 Mixing and extraction

Mixing is an important part of the process, assisting the physical extraction of bacteria and fungi from the compost. However, too rapid or forceful mixing can physically destroy beneficial microorganism populations in the tea. Mixing that is too slow may not be sufficient to extract enough organisms from the compost. In addition insufficiently vigorous or slow mixing can allow the development of bio-films and anaerobic conditions, with resulting formation of phytotoxic compounds in the liquid tea (Ingham, 2005). Compost tea that is well mixed and recirculated will require a shorter brewing time than tea made without adequate agitation.

Table 1: Compost Tea Production and Application Parameters that Influence Compost Tea Properties and Efficacy (Scheuerell, 2004)

Parameters	
Production Parameters	
Fermentation Vessel	Dimensions, manufacturer and model if applicable
Compost	Feedstock, age, stability, % moisture, available nutrients, microbial analysis, either volume and bulk density used or weight used per unit water.
Water Source	Volume, initial and final temperature.
Nutrient Additives	Types, concentrations, timing when added.
Dissolved Oxygen	Stirring, agitation, and/or aeration.
Temperature	Water temperature at start and throughout production
Production Duration	Method of storage, if not used immediately.
Application Parameters	
Filtration	Material and mesh size used for filtering
Dilution Ratio	Water source
Adjuvants	Nutrients, Surfactants, stickers, UV stabilizers, microorganisms.
Application Equipment	Make, model, nozzle specifications, pressure.
Application	Rate, time of day, weather, interval between applications.

4. Compost Tea Characteristics and Quality Assessment

There are many and varied ideas on improvements for compost teas, some of which focus on its use for more specific applications. For example, to combat plant pathogens, compost tea production focuses on maximizing microbial diversity, whereas, to supplement nutrients, manufacturers add nutrients either during production or as a post-production addition. It is yet unknown what teas attributes are effective for specific types of diseases. It is suggested to be more likely that each plant, each cultivar, each climate and each season requires a different set of organisms (Ingham, 2005). This is also likely to differ for soil applications and foliar applications. While there are so many unknown parameters, the most common approach is to use a tea with a diverse microbial community and let natural selection take over (Ingham, 2005; Scheuerell, 2003). A diverse assemblage of microbes possesses all the traits needed to effectively colonize plants and inhibit pathogens over a wide range of conditions (Scheuerell, 2003).

Scheuerell (2003) reports that it is important to understand the biology of each pathogen for optimizing the biological control of pathogens with compost teas including different requirements for growth, multiplication, survival and infection of pathogens than their antagonists (beneficial microorganisms that exhibit antagonistic properties towards plant pathogens). Scheuerell (2003) explains how plant pathogens differ in their requirements for survival and infection from beneficial microorganisms that exhibit antagonistic properties towards plant pathogens. Most bacteria that infect leaves must multiply or grow epiphytically (on the leaf surface) until a population capable of causing disease symptoms is reached. Epiphytic growth requires leaf surface nutrients, so colonizing the leaf with beneficial organisms that are capable of scavenging nutrients can reduce populations and growth of such pathogenic microorganisms. Such beneficial microorganisms tend to be robust relative to pathogens, better surviving desiccation and other stresses, growing over a wider temperature range and more effectively using available nutrients. This enables such beneficial microorganisms to colonize diverse surfaces, and to predate or parasitize pathogenic microorganisms.

The main characteristics of compost tea for disease suppression, as reported in the literature, are the presence of a maximum diversity of beneficial organisms, plant nutrients and low salt levels. The compost tea characteristics needed for different plants and soil types are presented in Table 2. Trees and shrubs are reported to require a fungal dominated soil to thrive, while row and other crops are reported to do best in bacterially dominated soils. Sandy type soils are claimed to require both bacteria and fungi to build good soil structure, whilst clayey type soils are reported to require mostly bacteria to form micro-aggregates and to cycle nutrients (Ingham, 2005). Plant nutrients in compost teas help to stimulate growth of beneficial microorganisms and can help strengthen their structural defences, physically waiving off invading pathogens (Scheuerell, 2003). Antibiotics and other metabolites, which can accumulate in compost tea during production are reported to activate natural plant defence responses (Scheuerell, 2003).

