ROOT PHENOMICS AND SOIL BIOLOGICAL ACTIVITY IN RESPONSE TO THERMOCHEMICAL ORGANIC FERTILIZER APPLICATION

By

RAMESHA G K

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VELLAYANI, THIRUVANANTHAPURAM - 695 522

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DECLARATION

I, hereby declare that this thesis entitled **"ROOT PHENOMICS AND SOIL BIOLOGICAL ACTIVITY IN RESPONSE TO THERMOCHEMICAL ORGANIC FERTILIZER APPLICATION"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associate ship, fellowship or other similar title, of any other University or Society.

Vellayani

Date: 03-10-19

Ramesha G K

(2017-11-121)

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CERTIFICATE

Certified that this thesis entitled **"ROOT PHENOMICS AND SOIL BIOLOGICAL ACTIVITY IN RESPONSE TO THERMOCHEMICAL ORGANIC FERTILIZER APPLICATION"** is a record of research work done independently by Mr. Ramesha G K (2017-11-121) under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to him.

Vellayani
Date: 03-10-19

Dr. Naveen Leno
(Major Advisor, Advisory Committee)
Assistant Professor
Department of Soil Science and
Agricultural Chemistry
College of Agriculture, Vellayani

CERTIFICATE

We, the undersigned members of the advisory committee of Mr. Ramesha G K (2017-11-121) a candidate for the degree of **Master of Science in Agriculture** with major in Soil Science and Agricultural Chemistry, agree that the thesis entitled "Root phenomics and soil biological activity in response to thermochemical organic fertilizer application" may be submitted by Mr. Ramesha G K (2017-11-121), in partial fulfilment of the requirement for the degree.

Dr. Naveen Leno
(Major Advisor, Advisory Committee)
Assistant Professor
Department of Soil Science &
Agricultural Chemistry
College of Agriculture, Vellayani

Dr. K. Ushakumari
(Member, Advisory Committee)
Professor and Head
Department of Soil Science &
Agricultural Chemistry
College of Agriculture, Vellayani

Dr. K. C. Manoramma Thampatti
(Member, Advisory Committee)
Professor
Department of Soil Science &
Agricultural Chemistry
College of Agriculture, Vellayani

Dr. Radhika N. S
(Member, Advisory Committee)
Assistant Professor
Department of Plant Pathology
College of Agriculture, Vellayani,

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LIST OF ABBREVIATIONS

%	Per cent
^0C	Degree Celsius
B	Boron
C	Carbon
Ca	Calcium
CD	Critical Difference
cm	centimetre
cm^2	square centimetre
Cu	Copper
$dS\ m^{-1}$	deci Siemens per meter
EC	Electrical Conductivity
et al.	and other co workers
Fe	Iron
Fig.	Figure
FYM	Farmyard manure
g	gram
$g\ kg^{-1}$	gram per kilogram
$g\ plant^{-1}$	gram per plant
$g\ pot^{-1}$	gram per pot
K	Potassium
kg	kilogram
$kg\ ha^{-1}$	kilogram per hectare
Mg	Magnesium

mg	milligram
mg kg^{-1}	milligram per kilogram
ml	millilitre
Mn	Manganese
N	Nitrogen
No.	Number
NS	Non-significant
P	Phosphorus
pH	Negative logarithm of hydrogen ions
ppm	parts per million
S	Sulphur
SEm (±)	Standard error of mean
Si	Silicon
sp.	species
t	tonnes
t ha^{-1}	tonnes per hectare
viz.	namely
Zn	Zinc

Dedicated to

My

Parents and Brothers

Introduction

1. INTRODUCTION

Sustainable agriculture aims at the maintenance of soil and plant health primarily by organic nutrition. Organic amendments can supply both macro and micro-nutrients directly, particularly with the long-term supply of N being regulated by the mineralization rate of the added organics. This is all the more relevant to a state like Kerala, which is on its path of becoming a full-fledged organic state. However, the nutrient content depends on the organic source and quality (Mukai, 2018). In the present scenario, there is a wide gap between demand and supply of organic manures and fertilizers required for large-scale business use both in organic farming and in farms with excellent farming methods. The total organic manure production including rural compost, farm yard manure and city compost in Kerala is estimated to be 19.84 lakh tons which constitutes merely 1.17 percent of the total organic manure production of the country (GOI, 2017). Organic manure production is being encouraged under the Paramparagat Krishi Vikas Yojana (PKVY) of National Mission for Sustainable Agriculture (NMSA). Different kinds of organic manures are utilized by the farmers. The most frequently used organic manure in India is farm yard manure (Reddy *et al.,* 2015). Poultry manure is the most appropriate organic fertilizer currently available for organic vegetable cultivation (Vimala *et al.,* 2001). Composting is a commonly used technology for converting organic waste into organic manure, recycling mineral nutrients viz. nitrogen, phosphorus and potassium for agricultural use, so it is a serious competitor for fertilizer market (Proietti *et al*., 2016).

Globally, urbanization and a continuous increase in the human population have led to solid waste being generated in big quantities. The ever increasing waste have brought with them a number of environmental, social and economic problems, particularly in developing nations (Sukholthaman and Sharp, 2016). Food waste accounts for the major proportion (45%) of total municipal solid waste in Europe and even more in developing countries (IPCC, 2006). Its final destination is either landfill disposal or incineration until a few years ago. Effective management policies for these wastes should be implemented. Usually biological procedures such as composting and anaerobic digestion are used for solid waste disposal (Cerda *et al.*, 2018). Composting is a biochemical method that converts organic waste into comparatively stable substances that can be used as a soil amendment or organic fertilizer (Tiquia, 2010). But the long-time span required for composting predisposes dumping of waste leading to leaching and consequent environmental pollution.

It is well established that addition of organic manures, in contrast to inorganic fertilizers, would serve to augment the fast depleting soil organic carbon reserves. Soil organic carbon is the back bone for soil biological activity providing the source and means for organisms. Soil biological activity plays a pivotal role in the sustenance of soil stability and fertility. Incorporating organic matter improves microbial diversity as well as population, thereby improving soil biological characteristics (Albiach *et al.*, 2000). It acts as an energy source for the proliferation of microorganisms in the soil in general and in the rhizosphere in particular. Organic matter can positively affect microbial population and stimulate development of plants. Long-term application of various manure and fertilizer treatments regulated the performance of microbial biomass and soil enzymes (Mandal *et al.*, 2007). Increased soil total nitrogen, organic carbon, microbial biomass and enzymatic activity observed with manure amended soil (Ge *et al.*, 2009). Activity of soil dehydrogenase and production of CO_2 were evaluated as soil biological activity indicators (Marinari, 2000). Soil microbial biomass, bacterial, fungi and actinomycete populations, as well as soil enzyme activity improved considerably in compost-treated soils (Chang *et al.*, 2007).

Plant growth in general and the soil biological activity in particular relies to a large extent on the basic framework and architecture of the plant root system, which sustains it. Plant roots are the hidden half of the plant and are main drivers of water and nutrients absorption that eventually reflect crop development and yield. Root phenomic alterations in the soil environment minimize the metabolic cost of maintaining the root system while maximizing the acquisition of nutrients (Hetrick, 1991). Plants can change their root architecture in response to biotic and abiotic signals (Rabbi *et al.*, 2017). The root system's capacity to react morphologically to localized nutrient supply is seen as an important characteristic of soil nutrient absorption. Root plasticity and spatial deployment of roots substantially determine the ability of a plant to attain higher root nutrient acquisition efficiency. Organic materials have a positive effect on root architecture, root spread and nutrient uptake (Trevisan, 2010). Application of farmyard manure improved soil physical conditions and enhanced root proliferation (Hati *et al.*, 2009). The root architecture benefited by organic matter and nutrients augments the acquisition of essential mineral elements and result in enhanced crop yields, which is a way towards sustainable agriculture. The ability of the root system to respond morphologically to localised nutrient supply is considered an important characteristic for nutrient uptake from soil (Rabbi *et al.*, 2017). The framework and architecture of the plant root system, especially in season bound vegetable crops assumes great significance.

The rapid thermochemical processing technology provides a quick solution for the disposal of degradable solid waste at source, converting it into a high-quality organic fertilizer, thus eliminating waste dumping and environmental and health issues caused by leachate (Sudharmaidevi *et al.*, 2017). Characterization studies and assessment of its suitability as a marketable organic fertilizer with comparable fertility index and clean index as a substitute to farmyard manure have been studied (Leno, 2017). The impact of thermochemical organic fertilizer on enhancing crop yield and soil properties in growing media as well as in field crops have been reported (Jayakrishna and Thampatti, 2016; Leno, 2017). Superiority of the thermochemical organic fertilizer has been established in providing a rhizosphere priming effect in comparison with other popular conventional organic manures (Jacob, 2018). But its effect on root phenomics and biological activity responses are yet to be studied.

Hence it is imperative to have an understanding of the impact of different organic manures on the specific root morphological and phenomic characters that nurture the rhizospheric microbial population and have a bearing on rhizospheric nutrient acquisition. The present project aims at studying the behaviour of the new organic fertilizer produced by thermochemical treatment in comparison with the popular organic manures giving thrust to root phenomics, biological activity responses and its effect on the growth and yield of amaranthus.

Review of Literature

2. REVIEW OF LITERATURE

A study entitled "Root phenomics and soil biological activity in response to thermochemical organic fertilizer application" was conducted from October 2017 to April 2019 at the Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani with the objective of studying the root phenomics and soil biological activity in response to thermochemical organic fertilizer application as compared with conventional organic manures and its effect on growth and yield of amaranthus. This is an attempt to present major findings related to characterization of organic manures, root phenomic characters and soil biological activity and the effects of organic manures on growth and yield of amaranthus.

2.1 PREPARATION OF ORGANIC MANURES

The organic manures improve long-term soil fertility and productivity. The quality and stability of the composts depend on the composition of raw material used for the compost production (Ranalli *et al.,* 2001).

The organic matter or organic carbon concentrations decreases in composting process which is evidenced in the degradation of organic materials during composting (Goyal *et al.,* 2005). In animal manures organic carbon losses during composting can reach 67% in cattle manure, 52% in poultry manure (Bernal *et al.*, 2009). Organic matter decomposition is carried out by different groups of microbial populations (Ryckeboer *et al.*, 2003).

During early stages of composting bacteria predominates, fungi are present during all the process of composting but is found more at water levels below 35% and are not active at temperatures >60 °C. In the composting process actinomycetes prevail during stabilisation and curing, and they are able to degrade resistant polymers. Bacteria, fungi and other microorganisms, including microarthropods are involved in the breakdown of organic materials to stable compounds (Bernal *et al.*, 2009).

The rate of composting and number of microorganisms at each stage of composting are dependent on the available substrates and activity of preceding microorganisms (Vaz-Moreira *et al*., 2008). In the first month of composting, the concentration of humic acids will change progressively and increases greatly in the second month. Contrary to that, concentration of fulvic acids decreases gradually during composting (Ko *et al*., 2008). In composting process, the formation of humus and humic acids through polymerisation and condensation occurred during maturity stage (Fels *et al*., 2014). Composting benefits include elimination of pathogens and weeds, microbial stabilization, reduction in quantity and humidity, removal and odour control, ease of storage, transport and use, production of excellent quality fertilizer (Kumar *et al.*,2010).

2.2 THERMOCHEMICAL ORGANIC FERTILIZER

Organic fertilizers derived from biowaste have potential to be an alternative source of chemical fertilizers. Commercializing the production of biofertilizer requires knowledge of the economic viability and potential environmental impacts, including the life cycle assessment of organic fertilizer production. Its nutrient content and sustainability of utilisation in soil are the major barriers for using the organic fertilizer. Though organic fertilizer is lower in agronomic yield potential compared to conventional inorganic fertilisers, it will contribute towards a greener environment through greenhouse gas mitigation (Chew *et al*., 2019). High temperature aerobic fermentation reactor is designed to explore the rapid degradation of food waste through continuous collision and friction of composting matrix under relatively high-temperature and organic fertilizers can be produced in 96 hours of fermentation (Jiang *et al.*,2015).

Conversion of waste into organic manure for use in agriculture is considered an alternative approach to manage wastes and improve the soil organic matter content in low-fertility soils (Sudharmaidevi *et al*., 2017). Thermochemical organic fertilizer (TOF) is a non-conventional organic manure produced by thermochemical treatment of degradable wastes. Thermochemical treatment of degradable wastes at 100 ^{0}C and ambient pressure will reduce the time taken for decomposition, without any problem of by product and leachate. Except for absence of microorganisms its quality is superior to conventional organic composts. This processing technology is a quick and viable key for waste disposal and the production of organic fertilizer (Sudharmaidevi *et al.*, 2017).

Custom-made thermochemical organic fertilizer for Nendran banana based on soil test and crop requirement recorded highest plant growth characters, total dry matter production and shelf life of fruits (Leno, 2017). Compared to farm yard manure it favoured continuous supply of micronutrients (Leno and Sudharmaidevi, 2018).

The nonconventional organic manure thermochemical organic fertilizer when fortified with nutrients had the highest N, K, S and micronutrients Mn, Zn, B content compared to conventional organic manures. With regard to C and N dynamics it showed a significant positive rhizosphere priming effect compared to conventional composts *viz,* microbial compost, vermicompost, aerobic compost and farmyard manure (Jacob, 2018).

2.3 CHARACTERIZATION OF ORGANIC MANURES

Turan (2008) reported that pH changes during composting. In the early stages of composting, pH declines initially and elevation in pH levels was observed, in the later stages of composting. Kalemelawa *et al.* (2012) reported that due to higher potassium release aerobic composting showed slightly higher pH than anaerobic process. A pH range of 7-8 is optimum for composting (Chan *et al.*, 2016). The pH of mature compost should be in the range of 6.0-8.5 (Hachicha *et al.*, 2009). Franke- Whittle *et al.* (2014) reported on the compost pH between 7.0 and 8.5, which is appropriate for a broad variety of microorganisms to grow optimally.

Composting results in increase of concentration of salts due to the decomposition of complex organic matter and formation of mineral salts such as ammonium ions and phosphates via transformation of organic matter. But EC decreases due to the volatilization of ammonia and precipitation of mineral salts (Chan *et al.*, 2016). At maturity, decrease in EC is due to formation of organic acids and volatilization of ammonia. EC value of animal manure composts will be higher than organic waste composts and higher EC indicates the higher nutrient or ion concentration (Ko *et al.*, 2008). Plant growth is supported by the mature composts with lower EC values and high EC causes negative effect on crop (Yang *et al.*, 2015). According to Mohee *et al.* (2015), the safe range of EC for the compost is <3.5 dS m^{-1}.

Raw green wastes will have 20 to 30% of TOC, 25 to 50% in household waste and 30 to 40% in sludge and during composting TOC decreases due to degradation and mineralisation of organic substances to CO_2 by microbial action (Azim *et al.*, 2018). C/N ratio is the common parameter used to judge the maturity of compost. A C/N ratio of less than 20 is considered to be mature compost. But it depends much on the initial materials used (Azim *et al.*, 2018). C/N ratio decreases during composting but it may not be a good indicator of compost maturity because it depends on raw material (Chen and Inbar, 1993).