The total microorganism populations will vary for each tea, even if the compost, mixing and amendments used were the same. Bess (2000) suggests that compost tea should be analysed for the same parameters as compost including beneficial microorganisms: aerobic and anaerobic bacteria, fungi, actinomycetes, pseudomonades; nitrogen fixing bacteria; and pathogens such as *E. coli* and *Salmonella*.

4.1 Compost tea quality during storage

Compost tea does not typically improve with time. For best results, it should be used as soon as possible and should be stored in a shaded area with agitation and ventilation of the tank (Bess, 2000; Ingham, 2005). Long storage times negatively impact upon the diversity of microorganisms, as well as nutrients carried by the tea for plant use (Bess, 2000). Number and activity of organisms reduces significantly with storage (Ingham, 2005). Reduction in active organisms is acceptable for a soil application but not for a foliar application. Active organisms are necessary for foliar protection. Continuous aeration and addition of bacterial and fungal food can extend shelf life of compost tea for a few days only.

Table 2: Compost Tea Characteristics for different Plant Types and Soil Types (Ingham, 2005)

	Plant Types				
Soil Type	**Broccoli, cabbage, cole** (Strongly bacterial)	**Row crops, grasses** (Slightly bacterial)	**Berries** (Equal bacteria and fungi)	**Deciduous trees, vines** (2-10 times more fungal)	**Conifers** (100+ more fungal than bacteria)
Sand	Need both bacteria and fungi to build good soil structure	Need mostly fungal activity, some bacteria to build soil structure	Need to maximize fungal activity	Need to maximize fungal activity	Need to maximize Mycorrhizal fungi
Loam	Improve bacteria significantly and some fungi	Need both bacteria and fungi	Need to maximize fungi	Need to maximize fungi to overcome compaction	Need to maximize fungi including mycorrhizal
Clay	Mostly need bacteria to form microaggregates and get nutrient cycling going	Need both bacteria and fungi	Need to improve both bacteria and fungi	Need to maximize fungi	Need to maximize fungi including mycorrhizal

Table 3: The Desired Minimal Ranges for different Organisms in Compost and Compost Tea (Ingham, 2005)

Product	**Active bacteria (µg)**	**Total bacteria (µg)**	**Active fungi (µg)**	**Total fungi (µg)**	**Protozoa (#)**			**Beneficial nematodes (#)**
					F	**A**	**C**	
Compost (per gram dry weight)	15-30	150-300	2-10	150-200	10,000	10,000	20 to 50	50-100
Compost tea (per ml)	10-150	150-300	2-10	2-20	1,000	1,000	20 to 50	2-10

5. Application of Compost Teas

5.1 Application methods

Compost tea can be applied either to the soil or to the plant foliage. Compost tea is commonly applied to the soil by drenching the soil, directing compost tea into the root zone and affects the rhizosphere of the plant. Nutrients supplied with the tea are used by the plants as well as by the microorganisms. The microbes in the compost tea compete with other soil microorganisms, and in turn, become part of the soil and rhizosphere microbial ecology (Bess, 2000). Compost tea for soil applications (except when applied via irrigation systems or sprayers) does not necessarily require fine filtration before application thereby retaining microbial organisms in compost teas therefore provide greater total population and diversity of microorganisms than spray applications. When applied to plant foliage, compost tea may alter the composition of organisms on the leaf surface, both through inoculation of organisms from the tea and through supply of foods that help support survival and growth of leaf-surface organisms (Ingham, 2005).

Compost tea applied to plant foliage has immediate impacts upon the plants welfare. Good quality compost tea that provides beneficial organisms and plant nutrients are essential, and should also avoid salt burn problems and risk of pathogens. The key is to achieve thorough coverage on both sides of the leaves. Leaves are coated in various waxes that tend to repel water droplets. Surfactants are added to the compost tea to reduce the water surface tension and allowing tea droplets to spread across the waxy surface (Scheuerell 2003).

The sticking agent helps the tea adhere to the surface, also reducing losses from rain. The addition of surfactants, sticking agents and ultra violet (UV) inhibitors (referred to as spray adjuvants) to compost tea can increase the proportion of leaf area covered by beneficial microorganisms, thereby increasing leaf coverage and prolonging microbial survival by protecting against desiccation and harmful UV light (Scheuerell, 2003). This can significantly reduce disease severity of foliar fungal pathogens compared to less effective foliar application of unamended compost tea (Scheurell, 2003).