In general the total nitrogen is 1 to 4% of the total dry weight of compost (Brinton and Evans, 2000). Zhang and Sun (2014) mentioned that compost particle size is essential for controlling exchange of gas and water, water holding capacity, and porosity. Faverial and Sierra (2014) recorded 46% organic matter, 2.2% N, 2.1% K and 20% lignin in composts based on a composting research of household degradable waste. Rao *et al.* (2008) observed that N content in urban waste compost increased from 0.78% to 1.29% and in industrial composts from 0.75% to 1.23%. Chaudhary *et al.* (2017) obtained values of 0.36 to 1.50 % for N, 0.05 to 1.60 % for P and 0.5-2.26 % for K in multiple organic manures from rice straw, wheat straw, FYM and green manure.

One gram of well ground sample was digested with 10 ml of concentrated HNO_3 and 3 ml $HClO_4$ in a 100 ml conical flask and evaporated to dryness. The residue was dissolved in 5 ml of 6 N HCl and made up to 50 ml with double distilled water and used for determination of total Pb, Cd and Ni using the standard conditions for each element in an atomic absorption spectrophotometer (AOAC, 1980).

Ko *et al.* (2008) stated that compost mass decrease (40%–50%) was accompanied by a rise in metal ion concentration. There has been a reduction in Fe, Mn, Ni, Cr and Zn in various compost kinds since the beginning of the composting cycle. The formation of metal-humus complexes caused heavy metals to decrease during composting, making them biologically unavailable (Bohacz, 2018).

2.4 COMPOST MATURITY PARAMETERS

According to Azim *et al.* (2018) when the composted material do not heat up more after turning, do not become anaerobic during storage and do not take nitrogen to the soil after its amendment, it shows maturity of compost. The agricultural value of a compost cannot be established by a single parameter, several chemical and stability parameters have been used (Bernal *et al.*, 2009).

2.4.1 Physical and chemical parameters

Some of the composting parameters which determine compost maturity are moisture content, carbon-nitrogen ratio, microbial activity, germination index, cation exchange ability, humic substance content, water-soluble carbon compost concentration, dissolved organic matter, and ratios of $NH_4{}^+$-N to $NO_3{}^-$-N (Azim *et al.*, 2018). Physical characteristics such as temperature, colour, odour and moisture are also components of the compost maturity description criteria (Oviedo-Ocana *et al.*, 2015).

Moisture content is a parameter strongly linked to microorganisms because they use water to transport nutrients and energy components through the cell membrane like all living humans (Roman *et al.*, 2015). If moisture is less than 30%, bacterial activity will be restricted and if over 65%, it will reduce the compost porosity resulting in anaerobic development and unpleasant odour emissions. (Azim *et al*, 2018). Maintaining an ideal temperature in the thermophilic range may be a prerequisite for faster and higher composting rate. Temperature affects both the particular nature of the microbiological population and the decomposition rate and type (Kumar *et al.*,2010).

During composting, cation exchange ability (CEC) tends to improve as organic materials are humified and carboxyl and phenolic functional groups are formed (Wichuk and McCartney, 2013). Compost must be considered mature by a CEC greater than 60 meq 100 g^{-1} of organic matter (Azim *et al.,* 2018).

The nitrate concentration should be higher than the ammonium concentration at the completion of composting activity and ratio of ammonium to nitrate nitrogen concentrations will indicate the compost maturity (Ko *et al*., 2008). The composting temperature must be maintained at a level that ensures a reduction of pathogens, usually 55° C for 3 to 5 days (Azim *et al*., 2018). Nitrifying microorganisms result in a reduction in ammonium content and an increase in the manufacturing of nitrate. The ratio of NO_3^- to NH_4^+ can be used as a compost maturity indicator (Albrecht, 2007).

2.4.2 Phytotoxicity parameters

One of the most significant characteristics in assessing composts as fertilizers that are directly linked to their maturity is the absence of phytotoxic impacts (Stachowiak *et al*., 2006).

Azim *et al.* (2017) performed a study to identify the prospective functional groups responsible for phytotoxicity in compost and to determine the optimum initial C: N ratio for peak residue regeneration. The findings showed that the least phytotoxic impact was observed with the compost with the original C: N ratio of 35 and it is the most humified. The findings indicated that a credible quality test for compost maturity could be the phytotoxicity test with 50 percent compost water extract.

Composting process will help to remove some organic contaminants like ammonia, phenol *etc* while most of the heavy metals will remain in the end product and composting will not vanish them. So it is important to analyse the concentration of heavy metals in the compost (Ko *et al*., 2008).

To ensure balanced nutrients for the microorganisms during composting, cow manure was co-composted with rice-straw. High density and humidity content of rice-straw reduced the nitrogen-carbon proportion of cow manure. Further Zhou *et al,* 2015 suggested thermochemical pre-treatment in order to enhance the composting of rice straw by solubilization of hemicellulose.

2.5 EFFECT OF ORGANIC MANURES ON ROOT PHENOMICS, SOIL BIOLOGICAL ACTIVITY AND ON GROWTH AND YIELD OF CROPS

2.5.1 Root phenomic characters

A main restriction of plant growth in terrestrial ecosystems is the suboptimal availability of water and nutrients. Therefore, acquiring soil resources through plant roots is a significant element of plant fitness and productivity in agriculture. Plant root systems consist of a collection of interacting phenes or characteristics. Phenes are the plant phenotype units and phene states are the variation in the shape and function that a specific phene may take. Root phenes can be categorized as affecting the acquisition or use of resources, influencing development by exploration or exploitation, and being either metabolically important or neutral (York *et al.*, 2013). Agronomic procedures affect the root development, proliferation and distribution in the soil profile, which in turn influences the characteristics and yield of the soil. The availability of soil water and nutrients in cropping systems changes root development and distribution (Liu *et al.*, 2015).

A research by Shao *et al.* (2019) on the plasticity of the architecture of the root system in reaction to planting density and its impact on maize yield showed that genotypes with medium root size, medium root angle and more inter-row root distribution had less root-to-root competition and increased yield at high planting density. In India, the most commonly used organic manure is FYM (Reddy *et al.*, 2015). Application of farmyard manure improved soil physical conditions and enhanced root proliferation (Hati *et al.*, 2009). The ability of the root system to respond morphologically to localised nutrient supply is considered an important characteristic for nutrient uptake from soil (Rabbi *et al.*, 2017).

Root phenomic alterations occur in response to soil environment to reduce the metabolic cost of maintaining the root system, while maximizing nutrient acquisition (Hetrick, 1991). Plants are capable of modifying their root architecture in response both biotic and abiotic signals received from soil (Rabbi *et al.*, 2017). Organic materials have a clear-cut influence on root architecture, root spread and nutrient uptake. Humic acids have auxin like activity and it stimulates lateral root development (Trevisan, 2010).

Soil profile with higher organic matter accumulation shows higher root density and promotes root proliferation. Organic fractions like humic acid, fulvic acid and humin have high potential to increase root length density compared to auxin. Among them humic acid has a high potential compared to humin and fulvic acid (Sainju and Good, 1993). The humic acid treatment induced the proliferation of root mitotic sites and favours cell differentiation and new lateral root induction. The number of lateral roots increased by 22 to 111% in maize treated with different humic acid. The humic acid produced through the composting process enhanced the principal root length by 30 to 40% compared to non-composted humic acid (Jindo *et al.*, 2012).

Rhizobium IRBG74 colonies on the roots of *Arabidopsis thaliana*, influenced the root development which leads to inhibition in the growth of main root but enhancement in the formation of lateral roots (Zhao *et al.*, 2018).Compared to topsoil foraging for P and deep steep root system for N acquisition K requires intermediate architecture to reach less mobile potassium in soil (White, 2013). Bilalis *et al.* (2015) from their research on pea crop confirmed that the organic fertilisation increased root density and decreased the root penetration resistance compared to conventional fertilisation.

Thermochemical digest, cocopeat and soil mixed in 1:2:1 ratio exhibited higher root weight and root volume compared to different treatments with thermochemical digest, coirpith compost and soil mixed in different ratios (Jayakrishna, 2016). In a study, barley crops were cultivated in sand culture for 21 days, continually irrigated at three distinct root system depths with nutrient solution. It was supplied with very low or high levels of a single inorganic nutrient, maintaining all other nutrients at a high concentration. The studies indicate that any portion of the root system requires appropriate external nitrogen and phosphorus levels for ideal lateral root development (Drew, 1975). When roots find a nutrient-rich area or patch, they often proliferate in it. Stress induced root modifications are suggested as the main mechanism by which crops obtain the naturally occurring heterogeneous nutrient supply in the soil (Hodge, 2004).

2.5.2 Soil biological activity

For many microbes, roots are the sources of substrates and energy and act as agents for biological, chemical and physical soil changes; they are an essential component of soil biology and soil science (Gregory, 2006). Variations were noted in soil microbial community structure with respect to soil type, clay content, organic carbon content, pH and ability to hold water (Brockett *et al.*, 2012).

2.5.2.1 Soil microfauna

The addition of organic matter enhances both microbial diversity and population (Albiach *et al.*, 2000). Tuyen *et al.* (2008) noted that the largest bacterial population were the largest among all other microorganisms based on the outcomes of a continuous fertilizer experiment. The soil microbial biomass, populations of bacteria, fungi, actinomycetes and microarthropods increased as well as soil enzyme activities boosted in the compost treated soils (Chang *et al.,* 2007).

In a research, straw application influenced fungal colonies more than bacterial number because saprotrophic fungi are recognized as efficient decomposers that contribute to the decomposition of organic matter and thus boost the mineralization of carbon in soil (Maarastawi *et al.,* 2018). Food waste compost are comprised of the remains of fruit and vegetables and rich in carbohydrate. It is an easy source of carbon, nitrogen and energy for microorganisms. This resulted in increased soil microbial populations and soil biomass. So, food waste compost could be a substitute for chemical fertilizer to increase soil microbial populations and improving the groundnut growth (Chitravadivu *et al.*, 2009).

2.5.2.2 Soil macrofauna

All earthworm species were abundant in organic fertilizers treated plots compared to no manure control. Application of both inorganic and organic fertilizers showed significantly higher earthworm count. Influence of organic fertilizer is more on populations of *Lumbricus terrestris* compared to other species

(Edwards *et al.*, 1995). Scullion and Ramshaw (1987) evaluated the impact on earthworm activity in grasslands of multiple manurial treatments and concluded that application of poultry manure enhanced earthworm population.

Earthworm population, total earthworm weight and average worm weight can be used as biological indicators of soil health. A good agricultural system will have earthworm population of 10 per square feet of soil surface (Reganold and Palmer, (1995). Kanchikerimath and Singh (2001) noticed that earthworm activity usually increased with the addition of FYM to the soil and that the earthworm biomass decreased with the use of chemical fertilizers without organic inputs and this trend increased with time.

In a long-term organic fertilization experiment of green manuring and application of farmyard manure behaviour of soil microarthropods were studied. Results revealed that farmyard manure increased the soil carbon and nitrogen whereas soil microarthropods were abundant due to green manure application. Here soil microarthropods increased by immediate food supply rather than soil chemical parameters (Kautz *et al*., 2006).

Soil microarthropods are capable of modifying the natural rhizosphere microflora. They are known for suppressing some soil born pathogens. Rhizosphere-inhabiting collembolans, *Proisotoma minuta* and *Onychiurus encarpatus* grazed preferentially upon the cotton-seedling pathogen *Rhizoctonia solani* (Curl *et al*., 1998). *Unychiurus urmafu* a soil-inhabiting species of Collembola, locates its source of food, hyphomycene fungi, from volatile compounds produced from mycelium (Bengtsson *et al*., 1988). The microarthropods did not affect the loss of nutrients and the biomass and community structure of other microbes. In terms of plant growth, microarthropod species are functionally insignificant (Liiri *et al*., 2002).

In a work done by Olla *et al*. (2013) soil pH, organic carbon (OC) and soil microarthropod population were studied in a soil contaminated with spent oil and ameliorated with different sources of organic manures. The addition of poultry manure considerably enhanced their population, especially the collembola population, by about 48.48 % compared to the control plots. The outcome showed the beneficial effect of organic manures on both soil chemical properties and population density of micro-arthropods. Through research on the root effect on soil organisms under separate fertilization, Eo and Nakamoto (2007) reported that increased population densities of microarthropods in organically fertilized plots apparently associated with increased microbial activity.

2.5.2.3 Soil enzyme activity and microbial biomass carbon

Dehydrogenase is an oxidoreductase enzyme that exists only in viable cells and are indicators of overall microbial metabolic activity (Taylor *et al.*, 2002). Soil dehydrogenase activity and CO_2 production were measured as indices of soil biological activity (Marinari, 2000). Aparna (2000) reported that higher activities of dehydrogenase recorded in an alluvial soil by the application of organic amendments such as vermicompost in combination with lime and fertilizers than that by FYM or green leaf manure.

Gopalaswamy and Kannaiyan (2000) stated that the dehydrogenase activity is the indicator of microbial metabolic activity in the soil and increased dehydrogenase response to FYM and application of vermicompost was primarily due to increased organic carbon content, which in turn improved the microbial population. Dehydrogenase activity is known to have strong correlation with soil organic C content (Madejon *et al.*, 2007). Long term applications of FYM @ 10 t ha^{-1} + 100 per cent NPK recorded significantly higher dehydrogenase activity and the rise in dehydrogenase activity was 18.6 and 8.9 percent over 100 percent of NPK and 150 percent of NPK treatments through mineral fertilizers alone (Bhattacharyya *et al.*, 2008).

The total nitrogen (N), organic carbon (C), microbial biomass contents in soil and enzymatic activity increased in manure-amended soil (Ge *et al.*, 2009). The microbial biomass and soil enzyme activities were increased by the long-term manure and fertilizer treatments (Mandal *et al.*, 2007). Poultry manure is the best source for enhancing total organic carbon, soil enzymatic activities and microbial biomass carbon in the soil compared to farm yard manure and municipal solid waste compost (Bashir *et al.,* 2015). This improved effect is due to greater fraction of organic matter in poultry manure and it is most degradable and susceptible to rapid mineralization (Tejada *et al*., 2006). Jannoura *et al*. 2014 conducted an experiment to compare effect of organic fertiliser on microbial biomass indices in soil and roots. The study revealed that soil microbial biomass and pea dry matter yield were positively correlated and organic fertiliser increased microbial biomass carbon.