Compost tea for foliar applications can be applied with a broad range of sprayers. Tea should be preferably applied as a fine mist, so the liquid will remain on the leaf and not drip off (Grobe, 2003). Compost tea can also be applied via irrigation systems. Compost tea is usually filtered before spraying for foliar applications or applying via irrigation systems to prevent the clogging of sprayer nozzles and irrigation systems. Filtration removes a sufficient amount of particulate matter and some types of microorganisms tend to live attached to this particulate matter. As a result, these organisms may be poorly represented in filtered compost tea because of the necessity to strain out particulate material to which they would normally be attached to meet the functional requirements of irrigation system equipment or sprayers (Bess, 2000; Ingham, 2005).

Selection of soil vs foliar application method will vary case by case basis depending on disease type, severity, crop type and environmental conditions. Both these methods have their merits and demerits. For example foliar applications can be used for immediate impact on disease when noticed on foliage, whilst soil application can be used to protect against soil diseases reaching the roots. Combination of soil and foliar application are claimed to provide best results.

5.2 Application rate

For foliar disease suppression, complete plant coverage is desirable. Therefore the crop canopy area determines application rates. For soil applications, sufficient volume should be applied to reach the entire root zone (Scheuerell, 2003). A general theory of covering at least 70% leaf surfaces by at least 60-70% active bacteria and 2-5% active fungi (determined by leaf examination) has been proposed, as this level of coverage prevents the colonization of the plant surface by plant pathogens. This theory needs assessment to validate under different conditions and for different pathogens that vary in their modes of survival and infection processes (Scheuerell, 2003). Ingham (2005) also suggests as general guide the application of about 50 L/ha of compost tea for foliar application and 150 L/ha for a soil drench.

Foliar applications and application of compost tea via various irrigation systems needs filtration before application (to avoid blockage of sprayer nozzles or irrigations systems) however, such fine filtration also removes beneficial fungi, actinomycetes and nematodes. Direct soil applications (except via irrigation systems) do not necessarily need such fine filtration and as a result higher populations of fungi, actinomycetes and nematodes are applied in the tea. Compost tea application rates vary significantly depending upon application. Reported application rates range for foliar application varies from 20 to 50 litres per hectare per application, whilst application rate for soil application ranges from 150 to 200 litres per hectare per application. Application rate also varies depending upon the height of foliage (e.g. foliar application of 50 L per hectare for 1m high foliage, higher application rate of 200 L per hectare for 4 m height foliage). Frequency of application varies depending upon crop and purpose of the application. Application frequency tends towards 5 to 6 applications per year. However, frequency of application may increase to weekly or fortnightly in the instance of disease outbreak/infestation.

5.3 Application time

For foliar applications the best time to apply compost tea is in the evening, when evaporation is minimum and ultraviolet light, which can be toxic to microorganisms, is minimal (Grobe, 2003).

For soil applications compost tea can be applied:

i. At transplant and seeding stages; and/or,
ii. To the base of full grown plants.

Application timing will also depend upon the disease that is being targeted and the timing and conditions that pose risks of infection by particular diseases.

6. Conclusion

Review of the literature indicates the need to conduct further control field trials to better understand the brewing techniques, the application process and the benefits claimed for compost tea and compost tea additives. There are data gaps on compost quality, the role of fermentation nutrients, the need for aeration and the impact of a shorter brewing process on the quality and efficacy of the finished compost tea. Furthermore little is known about composition of microbes in the tea or microbial additives and their interaction with plant pathogens in their natural environment. Together with concerns over regrowth of pathogens in compost tea, there is a pressing need to identify the active microbes that make up the compost tea and their survival rate following field application. Finally, with new data emerging on chemical contaminants in some compost or compost extract derived for recycled waste, there is a need for establishing standards for compost quality regardless of the brewing process. The effect of compost tea on plants is highly variable, even more so than the application of compost. For a consistent and safe use of compost tea, the standardization of as many parameters (source material, amendments, oxygen content, brewing duration and temperature) as possible is highly recommended.

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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