2.5.3 Growth and yield of crops

It is found that poultry manure (PM) is the most appropriate organic fertilizer currently available for organic vegetable cultivation, whether processed or unprocessed. Recommendations of PM for amaranthus on peat soil would be around 20 t ha^{-1} (Vimala *et al.*, 2001). Bashir *et al.* 2015 from their study indicated that different organic sources have different bio-chemical properties. Maerere *et al.* (2001) conducted pot and field experiments on amaranthus crop to compare the effects of farmyard manure, goat and poultry manures on crop yield, root growth and stated that shoot dry matter yield, tap root length and root dry weight followed the trend poultry manure > goat manure > dairy cow manure. They also conducted experiment over three monthly crop cycles to compare soil available levels of N and P and results showed that responses were highest after the third crop harvest suggesting that mineralization of organic N and P increased with time. Two organic fertilisers, manure extract and plant extract were compared to standard N-P-K fertilization and no fertilizer control on strawberry crop. Results showed that use of organic fertiliser effected growth of the strawberry plants at a level comparable to that of chemically fertilized plants (Malusa *et al.,* 2010). Yolou *el al.* (2015) noted that both the muncipal solid waste compost and the NPK fertilizer considerably enhanced the yield and yield characteristics of stove and grain relative to the control. A complete randomized block design experiment with three replications was conducted to study influence of organic fertilisers on growth and yield of tomato. Different organic fertilisers were applied at the rate of 20 t ha^{-1}. Tomato growth increased significantly as compared to control according to the treatments in the order of municipal waste compost > poultry manure> cow manure> sheep manure > no fertilizer (Mehdizadeh *et al*., 2013). Chicken manure, cow manure and paddy rice were mixed together in 1:1:0.5 ratio to from organic fertilizer and applied to the rice field at 5 levels (0.5, 1.0, 1.5, 2.0 and 2.5 t ha^{-1}). Maximum grain yield was observed with the 2 t ha^{-1} in two consecutive years (Siavoshi *et al.,* 2011). Agegnehu *et al.* (2016) revealed that the addition of compost and N fertilizer resulted in twice the yield of barley grain (3321 kg ha^{-1}) compared to the yield (1560 kg ha^{-1}) with the same N fertilizer alone. Kumar *et al.* (2018) investigated the impact of organic and inorganic nutrient sources on yield, quality and nutrient absorption by mustard variety, Pusa Mustard 30 (*Brassica juncea* L.) This experimental findings indicated that highest development parameters (plant height, branches plant^{-1}, dry matter accumulation and leaf zone index), yield attributes (silique length, silique plant^{-1}, silique seeds and test weight), yield (grain and stove) were registered using 50 percent RDF + FYM 6 tons ha^{-1} + vermicompost 2 tons ha^{-1} + biofertilizer at which was greater than the remaining treatments. Acharya and Kumar (2018) explored the impacts of organic manure sources such as vermicompost, poultry manure, sheep and goat manure and FYM livestock on development and yield attributing greenhouse plant characters with three organic manure application levels *viz.*10, 20 and 30 t ha^{-1}. The findings showed that the application of organic manure enhanced plant growth, improved yield of garlic and its parts, number of cloves per bulb, diameter and weight of the bulb. Highest yield of garlic (105.03 q ha^{-1}) was attained in plots with poultry manure application @ 20 t ha^{-1}.

A randomized complete block design experiment was conducted to study the influence of different organic manures on the growth, yield and quality of okra. Treatments were different organic manures including vermicompost, poultry manure and FYM with no manure control. The results showed that FYM applied at the rate of 20 t ha^{-1} recorded the highest yield of 10.39 t ha^{-1} with the BC ratio of 3.56 (Premsekhar and Rajashree, 2009). The study suggests the use of organic fertiliser over chemical fertilizer due to better performance in vegetative growth and development. Application of poultry manure at 10 t ha^{-1} yielded highest plant height, number of leaves, leaf length, leaf width, leaf area and leaf area index in amaranthus (Kahu *et al.*, 2019). This effect may due to slow decomposition and release of nutrients from organic fertiliser. Jayakrishna (2017) reported that the custom blended thermochemical digest had a significant impact on higher dry matter production and plant height at 30 D, 60 D and 90 D in chilly. Thermochemical digest fortification with NPK @ 25 g plant^{-1} yielded the largest output. In response to enhanced fertilizer N application, the highest potato yield was 36 Mg ha^{-1} (at 250 kg N ha^{-1}) without compost and 39 Mg ha^{-1} (at 213 kg N ha^{-1}) with compost (Peters *et al.*, 2004). In chilli substitution of recommended N with organic manures like neem cake, poultry manure or green manures like cowpea or glyricidia gave comparable yields and net returns as that of POP recommendation of KAU (Mecrabai *et al.*, 2003). According to Akparobi 2009, the highest mean values for plant growth parameters such as plant height, number of leaves, leaf area, fresh and dry weights are obtained with application of manure level of 35 t ha^{-1} for amaranthus. In a pot culture experiment with growth media treated with heavy metals lead and cadmium, the application of organic manure drastically reduced the heavy metal content in the root and shoots of amaranthus (Alamgir *et al.*, 2011).

As an essential component of plant bodies, roots are engaged in nutrient and water acquisition, plant hormone synthesis, plant anchorage, and are also the site of soil bacteria interaction. Reviewed studies (Maerere *et al.*, 2001; Jayakrishna, 2017) indicate positive response and correlation of root characters of different organic manures on the yield and productivity of vegetables like amaranthus. However detailed studies on the influence of various aspects of root phenomics on crop response is scanty. The exact relationship and interactions of rhizospheric microorganisms that influence these phenomic characters are also meagre. So present study aims at an in-depth assessment of various root phenomic characters in relation to the rhizospheric microbial activity and their impact on growth and yield of amaranthus.

Materials and Methods

3. MATERIALS AND METHODS

A study entitled "Root phenomics and soil biological activity in response to thermochemical organic fertilizer application" was conducted from October 2017 to April 2019 at the Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani with the objective of studying the root phenomics and soil biological activity in response to thermochemical organic fertilizer application as compared with conventional organic manures and its effect on growth and yield of Amaranthus. The three parts of study were. 1. The preparation and characterization of organic manures 2. Pot culture trial to study the effect of thermochemical organic fertiliser on root phenomics and soil biological activity 3. Field micro plot trials to study the effect of thermochemical organic fertilizer on root phenomics, soil biological activity and growth and yield of amaranthus. The materials and methods used for study are described in this chapter.

3.1 PREPARATION OF ORGANIC MANURES

The organic manures *viz*, conventional compost (CC), vermicompost (VC) compost using microbial inoculants (MC), thermochemical organic fertilizer (TOF) and fortified thermochemical organic fertilizer (TOF-F) were produced from same type and proportion of waste materials to facilitate the ease of comparison. The type and composition of wastes used for composting were as follows – food waste (85%), agriculture waste (10%) and leaf litter (5%). The food wastes used for composting comprised of vegetable wastes (85%), rice (10%), and fish and meat (5%).

All three composts *viz*, conventional compost (CC), vermicompost (VC) and compost using microbial inoculants (MC) were prepared in pits. Pits of size 2 m×1 m×0.5 m were dug and bunds were made at the borders to avoid entry of rain water and shade was provided. Vegetable wastes were collected from the HORTICORP market in Thiruvananthapuram city. These materials were chopped and mixed well with the other waste materials collected from the campus. First one-inch layer of coir pith and husk were put inside the pit. Above that degradable waste materials were filled in layers. The CC was prepared using cow dung slurry as

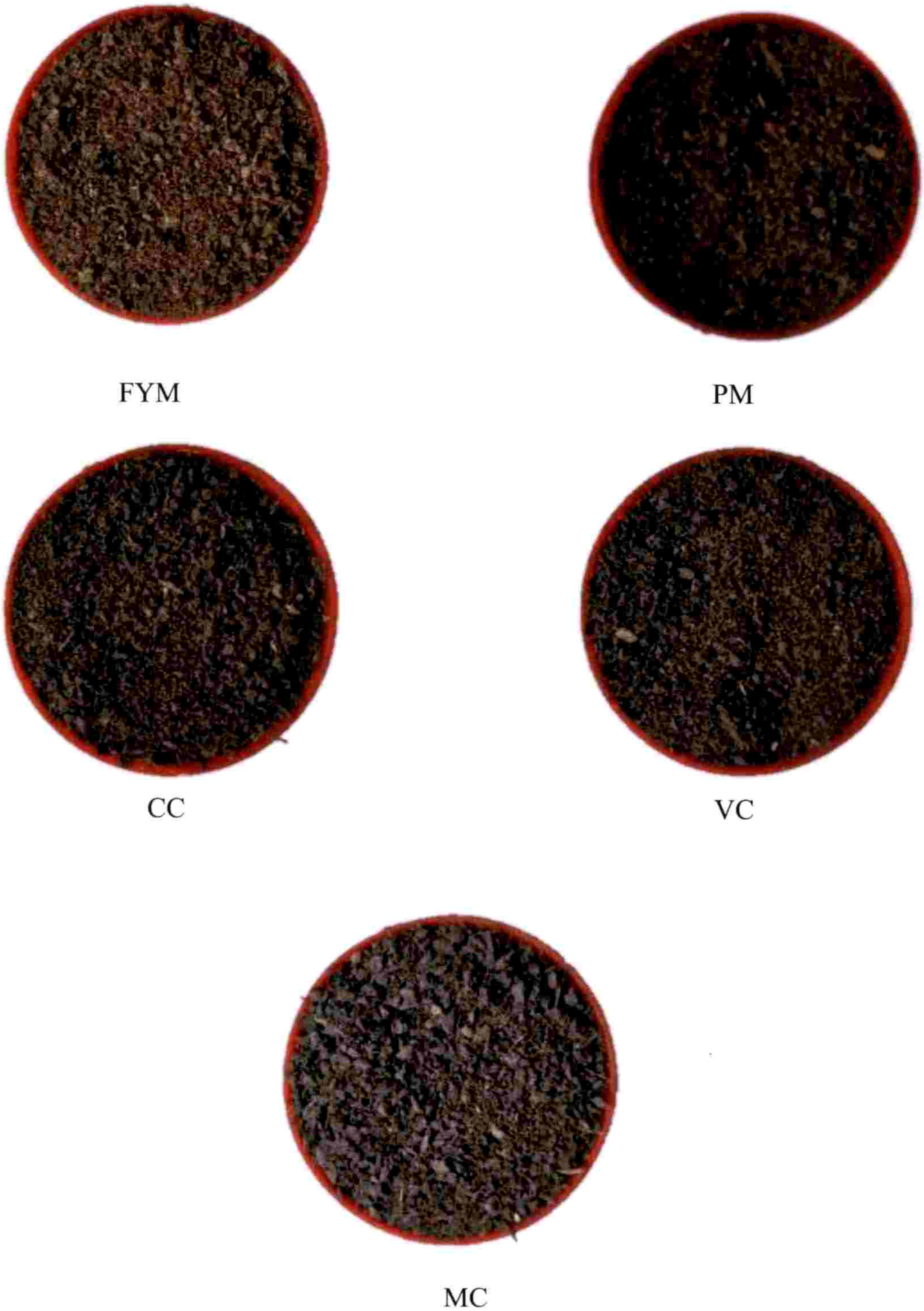

Plate 1. Organic manures used in the experiment (FYM-Farm Yard Manure; PM- Poultry manure; CC-Conventional compost; VC-Vermicompost; MC- microbial compost

inoculum. Composting waste materials were filled along with cow dung slurry in alternate layers. Composting materials were turned twice and regularly moistured to enhance the rate of decomposition process. Microbial compost (MC) was prepared using microbial inoculant obtained from Department of Agricultural Microbiology, College of Agriculture, Vellayani. Pits are filled with composting materials and microbial inoculant was spread over each layer. The pits were covered with sheets to avoid entry of rain water. VC was prepared using similar pits. Bottom layer of vermibed was made of a layer of coarse sand above which waste materials were filled in layers along with cow dung slurry. Waste materials were allowed to decompose. After two weeks earthworms were introduced to pits at the rate 1000–1200 adult worms (about 1 kg per quintal of waste material). Pits were covered with dry leaves and was kept moist by watering whenever necessary for the next one-month. In a period of two and a half months compost was ready for use (Plate1).

The thermochemical organic fertilizer (TOF) and fortified thermochemical organic fertilizer (TOF-F) were produced by the thermochemical decomposition of degradable solid wastes from the collected lot as described by Sudharmaidevi *et al.*, 2017 (Plate 2). The degradable waste materials were ground and subjected to thermochemical treatment, which resulted in the decomposition of degradable waste materials. Decomposed materials were blended with coir pith @ 40 g kg^{-1} waste and charcoal powder @ 30 g kg $^{-1}$ and dried in the sun. The TOF-F was prepared for the study by fortifying the TOF with N (1.5%), P (1%), Ca (1%), Mg (0.5%), Zn (50 mg kg^{-1}) and B (5 mg kg^{-1}).

Farmyard manure (FYM) and poultry manure (PM) were purchased from the Instructional Farm, Vellayani (Plate 1). All composts *viz*, CC, VC, MC, FYM and PM were sieved using 2 mm sieve and used in the experiment.

3.1.1 Characterization of organic manures

Design: CRD

Treatments: 8

Replication: 4

All the three prepared composts *viz*, conventional compost (CC), vermicompost (VC) and compost using microbial inoculants (MC),

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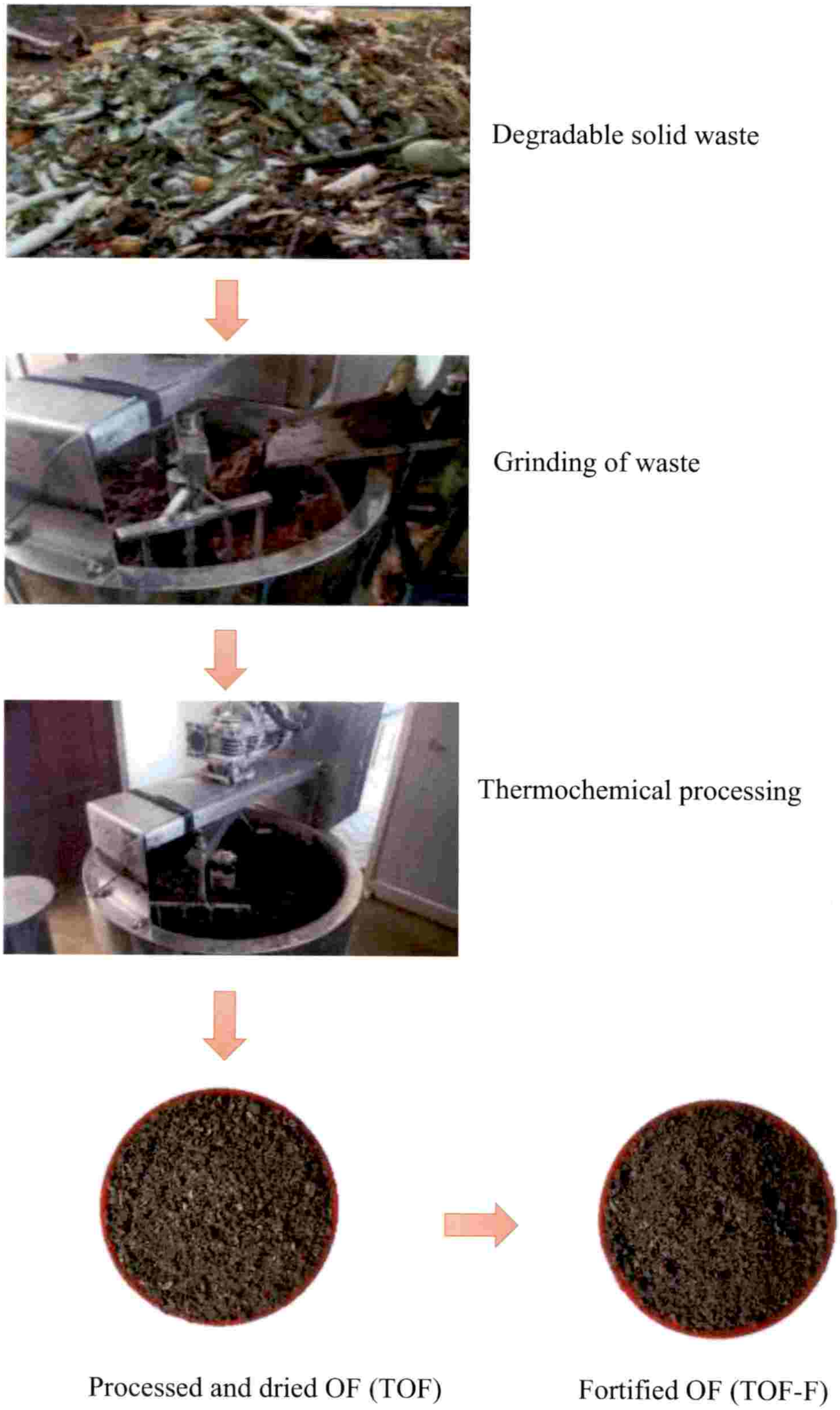

Plate 2. Preparation of thermochemical organic fertilizer

thermochemical organic fertilizer (TOF) and fortified thermochemical organic fertilizer (TOF-F), FYM and poultry manure were characterized for chemical properties as per standard methods detailed in Table 1.

Table 1. Standard analytical methods for manure characterization.

Parameter	Method	Reference
pH (1:2 w/v of solid: liquid)	Potentiometry (Cyber Scan PC510, EuTech Instruments, Singapore)	FAI (2017)
EC (1:2 w/v of solid: liquid)	Conductometry EC-TDS Analyzer (CM 183, Elico India)	FAI (2017)
Total organic carbon (TOC)	Weight loss on ignition CHNS Analyzer (Vario EI cube, Elementar, Germany)	FAI (2017)
Total N	Microkjeldahl distillation after digestion with H_2SO_4 (Kelplus Ultima Trio Dist TS)	Weishaar *et al.* (2003)
Total P	Nitric-perchloric (9:4) acid digestion and spectrophotometry technique using vanado-molybdo yellow colour method (Double Beam UV-VI spectrophotometer)	Greenberg *et al.* (1992)
Total K	Nitric-perchloric (9:4) acid digestion and flame photometry (Digital Flame Photometer 130, Systronics, India)	FAI (2017)
Total Ca, Mg,	Nitric-perchloric (9:4) acid digestion and titration with EDTA	FAI (2017)
Total Fe, Cu, Mn, Zn	Nitric-perchloric (9:4) acid digestion and atomic absorption spectrometry (A Analyst 400, Perkin Elmer Inc., USA)	FAI (2017)
Total B	Spectrophotometry - Azomethine-H method (Double Beam UV-VIS spectrophotometer 2201, Systronics)	Roig *et al.* (1996)
Total Pb and Cd	Nitric-perchloric (9:4) acid digestion and emission spectroscopy (ICP-OES)	Wei and Yang (2010)

3.2 POT CULTURE TRIAL

3.2.1 Location and season

A pot culture trial was conducted at the department of Soil Science and Agricultural chemistry, College of Agriculture, Vellayani to study the effect of thermochemical organic fertilizer on root phenomics and soil biological activity. Amaranthus variety – Arun was used as test crop. The experiment was conducted from November 2018 to December 2018.

3.2.2 Weather parameters

The weather data during cropping period showed that mean temperature of the location ranged from 23.73°C to 31.79°C and relative humidity from 73.73% to 93.04%. A total rainfall of 48.25 mm was received during the crop period. The weather parameters during the crop period are presented in Appendix 1.

3.2.3 Growing media preparation

The pot culture experiment to study the root phenomics and biological activity was conducted with growth media prepared using different organic manures. Potting mixture (1.40 kg) is prepared with perlite, coir pith compost (CPC) and organic manure in the ratio 1:2:1 on volume basis which would facilitate root phenomic studies. A no manure control was also kept (Plate 3).

3.2.4 Design of the experiment

Design : CRD Treatments : 8 Replication : 4

3.2.5 Treatments

The treatments of pot culture study are given in Table 2. Perlite, coir pith compost (CPC) and organic manure were mixed in the ratio of 1:2:1 on volume basis and filled in the pots. Amaranthus seedlings are grown in pro tray in nursery using similar growth mixtures as treatments. Two 15 days old seedlings are transplanted per pot and irrigation was given. Thinning was done after 5 days to maintain one plant per pot. Irrigation was given whenever necessary and crop was maintained for 30 days (Plate 3).

Pots filled with growing media

Amaranthus grown in pots

Plate 3. A view of pot culture trial

Table 2. Treatment combinations of pot culture experiment

Treatment code	Treatments
T1	Perlite + CPC + FYM
T2	Perlite + CPC + PM
T3	Perlite + CPC + CC
T4	Perlite + CPC + VC
T5	Perlite + CPC + MC
T6	Perlite + CPC + TOF
T7	Perlite + CPC + TOF-F
T8	Perlite + CPC

3.2.6 Growing media analyses

The growing media sampling was done initially and at harvest and analysed for various parameters by standard procedures as mentioned in Table 3.

Table 3. Analytical procedures of growing media in pot culture trial.

Parameter	Method	Reference
pH (1:2.5 w/v of solid: liquid)	Potentiometry (Cyber Scan PC510, EuTech Instruments, Singapore)	FAI (2017)
EC (1:2.5 w/v of solid: liquid)	Conductometry EC-TDS Analyzer (CM 183, Elico India)	FAI (2017)
OC	Wet digestion method	Walkley and Black (1934)
Available N	Alkaline potassium permanganate method (Kelplus Ultima Trio Dist TS-B)	Subbiah and Asija (1956)
Available P	Bray No. 1 extraction and spectrophotometry (Double Beam UV-VIS spectrophotometer 2201, Systronics)	Jackson (1973)

Available K	Neutral 1N ammonium acetate extraction and flamephotometry (Digital Flame Photometer 130, Systronics, India)	Jackson (1973)
Available Ca, Mg	EDTA titration method	Hesse (1971)
Available S	0.15% $CaCl_2$ extraction and turbidimetry (Double Beam UV-VIS spectrophotometer 2201, Systronics)	Massoumi and Cornfield (1963)
Available Fe, Mn, Zn, Cu	0.1 N HCl extraction and Atomic Absorption Spectrophotometry (A Analyst 400, Perkin Elmer Inc., USA)	Osiname *et al*. (1973)
Available B	Hot water extraction and spectrophotometry (Azomethine – H method) (Double Beam UV-VIS spectrophotometer 2201, Systronics)	Gupta (1967)
Available Pb and Cd	Nitric-perchloric (9:4) acid digestion and emission spectroscopy (ICP-OES)	Jackson (1973)

3.2.7 Plant analysis

The plant samples were taken at the time of harvesting. Root and shoot samples were taken separately. The samples were shade dried, oven dried and powdered and following analysis were done in shoot and root separately as per standard procedures mentioned in Table 4.

Table 4. Analysis of plant samples in pot culture experiment

Nutrient	Method	Reference
N	Microkjeldhal distillation after digestion in H_2SO_4 (Kelplus Ultima Trio Dist TS-B)	Jackson (1973)
P	Nitric-perchloric (9:4) acid digestion and spectrophotometry using vanado-molybdo yellow colour method (Double Beam UV-VIS spectrophotometer 2201, Systronics)	Jackson (1973)

K	Nitric-perchloric (9:4) acid digestion and flamephotometry (Digital Flame Photometer 130, Systronics, India)	Jackson (1973)
Ca, Mg	Nitric-perchloric (9:4) acid digestion and EDTA titration method	Piper (1966)
S	Turbidimetry- $BaCl_2$ method (0.15% $CaCl_2$ extraction) (Double Beam UV-VIS spectrophotometer 2201, Systronics)	Chesnin and Yien (1951)
Fe, Cu, Zn and Mn	Nitric-perchloric (9:4) acid digestion and atomic absorption spectrophotometry (A Analyst 400, Perkin Elmer Inc., USA)	Lindsay and Norvel (1978)
B	Azomethine- H specrophotometry (Double Beam UV-VIS spectrophotometer 2201, Systronics)	Bingham (1982)

3.2.8 Biological properties

Initial and final growing media samples of pot culture growing media were analysed for biological properties. Fresh samples were used for analysis which were maintained at field moisture level and refrigerated at 4 ^{0}C whenever necessary (Abellan *et al.*, 2011).

3.2.8.1 Soil micro fauna: Microbial load

Populations of bacteria, fungi and actinomycetes were determined by serial dilution method (Timonin, 1940).

3.2.8.2 Soil macrofauna

3.2.8.2.1 Earthworm population

Immediately after harvesting the whole plant, the pot mixture was spread on a sheet of paper and number of earthworms per pot were counted.

3.2.8.2.2 Micro arthropods

The method used for the extraction of micro arthropods in pot mixture was using the Modified Berlese-Tullgren Funnel Extractor method (Macfadyen, 1961). One kg growing media was placed over a wire gauze in a conical container. The bottom end of the container was dipped in a collecting vial containing ethanol-water mixture. The mixture was heated using 40 watts bulb and heating was continued for one day. The arthropods moved down in response to the temperature gradient created and eventually got collected in a collecting vial. The collection vial content was transmitted straight to a counting device and its population was counted under a binocular microscope.

3.2.8.3 Dehydrogenase activity

Dehydrogenase activity was determined as per the procedure described by Casida *et al.*, 1964.

3.2.8.4 Microbial biomass carbon

One gram of dry growing media was taken. The microbial biomass carbon was determined in the moist growing media by the chloroform fumigation extraction method (Vance *et al.*, 1987).

3.2.9 Shoot characters

3.2.9.1 Plant height

Amaranthus plant height was recorded in cm from the base to the growing tip just before harvest.

3.2.9.2 Primary branches per plant

Total number of branches arising from main stem were counted.

3.2.9.3 Shoot weight

The fresh weight of harvested amaranthus shoot including leaves was recorded in g plant^{-1}.

3.2.9.4 Shoot dry matter

The fresh samples of shoots were initially shade dried and then oven dried at 65 ^{o}C till it attained constant dry weight and was expressed in g plant^{-1}.

3.2.10 Root phenomics

The plants were uprooted before flowering and the roots were washed in water and the following biometric observations were taken.

3.2.10.1 Number of primary roots

In amaranthus primary root develops into tap root, which was counted.

3.2.10.2 Number of secondary roots

All roots arising from primary roots were counted and recorded.

3.2.10.3 Root diameter

Root diameter was measured using vernier callipers. Observations were taken at three points along the length of roots and the average value was noted in mm.

3.2.10.4 Root weight

The fresh weight of uprooted amaranthus root was recorded in g plant^{-1}.

3.2.10.5 Root dry matter

The fresh root samples were initially shade dried and then oven dried at 65^{o}C. Drying was continued until it attained constant dry weight and was expressed in g plant^{-1}.

3.2.10.6 Root volume

Root volume was estimated using Archimedes water replacement principle. Root tissue was submerged in known volume of water in a measuring cylinder and the volume of water displaced was measured in cm$^{3.}$

3.2.10.7 Total root length

Root length of the uprooted plants was measured from base of the stem to the tip of main root in cm.

3.2.10.8 Root: shoot ratio

It is the ratio of the root dry weight to that of the shoot dry weight.

3.3 FIELD MICRO PLOT TRIALS

3.3.1 Experimental site and season

The field micro plot trial was conducted at the Model Organic Farm in College of Agriculture, Vellayani to study the effect of thermochemical organic fertilizer on root phenomics and soil biological activity. High yielding red amaranthus variety – Arun was used as the crop. Three crops of amaranthus were taken consecutively from January 2019 to April 2019.

Crop I (C1) – 5th January 2019 to 5th February 2019 (30 days)

Crop II (C2) – 15th February 2019 to 15th March 2019 (30 days)

Crop III (C3) – 20th March 2019 to 20th April 2019 (30 days)

3.3.2 Weather parameters

The weather data from the meteorological observatory located at the Instructional Farm, Vellayani was collected. The mean temperature of the location ranged from 22.66°C to 32.16°C and relative humidity from 66.15% to 91.11%. A total rainfall of 8.06 mm was received during the crop period. The weather parameters during the crop period were depicted in Fig 1.

3.3.3 Field preparation

The field was prepared to a fine tilth and 32 micro plots of 1.2 m×1.0 m size were formed. The amounts of manures/composts/organic fertilizers required were calculated and applied to respective treatment plots. Manures were mixed well with the soil in individual plots and left for one week before transplanting the seedlings (Plate 4).

3.3.4 Treatments

The quantity of manures/composts/organic fertilizers in the individual plots were computed on nitrogen equivalent basis of FYM. The treatments of the field micro plot trial are given in Table 5.

Table 5. Treatment combinations of the field micro plot trial

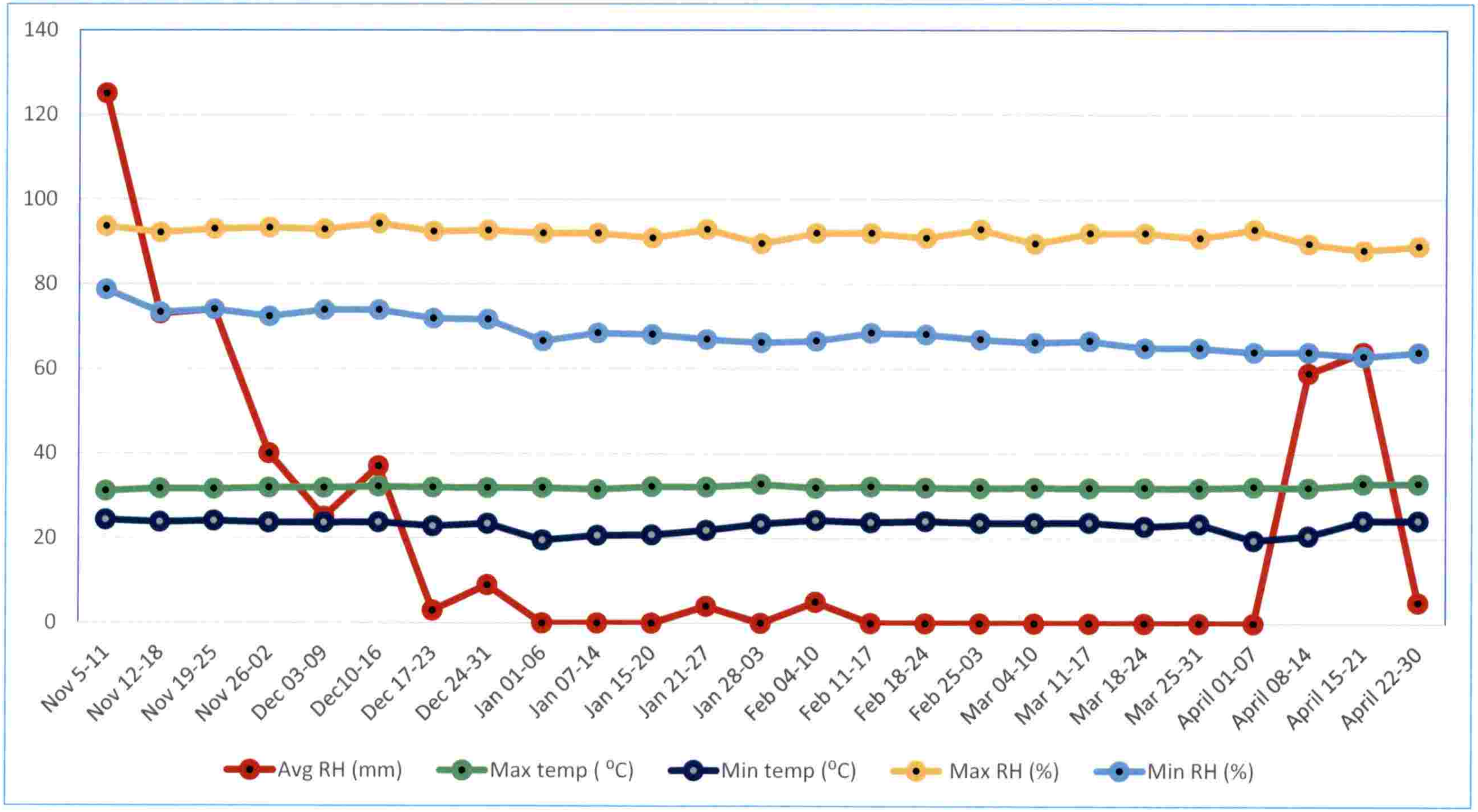

Fig. 1 Weather data from November 2018 to April 2019

Treatment code	Treatments
T1	Soil application of FYM as per organic POP (3 kg per plot)
T2	Soil application of PM (1 kg per plot)
T3	Soil application of CC (2.8 kg per plot)
T4	Soil application of VC (1.8 kg per plot)
T5	Soil application of MC (1.5 kg per plot)
T6	Soil application of TOF (1.1 kg per plot)
T7	Soil application of TOF-F (1.0 kg per plot)
T8	Control plot without manure

3.3.5 Design and layout of the experiment

Design : RBD

Replication : 4

Treatments : 8

Plot size : 1.2 × 1.0m

Spacing : 30×20 cm

No. of crops : 3

Table 6. Layout of the field micro plot trial

T_4R_1	**T_3R_2**	**T_1R_3**	**T_2R_4**
T_8R_1	**T_5R_2**	**T_6R_3**	**T_4R_4**
T_1R_1	**T_7R_2**	**T_5R_3**	**T_3R_4**
T_2R_1	**T_4R_2**	**T_8R_3**	**T_6R_4**
T_6R_1	**T_2R_2**	**T_7R_3**	**T_1R_4**
T_5R_1	**T_1R_2**	**T_4R_3**	**T_8R_4**
T_3R_1	**T_8R_2**	**T_2R_3**	**T_7R_4**
T_4R_1	**T_6R_2**	**T_3R_3**	**T_5R_4**

Field preparation

First crop

Second crop

Third crop

Plate 4. A view of field micro plot trials

Seedlings were grown in the nursery and 15-day old seedlings were transplanted in the field. Twenty seedlings were transplanted per plot at a spacing of 30 cm×20 cm. Field was irrigated twice a day to ensure better crop stand. The frequency of irrigation was reduced to once a day after a week. Crop was maintained for 30 days and harvested. Second and third crops were raised on the same plots with fresh addition of manures to respective treatments (Plate 4).

3.3.6 Plant protection

As red amaranthus varieties are susceptible to leaf blight disease preventive measures were taken. PGPR Mix II was collected from Department of Agricultural Microbiology, College of Agriculture, Vellayani. Foliar application @ 2% PGPR Mix II was done twice for a crop. Crop was irrigated without splashing of water to avoid spread of soil borne fungal spores of leaf blight disease.

3.3.7 Soil analyses

Soil sampling was done initially and after harvest of each crops. Samples are dried in shade, sieved using 2mm sieve and analysed for various parameters by standard procedures as mentioned in Table 3.

3.3.8 Plant analysis

The plant samples were taken at the time of harvesting. Root and shoot samples were taken separately. The samples were shade dried, oven dried at 67 °C and powdered and following analysis were done in shoot and root separately as per standard procedures mentioned in Table 4.

3.3.9 Biological properties

Initial soil sample as well as soil samples at harvest after each crop were analysed for biological properties as mentioned in section 3.2.8.

3.3.10 Shoot characters

Different shoot characters were measured as described in section 3.2.9.

3.3.11 Root phenomics

The roots were washed in water and the biometric observations were taken as mentioned in 3.2.10.

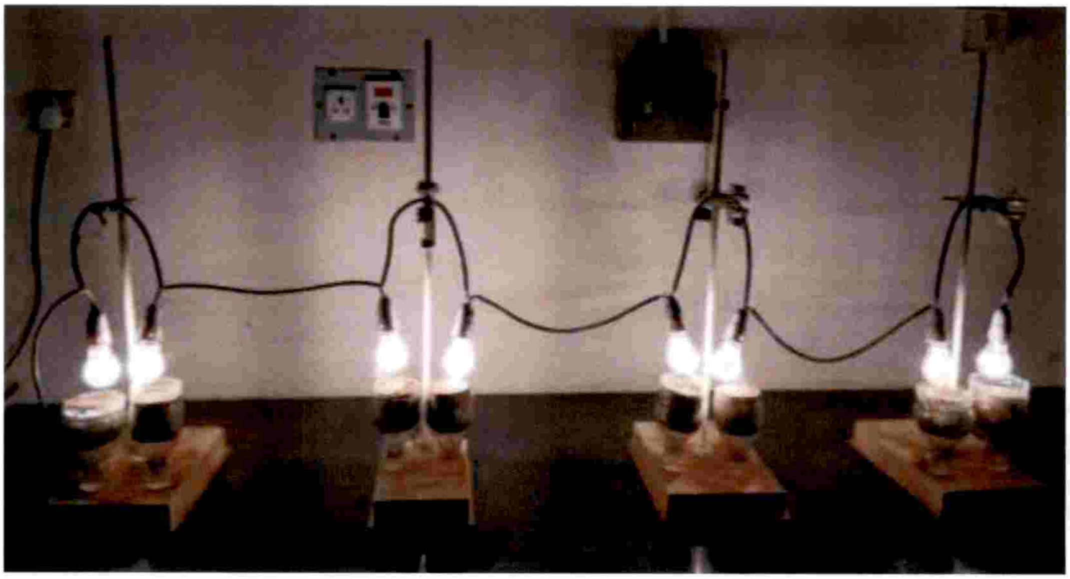

Plate 5. Microarthropod estimation by

Modified Berlese- Tullgren Funnel Extractor Method

Plate 6. Estimation of dehydrogenase activity

3.3.12 Incidence of pest and diseases

Disease incidence was calculated for amaranthus leaf blight.

$$\text{Disease incidence} = \frac{Number\ of\ plants\ infected}{Totol\ number\ of\ plants} \times 100$$

Percent disease index (PDI) was calculated based on disease scoring.

0-9 scale of disease scoring:

0 : No leaf area infected

1 : <1% of leaf area infected

3 : 1-10% of leaf area infected

5 : 11-25% of leaf area infected

7 : 26-50% of leaf area infected

9 : >51% of leaf area infected

$$\text{PDI} = \frac{Sum\ of\ all\ rating}{Totol\ number\ of\ rating \times Maximum\ rating} \times 100$$

3.3.13 B: C ratio

The benefit: cost ratio was calculated by using the following formula

$$\text{Benefit: cost ratio} = \frac{Gross\ monetary\ returns\ (Rs)}{Cost\ of\ cultivation\ (Rs)}$$

3.4 STATISTICAL ANALYSIS

The data generated from the characterisation of organic manures, pot culture trial and field micro plot trial were analysed statistically using OPSTAT software package. The means of treatments were compared with the values of critical differences at the 5% probability significance level, if the effects were significant.

Results

RESULTS

The results of the study entitled "Root phenomics and soil biological activity in response to thermochemical organic fertilizer application" at the Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani are presented in this chapter.

4.1 CHARACTERIZATION OF ORGANIC MANURES

All organic manures were characterised for electro-chemical and nutritional properties. Most of the important properties were observed to be significant.

4.1.1 Electro-chemical properties and TOC

All manures had slightly acidic to neutral pH and the highest pH was recorded by MC. All organic manures had safe limits of EC and the highest EC was noticed in TOF-F. TOF recorded the highest TOC (41.55%) which was on par with FYM and TOF-F. C: N ratio was highest in FYM (Table 7).

4.1.2 Nutritional properties

4.1.2.1 Major primary nutrients

The N content of all organic manures remained significant, PM had highest content (2.38%) and it was on par with TOF-F (2.18%). Both these organic fertilizers significantly differed in N content from other conventional organic manures. This was followed by TOF (2.02%), MC (1.50%), FYM (1.31%), VC (1.29%), CC (1.03%). P content significantly differed and PM was having highest content. TOF-F and TOF are having considerably higher values as compared to all other conventional organic manures. Both TOF-F and TOF are having superior values for K content than other manures. Among them TOF-F was significantly higher and TOF was on par with it (Table 7).

4.1.2.2 Major secondary nutrients

The Ca content in different organic manures were significant and ranged from 1.22% to 0.80%. Highest Ca content was found in TOF-F which was on par with PM. The PM was found with highest Mg content (0.62%) and it was significantly superior. The S content varied significantly among the manures with TOF-F registering the highest value of 60 mg kg^{-1} followed by TOF with 40 mg kg^{-1} and PM with 34.85 mg kg^{-1}, The conventional manures MC was found with 33.90 mg kg^{-1}, CC was found with 28.00 mg kg^{-1}, VC was found with 26.00 mg kg^{-1} and FYM had the lowest value of 19.20 mg kg^{-1}.

4.1.2.3 Micronutrients

The micronutrient content of various organic manures are presented in Table 7. The fortification of TOF resulted in TOF-F superior in micronutrients except Fe. The Fe content of organic manures was significantly different and MC (4398.53 mg kg^{-1}) recorded the highest value followed by TOF-F (4296.56 mg kg^{-1}), PM (4086.15 mg kg^{-1}), TOF (3904.78 mg kg $^{-1}$), CC (2928.10 mg kg^{-1}), VC (2862.16 mg kg^{-1}) and FYM (1514.21 mg kg^{-1}). Significant difference was noticed among the manures in the content of Mn. The TOF-F had the highest Mn content and CC had the lowest. The TOF-F had 187.16 mg kg $^{-1}$, PM 162.06 mg kg^{-1}, TOF 155.65 mg kg $^{-1}$, MC 153.15 mg kg^{-1}, FYM 112.15 mg kg^{-1}, VC 110.84 mg kg^{-1} and CC 108.13 mg kg^{-1} Mn concentration.

Manure Zn content also differed significantly. The highest value was noticed in TOF-F. The Zn content of organic manures differed in the order as follows TOF-F (105.50 mg kg^{-1}) > TOF (81.24 mg kg^{-1}) > MC (76.80 mg kg^{-1}) > VC (71.9 mg kg^{-1}) > PM (65.20 mg kg^{-1}) > FYM (61.51 mg kg^{-1}) > CC (52.30 mg kg^{-1}). The TOF-F had significantly higher Cu content and FYM, the lowest. The Cu content of various manures after analysis were recorded as TOF-F (37.64 mg kg^{-1}), PM (33.15 mg kg^{-1}), TOF (32.49 mg kg^{-1}), CC (28.41 mg kg $^{-1}$), VC (24.18 mg kg^{-1}) and FYM (24.15 mg kg^{-1}). The B content of the different organic manures varied significantly and ranged from 5.08 mg kg^{-1} to 0.54 mg kg^{-1}. The fortified nonconventional manure (TOF-F) recorded the highest value of 3.08 mg kg^{-1} B followed by TOF with 2.63 mg kg^{-1}, VC with 2.34 mg kg^{-1}, CC with 1.89 mg kg^{-1}, MC with 1.80 mg kg^{-1}, PM with 1.53 mg kg^{-1} and FYM 0.54 mg kg^{-1} B concentration. Heavy metals Pb and Cd were below detectable limits irrespective of the kind of manure.

Table 7. Chemical characteristics of organic manures

Manures	pH	EC (dS m^{-1})	TOC (%)	N (%)	C: N	P (%)	K (%)	Ca (%)	Mg (%)	S (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg-1)	Zn (mg kg^{-1})	Cu (mg kg^{-1})	B (mg kg^{-1})	Pb	Cd
FYM	6.62	0.08	40.00	1.31	30.53	0.76	0.22	1.01	0.50	19.20	1574.21	112.15	61.51	24.15	0.54	BDL	BDL
PM	6.76	0.32	22.84	2.38	9.60	1.02	1.12	1.17	0.62	34.85	4086.15	162.06	65.20	33.15	1.53	BDL	BDL
CC	7.02	0.22	19.64	1.03	19.07	0.62	0.78	0.80	0.12	28.00	2928.10	108.13	52.30	28.41	1.89	BDL	BDL
VC	7.00	0.28	18.18	1.29	14.09	0.51	0.80	0.97	0.33	26.00	2862.16	110.84	76.80	24.18	2.34	BDL	BDL
MC	7.06	0.37	17.28	1.50	11.52	0.77	0.94	1.08	0.49	33.90	4398.53	153.15	71.91	26.88	1.80	BDL	BDL
TOF	6.76	0.37	41.55	2.02	20.57	0.77	1.40	1.16	0.50	40.00	3904.78	155.65	81.24	32.49	2.63	BDL	BDL
TOF-F	6.80	0.39	39.29	2.18	18.02	0.93	1.45	1.22	0.52	60.00	4296.56	187.16	105.50	37.64	3.08	BDL	BDL
SE m ±	0.18	0.07	3.06	0.06	0.28	0.06	0.26	0.03	0..04	0.63	19.33	5.15	4.92	1.16	0.09	-	-
CD (0.05)	NS	0.21	9.16	0.26	5.02	0.19	0.48	0.05	0.11	5.54	45.50	25.454	12.64	4.85	0.58	-	-

NS- Non significant; BDL-Bellow detectable level

FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified.

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4.2 POT CULTURE TRIAL (TO STUDY THE ROOT PHENOMICS AND SOIL BIOLOGICAL ACTIVITY)

4.2.1 Analysis of initial and final samples of growing media

4.2.1.1 pH, EC and OC

From the Table 8, it is clear that pH decreased in the sample at harvesting stage as compared to the initial sample. CC recorded the highest soil pH in initial sample and it was on par with MC. Final sample showed significantly higher pH in VC. EC increased in final sample than initial. Though there was no significant difference in EC before the crop, it was significantly higher in TOF-F and PM at harvest. Decrease in OC was observed at harvest compared to initial. A significantly higher OC was found in media added with TOF-F in both initial and final samples (3.19%, 1.83%) and it was on par with TOF in final sample (1.81%).

4.2.1.2 Major primary nutrients

The contents of all available nutrients decreased after the harvest of the crops in all treatments. The N content of initial samples were on par in all PM (407.68 kg ha^{-1}), TOF-F (382.59 kg ha^{-1}) and MC (376.32 kg ha^{-1}). Final sample showed significantly higher N content in PM. TOF-F was on par with PM in initial sample for P content. Final sample showed significantly higher P content in PM. K content was superior in TOF-F compared to all other treatments. Both initial and final samples of TOF-F were significantly higher in K content (Table 9).

4.2.1.3 Major secondary nutrients

The variation in available Ca content of soil under pot culture trial is presented in Table 10. In the initial sample TOF-F (186 mg kg^{-1}) had significantly higher available Ca content and it was on par with PM (160 mg kg^{-1}) and MC (150 mg kg^{-1}). But at harvest significant higher Ca content was observed in TOF-F alone. From the table it is clear that in the pot culture study, PM recorded the highest Mg content in both initial and final samples. VC was on par with it at initial stage. The variation in available S content of growing media as a result of application of treatments under pot culture trial showed significantly higher value for TOF-F in initial and for PM at harvest. PM was on par with TOF-F in initial sample.

Table 8. pH, EC and OC of growing media used in pot culture experiment

Treatments	pH		EC (dS m^{-1})		OC (%)	
	I	H	I	H	I	H
FYM	7.33	7.03	0.43	0.53	2.45	2.05
PM	7.21	6.93	0.73	0.77	2.82	1.46
CC	7.82	7.07	0.48	0.70	2.36	1.95
VC	7.63	7.56	0.49	0.57	2.30	1.86
MC	7.72	7.13	0.51	0.71	2.20	1.99
TOF	7.16	6.99	0.57	0.62	2.44	1.81
TOF-F	7.36	7.29	0.60	0.77	3.19	1.83
C	7.24	7.06	0.11	0.15	2.48	1.36
SE m ±	0.09	0.12	0.01	0.01	0.01	0.01
CD (0.05)	0.16	0.35	NS	0.07	0.02	0.08

NS- Non significant; I- Initial; H- At harvest
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Control.

Table 9. Influence of treatments on major nutrients in growing media, kg ha^{-1}

Treatments	N		P		K	
	I	H	I	H	I	H
FYM	363.77	181.88	32.48	24.64	183.60	161.20
PM	407.68	344.96	123.20	78.40	205.00	166.80
CC	282.24	257.15	56.56	21.84	183.60	126.00
VC	332.41	125.44	33.04	26.88	194.80	178.00
MC	376.32	257.15	61.60	45.36	206.00	183.60
TOF	326.14	282.24	99.28	52.48	211.10	183.60
TOF-F	382.59	282.24	112.00	67.20	242.20	217.20
C	232.06	119.16	20.40	15.68	178.00	161.20
SE m ±	16.64	4.95	3.35	6.88	9.29	4.85
CD (0.05)	48.89	14.56	11.65	10.21	87.30	14.24

I- Initial; H- At harvest
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Control.

4.2.1.4 Micronutrients

From the Table 10, it is clear that all micronutrients are decreasing at harvest from the initial sample. TOF-F was superior in micronutrients except Fe in both initial and final samples. The Fe content of organic manures was non-significant in initial sample. It was significantly different at harvest and MC (102.00 mg kg^{-1}) recorded the highest value. Significant difference was noticed among the treatments for Mn in the final sample and there was no significant difference in initial sample. At harvest, the TOF-F had 13.33 mg kg^{-1} Mn concentration followed by PM (12.73 mg kg^{-1}), VC (12.55 mg kg^{-1}), TOF (12.42 mg kg $^{-1}$), MC (12.26 mg kg^{-1}), CC (11.01 mg kg^{-1}), FYM – 10.56 mg kg^{-1} and C- 10.40 mg kg^{-1}.

The Zn content did not show significant difference in both initial and final samples. The highest value was noticed in TOF-F. The TOF-F had the highest Cu content but there was no significant variation. The B content of the different organic manures did not show significant variation and ranged from 0.31 mg kg^{-1} to 0.08 mg kg^{-1} in the initial sample and from 0.18 mg kg^{-1} to 0.02 mg kg^{-1} in final sample. Heavy metals Pb and Cd were below detectable limits irrespective of the treatment in both initial and final sample.

4.2.1 Plant nutrients

4.2.2.1 Major and secondary nutrient content in shoot

The N content in plant shoots varied among the treatments as represented in Table 11. The highest N content was recorded by the treatment PM and the lowest by control C. N content of TOF-F (2.85%) and MC (2.46%) were on par with PM (2.91%). It was followed by VC (2.09%), TOF (2.01%), CC (1.91%), FYM (1.68%) and C (1.00%). The treatment PM had the highest P content in plant tissue. It was on par with TOF-F and TOF. The P content of treatments decreased in the order PM (0.80 %) > TOF-F (0.77 %) > TOF (0.63%) > MC (0.59 %) > FYM (0.58 %) > VC (0.48 %) > CC (0.47%) > C (0.37%). As shown in Table 11, TOF-F (2.56%) had the highest K content in shoot sample followed by PM (2.26%), TOF (1.98%), MC (1.86%), FYM (1.52%), CC (1.40%), VC (1.12%) and C (1.08%). PM, TOF and MC were on par with TOF-F.

Table 10. Secondary, micronutrients and heavy metal concentration of growing media, mg kg^{-1}

Treatments	Ca		Mg		S		Fe		Mn		Zn		Cu		B		Pb		Cd	
	I	H	I	H	I	H	I	H	I	H	I	H	I	H	I	H	I	H	I	H
FYM	110	100	115	102	42	36	67.42	21.44	11.17	10.56	5.58	3.64	0.35	0.17	0.17	0.15	BDL	BDL	BDL	BDL
PM	160	102	162	126	64	52	120.60	97.28	13.44	12.73	5.39	5.46	0.64	0.19	0.19	0.09	BDL	BDL	BDL	BDL
CC	135	125	112	101	54	42	127.10	63.66	11.97	11.01	6.12	5.21	0.45	0.20	0.18	0.13	BDL	BDL	BDL	BDL
VC	118	75	154	117	48	30	83.72	42.32	14.12	12.55	6.96	5.23	0.43	0.42	0.26	0.12	BDL	BDL	BDL	BDL
MC	150	141	110	96	53	40	153.30	102.00	12.76	12.26	7.23	5.19	0.75	0.29	0.09	0.06	BDL	BDL	BDL	BDL
TOF	148	99	110	80	57	35	76.73	36.46	13.21	12.42	7.11	5.47	0.70	0.36	0.21	0.16	BDL	BDL	BDL	BDL
TOF-F	186	155	115	75	72	40	127.80	65.23	14.62	13.33	7.81	5.65	0.77	0.46	0.31	0.18	BDL	BDL	BDL	BDL
C	99	54	65	45	34	27	58.82	20.20	11.15	10.40	3.55	2.40	0.38	0.09	0.08	0.02	BDL	BDL	BDL	BDL
SE m ±	4.41	2.76	1.47	0.94	0.35	2.95	1.44	1.44	0.05	0.06	0.03	0.06	0.03	0.01	0.26	0.05	-	-	-	-
CD (0.05)	32.32	7.47	8.68	6.26	6.27	9.03	NS	4.24	NS	0.17	NS	NS	NS	NS	NS	NS	-	-	-	-

BDL-Bellow detectable level; NS- Non significant; I- Initial; H- At harvest
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Control.

The Ca content in plant varied significantly among the treatments (Table 11). It ranged from 1.72% (TOF-F) to 1.44% (C). The treatment TOF-F had the highest levels of Ca followed by PM and TOF-F was found to have significant difference with all other treatments. The TOF-F recorded highest Mg content and it was significantly superior. PM (1.08%) was on par with TOF-F (0.52%) in shoot Mg concentration. The treatment TOF-F had the highest S content when compared with other treatments. MC was on par with TOF-F. In shoot sample the TOF-F had 230.34 mg kg, $^{-1}$ MC – 220.98 mg kg^{-1}, TOF – 210.32 mg kg^{-1}, VC- 180.51 mg kg $^{-1}$, PM- 150.42 mg kg^{-1}, CC- 120.74 mg kg^{-1}, FYM – 120.12 mg kg^{-1} and C- 100.74 mg kg^{-1} S concentration.

4.2.2.2 Micronutrient content of shoot sample

The Fe content among the treatments ranged from 472.80 mg kg^{-1} (MC) to 130 mg kg^{-1}(C) as pointed out in the Table 12. The Fe content of shoot tissue was significantly different and MC recorded the highest value. The Mn content in plant tissue varied among the treatments. TOF-F had the highest Mn content (80 mg kg^{-1}) which was found to have significant difference with all other treatments. The TOF-F had the highest Zn content of 81.20 mg kg^{-1} and was found to have significant difference with others. From the Table 12, it is clear that significant differences were there for Cu content among TOF-F and other treatments. The highest Cu content was recorded by the treatment TOF-F (6.20 mg kg^{-1}). Shoot B content was non-significant. The TOF-F had the highest B content of 2.30 mg kg^{-1} and was lowest in PM (1.00 mg kg^{-1}).

4.2.2.3 Major and secondary nutrient content in root

The N content in root varied among the treatments as represented in Table 13. The highest N content was recorded by the treatment PM (2.21%) and it was significantly different. It was followed by TOF-F (1.84%), VC (1.83%), TOF (1.73%) , CC (1.70%), MC (1.59%), FYM (1.03%), and C (0.89%) . The treatment PM had the highest P content in plant tissue. TOF-F was on par with PM. The P content of treatments differed in the order as follows PM – 0.52 % > TOF-F – 0.44 % > TOF- 0. 34% > VC – 0.33 %> FYM – 0.30 % >MC – 0.27 %^{1} >CC – 0.25%

Table 11. Major and secondary nutrient content in amaranthus shoot, %

Treatments	N	P	K	Ca	Mg	S (mg kg^{-1})
FYM	1.68	0.58	1.52	1.32	0.76	120.12
PM	2.91	0.80	2.26	1.44	0.52	150.42
CC	1.91	0.47	1.40	1.35	0.92	120.74
VC	2.09	0.48	1.12	1.00	0.88	180.51
MC	2.46	0.59	1.86	1.30	0.92	220.98
TOF	2.01	0.63	1.98	1.41	0.92	210.32
TOF-F	2.85	0.77	2.56	1.72	1.08	230.34
C	1.00	0.37	1.08	0.50	0.68	100.74
SE m ±	0.254	0.066	0.293	0.126	0.08	2.40
CD (0.05)	0.75	0.19	0.86	0.37	0.23	12.19

FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Control.

Table 12. Effect of nutrients on micronutrient content of shoot, mg kg^{-1}

Treatments	Fe	Mn	Zn	Cu	B
FYM	315.60	27.60	19.20	3.04	1.20
PM	376.40	60.40	66.00	4.76	1.00
CC	217.60	20.40	52.00	2.24	1.50
VC	296.40	61.60	62.80	2.72	1.60
MC	472.80	56.00	52.00	3.88	1.10
TOF	356.40	33.20	56.80	4.64	1.50
TOF-F	429.60	80.00	81.20	6.20	2.30
C	130.00	24.00	44.00	2.00	0.70
SE m ±	5.77	2.30	2.30	0.30	0.02
CD (0.05)	16.95	6.78	6.78	1.78	NS

NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Control.

>C – 0.21%. As shown in Table 13, TOF-F (1.82%) had the highest K content in root sample followed by PM (1.66%), TOF (1.58%), CC (1.48%), MC (1.42%), VC (1.40%), FYM (1.40%) and C (1.18%). PM was on par with TOF-F.

The Ca content in plant varied significantly among the treatments (Table 13). It ranged from 1.83% (TOF-F) to 1.06% (C). The treatment TOF-F had significantly higher level of Ca which was on par with TOF and MC. The PM (0.72%) recorded highest Mg content and it was significantly superior. The treatment TOF-F had the highest S content when compared to other treatments. In root sample the TOF-F had 230.64 mg kg, $^{-1}$ TOF – 140.61 mg kg^{-1}, PM – 140.61 mg kg^{-1}, MC- 100.98 mg kg $^{-1}$, VC- 100.78 mg kg^{-1}, CC- 100.41 mg kg^{-1}, FYM – 90.48 mg kg^{-1} and C- 60.98 mg kg^{-1} S concentration.

4.2.2.4 Micronutrient content of root sample

The Fe content among the treatments ranged from 467.60 mg kg^{-1} (MC) to 289.60 mg kg^{-1}(C) as pointed out in the Table 14. The Fe content of shoot tissue was significantly different. TOF-F recorded the highest value and was on MC par with it. The Mn content in plant tissue varied among the treatments. TOF-F had the highest Mn content (88.80 mg kg^{-1}) which was found to have significant difference with all other treatments. The TOF-F had the highest Zn content of 83.60 mg kg^{-1} and was found to have significant difference others. From the Table 14, it is clear that statistical differences were there for Cu content among with TOF-F and other treatments. The highest Cu content was recorded by the treatment TOF-F (6.10 mg kg^{-1}). Shoot B content was non-significant. The TOF-F had the highest Zn content of 1.50 mg kg^{-1} and lowest was in C (0.90 mg kg^{-1}).

4.2.3 Biological properties of initial and final samples of growing media

4.2.3.1 Micro fauna: microbial load

The effect of organic manures on microbial load is shown in Table 15. Microbial load of bacteria, fungi and actinomycetes showed an increasing trend. The treatment MC had maximum bacterial number at both initial and final samples (7.91 $\times 10^6$ cfu g^{-1}, 9.15 $\times 10^6$ cfu g^{-1}). TOF-F (8.99 $\times 10^6$ cfu g^{-1}) was found to be on par with PM at harvest.

Table 13. Major and secondary nutrients in root, %

Treatments	N	P	K	Ca	Mg	S (mg kg^{-1})
FYM	1.03	0.30	1.40	1.35	0.40	90.48
PM	2.21	0.52	1.66	1.49	0.72	130.56
CC	1.70	0.25	1.48	1.35	0.20	100.45
VC	1.83	0.33	1.40	1.49	0.44	100.78
MC	1.59	0.27	1.42	1.59	0.52	110.98
TOF	1.73	0.34	1.58	1.59	0.52	140.61
TOF-F	1.84	0.44	1.82	1.83	0.61	230.64
C	0.89	0.21	1.18	1.06	0.32	60.98
SE m ±	0.08	0.05	0.095	0.09	0.05	0.13
CD (0.05)	0.22	0.15	0.28	0.26	0.10	30.30

FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Control.

Table 14. Effect of treatments on micronutrient content in root, mg kg^{-1}

Treatments	Fe	Mn	Zn	Cu	B
FYM	321.60	59.20	55.20	2.76	1.30
PM	421.60	50.40	69.60	4.24	1.10
CC	366.80	34.00	47.20	2.64	0.60
VC	424.40	48.00	61.20	4.60	0.90
MC	455.60	72.80	63.20	4.96	0.30
TOF	378.40	61.60	62.40	5.72	1.40
TOF-F	467.60	88.80	83.60	6.10	1.50
C	289.60	36.00	36.00	1.96	0.90
SE m ±	5.77	2.31	2.31	0.03	0.05
CD (0.05)	16.95	6.78	6.78	0.30	NS

NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Control.

The fungal population remained significant at both initial and final samples. A high population was recorded MC in both samples (4.45×10^4 cfu g^{-1}, 4.68×10^4 cfu g^{-1}). TOF-F (4.59×10^4 cfu g^{-1}) and PM (4.57×10^4 cfu g^{-1}) were next to MC in fungal population at harvest and they were on par with it.

A peak level in population of actinomycetes was recorded in MC at both initial and final samples (4.02×10^3 cfu g^{-1}, 4.49×10^3 cfu g^{-1}) as pointed out in Table 15. FYM (4.47×10^3 cfu g^{-1}) and TOF-F (4.40×10^3 cfu g^{-1}) were on par with MC at harvest.

4.2.3.2 Macro fauna: earthworm and microarthropods count

Earthworm count was registered zero in the pots before growing crops as pointed out in the Table 16. Population (4 number per pot) was observed in final sample with application of VC. Microarthropod count increased at harvest than initial but it was non-significant in both stages of sampling. Highest count was observed in MC in both initial and final samples (19.25 number kg^{-1} pot mixture, 31.25 number kg^{-1} pot mixture).

4.2.3.3 Dehydrogenase activity

The variation in soil enzyme dehydrogenase activity as influenced by the the treatments is evident from the Table 17. Dehydrogenase activity of all treatments increased at the harvest from the initial value. It was clear that the MC was significantly highest in both initial and final samples among all the treatments. In final sample dehydrogenase activity of TOF-F (71.00 µg of TPF g^{-1} soil 24 h^{-1}) was on par with MC (85.50 µg of TPF g^{-1} soil 24 h^{-1}).

4.2.3.4 Microbial biomass carbon

The microbial biomass carbon among the treatments ranged from 137.18 µg g^{-1} soil (MC) to 41.56 µg g^{-1} soil (C) in initial sample and from 171.15 µg g^{-1} soil (MC) to 56.86 µg g^{-1} soil (C) in final samples and was found increasing in all treatments between initial and final samples as pointed out in the Table 17. The microbial biomass carbon of MC was significantly highest than all other treatments at both stages of sampling. The microbial biomass carbon of treatments at harvest

Table 15. Effect of treatments on microbial load, number of cfu g^{-1} soil

Treatments	Bacteria (×10^6)		Fungi (×10^4)		Actinomycetes (×10^3)	
	I	H	I	H	I	H
FYM	7.85	8.00	4.27	4.37	3.85	4.47
PM	7.58	8.85	4.13	4.57	3.65	4.24
CC	7.68	7.72	4.33	4.35	3.85	4.20
VC	7.63	8.86	4.33	4.28	3.65	4.26
MC	7.91	9.15	4.45	4.68	4.02	4.49
TOF	7.44	8.74	4.29	4.52	3.84	3.98
TOF-F	7.42	8.99	4.39	4.59	3.85	4.40
C	7.19	7.47	4.06	4.23	2.85	4.09
SE m ±	0.01	0.06	0	0	0.01	0.01
CD (0.05)	0.04	0.16	0.05	0.11	0.01	0.03

I- Initial; H- At harvest
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Control.

Table 16. Macro fauna: earthworm and microarthropod count as influenced by different treatments

Treatments	Earthworm (number per pot)		Micro arthropods count (number kg^{-1} pot mixture)	
	I	H	I	H
FYM	0	0	15.00	20.00
PM	0	0	17.50	22.50
CC	0	0	17.75	22.75
VC	0	4	15.25	20.25
MC	0	0	19.25	31.25
TOF	0	0	14.50	29.50
TOF-F	0	0	15.25	20.25
C	0	0	12.50	27.50
SE m ±	-	0.29	3.72	5.72
CD (0.05)	-	0.85	NS	NS

NS- Non significant; I- Initial; H- At harvest
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Control.

decreased in the order MC (171.15 μg g^{-1} soil) > TOF-F (141.48 μg g^{-1} soil) > TOF (138.89 μg g^{-1} soil) > FYM (125.45 μg g^{-1} soil) > PM (111.45 μg g^{-1} soil) > VC (98.45 μg g^{-1} soil) > CC (85.89 μg g^{-1} soil) > C (56.86 μg g^{-1} soil).

4.2.2 Plant observations

4.2.3.1 Shoot characters

The effect of treatments on plant height of amaranthus was found to be significant as evident from Table 18. PM had the highest plant height followed by TOF-F and MC, but all the three were on par. The plant height of treatments differed in the order PM (91.00 cm) > TOF-F (89.00 cm) > MC (88.00 cm) > TOF (76.75 cm) > VC (74.50 cm) > CC (70.75 cm) > FYM (56.50) > C (42.50 cm).

TOF-F had the highest number of primary branches per plant (20) followed by MC (18). The maximum shoot weight was recorded by TOF-F (149.20 g plant $^{-1}$) and PM (148.40 g plant $^{-1}$) was on par with it. It was followed by 134.34 g plant $^{-1}$ (TOF), 118.16 g plant^{-1} (MC), 107.86 g plant^{-1} (VC), 95.96 g plant^{-1} (CC) 81.26 g plant^{-1} (FYM) and 50.73 g plant^{-1} (C). The effects of treatments on shoot dry matter of amaranthus was found to be significant. The PM (10.68 g plant $^{-1}$) was significantly highest and TOF-F (9.05 g plant $^{-1}$) was on par with it.

4.2.3.2 Root phenomics

Amaranthus has a single primary root which develops into tap root. Variation in number of secondary roots in different treatment did not show significance. Highest number was observed in TOF-F as shown in Table 19. The root diameter remained significant. The TOF-F (10.50 mm) had highest diameter and it was on par with TOF (7.75 mm). The root weight varied among the treatments significantly ranging from 30.31 g plant^{-1} to 8.10 g plant^{-1}. The maximum root weight was recorded by TOF-F (30.31 g plant $^{-1}$) and it was followed by 23.65 g plant $^{-1}$ (TOF), 23.03 g plant $^{-1}$ (MC), 22.48 g plant^{-1} (PM), 21.88 g plant^{-1} (VC), 21.62 g plant^{-1} (CC) 16.44 g plant^{-1} (FYM) and 8.10 g plant^{-1} (C).

As evidenced from Table 20, TOF-F had the significantly highest root dry matter (3.37 g plant^{-1}) followed by TOF (2.63 g plant^{-1}) and MC (2.56 g plant^{-1}). The maximum root volume was recorded by TOF-F (11.00 cm^3). It was

Table 17. Effect of treatments on dehydrogenase activity and microbial biomass carbon

Treatments	Dehydrogenase (μg TPF g^{-1} growing media 24 h^{-1})		Microbial biomass carbon (μg g^{-1} dry growing media)	
	I	H	I	H
FYM	36.74	51.00	100.24	125.45
PM	46.30	58.60	83.42	111.45
CC	42.50	66.30	51.68	85.89
VC	34.80	49.00	83.87	98.45
MC	51.70	85.50	137.18	171.15
TOF	37.10	70.10	83.78	138.89
TOF-F	35.20	71.00	83.45	141.48
C	21.20	39.00	41.59	56.86
SE m ±	0.56	2.06	5.06	6.06
CD (0.05)	6.19	15.10	21.10	35.18

I- Initial; H- At harvest

FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Control.

Table 18. Effect of different organic manures on shoot characters

Treatments	Plant height (cm)	Primary branches per plant	Shoot weight (g $plant^{-1}$)	Shoot dry matter (g $plant^{-1}$)
FYM	56.50	5	81.26	3.39
PM	91.00	16	148.41	10.68
CC	70.75	7	95.96	5.15
VC	74.50	16	107.86	7.05
MC	88.00	18	118.16	6.09
TOF	76.75	15	134.34	8.55
TOF-F	89.00	20	149.20	9.05
C	42.50	3.75	50.73	1.94
SE m ±	2.13	0.78	2.88	0.69
CD (0.05)	6.26	2.29	8.47	2.04

FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Control.

Table 19. Effect of treatments on root phenomics of amaranthus

Treatments	Number of primary roots	Number of secondary roots	Root diameter (mm)	Root weight (g plant^{-1})
FYM	1	53.75	3.25	16.44
PM	1	110.50	7.50	22.48
CC	1	75.00	4.00	21.62
VC	1	91.25	6.25	21.88
MC	1	97.25	7.00	23.04
TOF	1	83.75	7.75	23.65
TOF-F	1	117.50	10.50	30.31
C	1	36.25	2.50	8.10
SE m ±	-	11.79	1.18	0.64
CD (0.05)	-	NS	3.18	1.87

FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Control.

Table 20. Root characters of amaranthus influenced by different organic manures

Treatments	Root dry matter (g plant^{-1})	Root volume (cm^3)	Total root length (cm)	Root: shoot ratio
FYM	0.72	2.00	22.00	0.21
PM	2.50	5.75	27.75	0.23
CC	2.40	2.00	20.88	0.34
VC	2.43	5.75	24.25	0.47
MC	2.56	8.50	32.25	0.42
TOF	2.63	8.05	26.88	0.31
TOF-F	3.37	11.00	34.75	0.37
C	0.46	1.82	17.13	0.24
SE m ±	0.07	1.76	3.66	0.03
CD (0.05)	0.21	5.16	8.74	0.06

FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Control.

significantly higher and on par with MC and TOF. TOF-F had the highest total root weight followed by MC, PM and TOF, and they were on par with TOF-F. The total root length of treatments decreased in the order TOF-F (34.75 cm) > MC (32.25 cm) > PM (27.75 cm) > TOF (26.88 cm) > VC (24.25 cm) > FYM (22.00 cm) > CC (20.88 cm) > C (17.13 cm). Root: shoot ratio of TOF-F was lower than VC and MC.

4.3 FIELD MICRO PLOT TRIAL TO STUDY THE ROOT PHENOMICS AND SOIL BIOLOGICAL ACTIVITY

4.3.1 Fertility parameters and biological properties of experimental site

The fertility parameters of the field micro plot trial experimental site are outlined in Table 21. The pH of the soil was strongly acidic (5.26) and in safe EC limits (0.17). The soil was medium in organic carbon (1.16%), low in N (125.44 kg ha^{-1}) and K (93.80 kg ha^{-1}). A high P content of 94.78 kg ha^{-1} was recorded in the soil. The soil was found to be deficient in Ca (263.75 mg kg^{-1}) and S (4.06 mg kg^{-1}), but Mg (132.75 mg kg^{-1}) was sufficient. The micronutrients Fe (38.00 mg kg^{-1}), Mn (28.90 mg kg^{-1}), Zn (17.61 mg kg^{-1}) and Cu (1.77 mg kg^{-1}) were sufficient but B (0.10 mg kg^{-1}) content of soil was deficient.

The biological properties of the field micro plot trial experimental site are recorded in Table 22. The microbial load of initial soil was recorded as bacteria 6.86 $\times 10^6$ cfu g^{-1}, fungi 4.03 $\times 10^4$ cfu g^{-1}, actinomycetes 3.79 $\times 10^3$ cfu g^{-1}. An average of 1 number of earthworms per square meter and 20.34 number of microarthropods per kg of soil were noticed in the experimental site. The DA of initial soil sample was 24.50 μg of TPF g^{-1} soil 24 h^{-1} and MBC was 123.48 μg g^{-1}.

4.3.2 Soil chemical properties after each crop harvest

4.3.2.1 Soil pH

The pH had a decreasing trend after all three crops as outlined in Table 23. At all three crops an acidic pH was observed for every treatment. Significant difference between treatments was observed only after C1. The highest pH was

Table 21. Fertility parameters of field micro plot experimental site

Fertility parameters	Content	Status
pH	5.26	Strongly acidic
EC (dS m^{-1})	0.17	Safe
OC (%)	1.16	Medium
N (kg ha^{-1})	125.44	Low
P (kg ha^{-1})	94.78	High
K (kg ha^{-1})	93.80	Low
Ca (mg kg^{-1})	263.75	Deficient
Mg (mg kg^{-1})	132.75	Sufficient
S (mg kg^{-1})	4.06	Deficient
Fe (mg kg^{-1})	38.00	Sufficient
Mn (mg kg^{-1})	28.90	Sufficient
Zn (mg kg^{-1})	17.61	Sufficient
Cu (mg kg^{-1})	1.77	Sufficient
B (mg kg^{-1})	0.40	Deficient

Table 22. Biological properties of initial soil sample

Biological properties	Content
1. Soil microfauna: Microbial load (number of cfu g^{-1} soil)	
Bacteria ($\times 10^6$)	6.86
Fungi ($\times 10^4$)	4.03
Actinomycetes ($\times 10^3$)	3.79
2. Soil macrofauna	
Earthworm (number m^{-2})	1
Microarthropods (number kg^{-1} soil)	20.34
3. Dehydrogenase activity (µg of TPF g^{-1} soil 24 h^{-1})	24.50
4. Microbial biomass carbon (µg g $soil^{-1}$)	123.48

Table 23. Effect of treatments on soil pH in three successive crops of field micro plot trials

Treatments	At harvest		
	C1	C2	C3
FYM	5.49	5.32	5.15
PM	5.14	4.99	4.91
CC	5.82	5.10	4.99
VC	5.40	5.15	5.08
MC	5.41	5.23	5.20
TOF	5.24	5.02	5.15
TOF-F	5.25	5.21	5.19
C	5.10	5.08	5.10
SE m ±	0.08	0.01	0.09
CD (0.05)	0.24	NS	NS

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 24. Soil EC in three successive crops, dS m^{-1}

Treatments	At harvest		
	C1	C2	C3
FYM	0.29	0.38	0.47
PM	0.31	0.43	0.44
CC	0.38	0.46	0.47
VC	0.36	0.45	0.54
MC	0.39	0.50	0.51
TOF	0.38	0.43	0.52
TOF-F	0.44	0.53	0.54
C	0.30	0.30	0.41
SE m ±	0.06	0.002	0.02
CD (0.05)	NS	NS	NS

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

recorded by CC (5.82) after C1 which was found to have significant difference with all other treatments. After C2 and C3 it was non-significant.

4.3.2.2 Soil EC

The soil EC of all three crops of field micro plot trial remained non-significant as presented in Table 24. The soil EC showed an increasing trend with continuous application of different organic manures but was in safe limits. The treatment TOF-F had the highest values for EC after C1 and C2 (0.44 dS m^{-1}, 0.53 dS m^{-1})) and after the C3 both TOF-F (0.54 dS m^{-1}) and VC (0.54 dS m^{-1}) had the highest values.

4.3.2.3 Soil organic carbon

From the Table 25, it is clear that soil OC was increasing due to continuous application of different organic manures after each crop. Significant difference between treatments was observed only after C1. The significantly highest soil OC was recorded by TOF-F (1.28%) after C1 and it was on par with TOF (1.26%). After C2 and C3 it was non-significant and highest soil OC was found in TOF-F (1.30%, 1.37%).

4.3.2.4 Soil available N

The available nitrogen content of the soil in the experimental site increased after each crop in all treatments except control (Table 26). It ranged from 77.08 kg ha^{-1} (C after C3) to 170.79 kg ha^{-1} (PM after C3). After all three crops PM had highest soil available N content (155.33 kg ha^{-1}, 163.25 kg ha^{-1}, 170.79 kg ha^{-1}). The TOF-F was on par with PM (149.10 kg ha^{-1}, 159.52 kg ha^{-1}, 165.79 kg ha^{-1}) and TOF had higher soil available N content than conventional FYM after all seasons. After C1, MC (146.66 kg ha^{-1}) and TOF (140.44 kg ha^{-1}) were on par but after C3 only MC (160.89 kg ha^{-1}) found to be on par with PM.

4.3.2.5 Soil available P

The high soil P status before start of the crop continued even after all three crops and it further increased after each successive crop irrespective of the treatment. The treatment PM recorded the highest soil available P content after all

Table 25. Soil OC influenced by different treatments during three successive crops, %

Treatments	At harvest		
	C1	C2	C3
FYM	1.19	1.24	1.24
PM	1.18	1.28	1.34
CC	1.05	1.15	1.30
VC	1.05	1.16	1.33
MC	1.21	1.26	1.35
TOF	1.26	1.29	1.30
TOF-F	1.28	1.30	1.37
C	1.13	1.12	1.10
SE m ±	0.05	0.08	0.05
CD (0.05)	0.14	NS	NS

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 26. Effect of treatments on soil available N content, kg ha^{-1}

Treatments	At harvest		
	C1	C2	C3
FYM	119.10	129.34	141.89
PM	155.33	163.25	170.79
CC	134.22	155.79	159.06
VC	134.22	154.43	156.98
MC	146.66	155.07	160.89
TOF	140.44	141.89	148.16
TOF-F	149.10	159.52	165.79
C	95.77	87.98	77.08
SE m ±	1.32	1.705	4.642
CD (0.05)	10.58	6.85	10.75

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

three seasons (104.77 kg ha^{-1}, 115.82 kg ha^{-1}, 128.22 kg ha^{-1}). The TOF-F was on par with PM after all seasons (90.63 kg ha^{-1}, 105.39 kg ha^{-1}, 117.79 kg ha^{-1}) and TOF had higher soil available P content than conventional FYM (Table 27).

4.3.2.6 Soil available K

A general increase in soil available K content compared to the initial level was observed after all the crops after the experiment except control. The level of K content of soil ranged from 83.60 kg ha^{-1} (C after C3) to 252.80 kg ha^{-1} (TOF-F after C3) in field micro plot trials. The treatment TOF-F was found to have the highest K content after every individual crop. The estimated highest K content after all three crops were as follows- 195.20 kg ha^{-1} (C1), 208.00 kg ha^{-1} (C2), 252.80 kg ha^{-1} (C3). The TOF-F was found to be significantly different from other treatments and TOF on par with it after all three crops (172.80 kg ha^{-1}, 202.40 kg ha^{-1}, 247.20 kg ha^{-1}).

4.3.2.7 Soil available Ca

The variation in available Ca content of field micro plot trials are presented in Table 29. Content increased after each successive crop. In C1 it was non-significant. Significant difference was observed between treatments after C2 and C3. After C2, TOF-F (290.80 mg kg^{-1}) had significantly higher soil available Ca content and PM (287.06 mg kg^{-1}) was on par with it and after C3, TOF-F (296.18 mg kg^{-1}), was on par with PM (302.80 mg kg^{-1}).

4.3.2.8 Soil available Mg

From Table 30, it is clear that in the field trial PM recorded the highest Mg content and TOF-F was on par with it after all three crops while TOF was on par with PM after C1. The soil available Mg content of TOF-F after all three crops were as follows- 132.02 mg kg^{-1} (C1), 117.45 mg kg^{-1} (C2), 112.22 mg kg^{-1} (C3) and soil available Mg content of TOF-F were as follows-129.52 mg kg^{-1} (C1), 117.45 mg kg^{-1} (C2), 93.48 mg kg^{-1} (C3).

4.3.2.9 Soil available S

The variation in soil available S content as a result of application of different organic manures is presented in Table 31. It was found to be non-significant after

Table 27. Influence of treatments on soil available P content, kg ha^{-1}

Treatments	At harvest		
	C1	C2	C3
FYM	83.07	79.71	102.11
PM	104.77	115.82	128.22
CC	87.27	90.41	112.81
VC	82.85	78.59	100.99
MC	98.36	86.94	109.34
TOF	86.43	81.45	103.85
TOF-F	90.63	105.39	117.79
C	77.42	78.59	80.99
SE m ±	6.876	2.178	2.178
CD (0.05)	14.36	20.45	10.45

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 28. Effect of treatments on soil available K, kg ha^{-1}

Treatments	At harvest		
	C1	C2	C3
FYM	105.60	130.40	175.20
PM	127.20	148.00	182.80
CC	102.00	123.20	168.00
VC	114.00	122.00	186.80
MC	133.60	161.60	206.40
TOF	172.80	202.40	247.20
TOF-F	195.20	208.00	252.80
C	88.40	88.00	83.60
SE m ±	5.666	1.88	1.08
CD (0.05)	13.78	7.02	7.02

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

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Table 29. Soil available Ca influenced by different organic manures, mg kg^{-1}

Treatments	At harvest		
	C1	C2	C3
FYM	265.12	265.75	273.06
PM	280.42	287.06	299.80
CC	245.15	250.50	270.09
VC	215.45	275.80	283.70
MC	255.16	270.09	273.60
TOF	265.87	275.70	283.65
TOF-F	285.54	290.80	298.18
C	205.50	215.50	203.20
SE m ±	2.18	1.22	1.16
CD (0.05)	NS	6.19	4.43

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 30. Effect of treatments on soil available Mg, mg kg^{-1}

Treatments	At harvest		
	C1	C2	C3
FYM	104.15	105.52	105.90
PM	135.65	125.23	122.70
CC	108.61	107.16	99.18
VC	123.12	84.46	90.15
MC	114.31	80.45	96.78
TOF	129.52	81.55	93.48
TOF-F	132.02	117.45	112.22
C	71.02	66.45	50.84
SE m ±	1.627	3.81	7.88
CD (0.05)	7.46	11.28	13.33

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

C1 and C2 but, significant difference was observed after C3. The TOF-F (21.75 mg kg^{-1}) recorded significantly higher value after C3 and PM (19.98 mg kg^{-1}) was on par with it.

4.3.2.10 Soil available micronutrients

The variation among treatments in Fe content was found to be significant under field trial as evidenced in Table 32. After all three crops MC recorded the highest value for Fe content (70.26 mg kg^{-1}, 83.46 mg kg^{-1}, 94.96 mg kg^{-1}). TOF-F was on par with it after C2 and C3 (82.50 mg kg^{-1}, 85.00 mg kg^{-1}). The TOF application recorded higher Fe content than CC and FYM after all the three seasons.

As evidenced in Table 33, the Mn content varied significantly among the treatments and registered a general increase in values in all the treatments after all three crops. The treatment MC showed the highest soil available Mn after C1 (38.14 mg kg^{-1}) while TOF-F (35.42 mg kg^{-1}) and PM (33.57 mg kg^{-1}) were on par with it. After C2 and C3, TOF-F (37.58 mg kg^{-1}, 38.08 mg kg^{-1}) recorded highest soil available Mn while TOF (33.50 mg kg^{-1}, 34.00 mg kg^{-1}) and MC (33.75 mg kg^{-1}, 34.23 mg kg^{-1}) were on par with it.

The status of Zn in soil in all the treatments after all three crops remained sufficient but varied significantly between treatments. The comparatively high Zn content after all three crops was observed in TOF-F (17.02 mg kg^{-1}, 19.84mg kg^{-1}, 20.34 mg kg^{-1}) as evidenced from Table 34 may be due to result of fortification. After all three seasons TOF (15.55 mg kg^{-1}, 15.78 mg kg^{-1}, 16.28 mg kg^{-1}) application recorded higher Zn content than CC (14.44 mg kg^{-1}, 15.51 mg kg^{-1}, 16.01 mg kg^{-1}) and FYM (15.29 mg kg^{-1}, 14.92 mg kg^{-1}, 15.42 mg kg^{-1}).

From Table 35, it is apparent that there exists variation among the treatments for soil Cu availability in field experiment. The highest Cu content after all three crops was observed in TOF-F (2.00 mg kg^{-1}, 2.45 mg kg^{-1}, 2.95 mg kg^{-1}). The TOF application recorded higher Cu content than conventional FYM after all three seasons. The variation in B content between the treatments in field micro plot trial is evident from Table 36. It was clear that the status of B was sufficient in all the

Table 31. Effect of treatments on soil available S, mg kg^{-1}

Treatments	At harvest		
	C1	C2	C3
FYM	4.90	11.25	15.75
PM	5.05	15.48	19.98
CC	6.08	14.00	18.08
VC	6.00	13.73	14.78
MC	6.10	14.50	17.00
TOF	6.20	14.98	17.48
TOF-F	7.03	17.25	21.75
C	4.48	5.75	7.30
SE m ±	1.17	2.33	0.13
CD (0.05)	NS	NS	3.02

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 32. Effect of treatments on soil available Fe in three successive crops, mg kg^{-1}

Treatments	At harvest		
	C1	C2	C3
FYM	49.71	60.20	70.70
PM	55.90	72.57	83.07
CC	62.35	74.57	75.07
VC	57.69	76.14	66.64
MC	70.26	83.46	94.96
TOF	58.36	74.84	75.34
TOF-F	67.72	82.50	85.00
C	31.34	42.21	45.15
SE m ±	0.30	0.30	0.43
CD (0.05)	2.21	1.19	11.19

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 33. Effect of treatments on soil available Mn, mg kg^{-1}

Treatments	At harvest		
	C1	C2	C3
FYM	19.30	30.83	32.33
PM	33.57	31.52	32.02
CC	31.62	30.54	32.04
VC	26.47	26.14	26.64
MC	38.14	33.73	34.23
TOF	19.93	33.50	34.00
TOF-F	35.42	37.58	38.08
C	16.69	20.47	21.97
SE m ±	2.06	1.60	1.4
CD (0.05)	6.11	4.75	4.75

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 34. Effect of treatments on soil available Zn in three successive crops, mg kg^{-1}

Treatments	At harvest		
	C1	C2	C3
FYM	15.29	14.92	15.42
PM	15.10	15.44	15.94
CC	14.44	15.51	16.01
VC	14.36	14.58	15.08
MC	15.51	15.66	16.16
TOF	15.55	15.78	16.28
TOF-F	17.02	19.84	20.34
C	9.31	10.02	10.52
SE m ±	0.46	0.29	0.29
CD (0.05)	1.37	2.86	1.87

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 35. Effect of treatments on soil available Cu, mg kg^{-1}

Treatments	At harvest		
	C1	C2	C3
FYM	1.38	1.60	2.00
PM	1.90	1.71	2.21
CC	1.74	1.54	2.04
VC	1.71	1.73	2.23
MC	1.60	1.68	2.18
TOF	1.45	1.65	2.05
TOF-F	2.00	2.45	2.95
C	1.62	1.76	2.26
SE m ±	0.05	0.07	0.07
CD (0.05)	0.137	0.19	0.20

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 36. Effect of treatments on soil B in three successive crops, mg kg^{-1}

Treatments	At harvest		
	C1	C2	C3
FYM	1.12	1.21	1.26
PM	1.22	1.42	1.32
CC	1.42	1.52	1.45
VC	1.34	1.34	1.43
MC	1.43	1.60	1.35
TOF	1.41	1.24	1.34
TOF-F	1.52	1.63	1.64
C	0.41	0.44	0.48
SE m ±	0.02	0.05	0.08
CD (0.05)	NS	0.07	NS

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

treatments except control after all three crops. It was significant after C2 and non-significant after C1 and C3. After C2 significantly higher content was found in TOF-F (1.63 mg kg^{-1}) and it was on par with MC (1.60 mg kg^{-1}).

4.3.3 Shoot nutrients

4.3.3.1 Shoot N

The N content in shoot varied among the treatments except in C1 as represented in Table 37. Significant difference was found in C2 and C3. The highest N content was recorded by the treatment PM (3.72%, 3.72%, 3.82%) at all three crops and the lowest by control C (3.28%, 2.69%, 2.70%). In C2 and C3 TOF-F had 3.44% N and 3.76% N respectively and it was on par with PM and differed significantly from other treatments. The TOF application recorded higher plant N content than CC and FYM after all three seasons.

4.3.3.2 Shoot P

As presented in Table 38 the treatments differed significantly except in C2. The treatment MC recorded 0.82% P in C1, 0.58% P in C3 and was found to be superior to all other treatments in terms of P content. TOF-F was on par with MC in C1 and C3 (0.58%, 0.52%).

4.3.3.3 Shoot K

As depicted in Table 39 TOF-F had the highest K content followed by TOF in all three crops. The TOF-F was significantly higher and TOF was on par with it compared to other treatments. The K content by TOF-F was reported as 4.78% K in C1, 5.04% K in C2, 4.90% K in C3 and the K content in TOF was reported as 4.38% K in C1, 5.54% K in C2, 4.57% K in C3.

4.3.3.4 Shoot Ca

The Ca content in shoot tissue varied significantly among the treatments in all three seasons as depicted in Table 40. The treatment TOF-F had the significantly highest levels of Ca in C1 and C2 (3.50%, 2.97%). In C3 TOF-F (2.96%) was on par with MC (3.05%). The TOF application recorded higher shoot Ca content than CC and FYM after all three seasons.

Table 37. Effects of treatments on N content in amaranthus shoot, %

Treatments	C1	C2	C3
FYM	3.39	2.77	2.55
PM	3.72	3.72	3.82
CC	3.33	2.77	3.20
VC	3.47	3.11	3.18
MC	3.36	3.19	3.40
TOF	3.42	3.23	3.32
TOF-F	3.53	3.44	3.76
C	3.28	2.69	2.70
SE m ±	0.11	0.09	0.02
CD (0.05)	NS	0.29	0.07

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 38. Effects of treatments on P content in amaranthus shoot, %

Treatments	C1	C2	C3
FYM	0.47	0.21	0.46
PM	0.55	0.32	0.48
CC	0.43	0.26	0.18
VC	0.46	0.27	0.24
MC	0.82	0.33	0.58
TOF	0.52	0.25	0.48
TOF-F	0.58	0.38	0.52
C	0.4	0.14	0.2
SE m ±	0.07	0.05	0.06
CD (0.05)	0.25	NS	0.10

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 39. Influence of treatments on K content in amaranthus shoot, %

Treatments	C1	C2	C3
FYM	3.92	3.54	3.65
PM	3.94	3.80	3.92
CC	3.56	3.24	3.68
VC	3.70	3.76	3.80
MC	3.82	4.20	3.98
TOF	4.38	4.54	4.57
TOF-F	4.74	5.04	4.90
C	3.04	2.26	3.01
SE m ±	0.16	0.16	0.12
CD (0.05)	0.48	0.58	0.55

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 40. Effects of treatments on Ca content of shoot sample, %

Treatments	C1	C2	C3
FYM	2.11	1.86	2.02
PM	2.44	1.63	2.10
CC	2.35	1.87	2.10
VC	2.92	2.02	2.76
MC	3.02	2.64	3.05
TOF	2.30	2.11	2.50
TOF-F	3.50	2.97	2.96
C	2.30	2.06	2.00
SE m ±	0.28	0.16	0.01
CD (0.05)	0.45	0.38	0.15

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

4.3.3.5 Shoot Mg

The Mg concentration in shoot tissue in all three crops is presented in Table 41. The treatment PM recorded 0.48% Mg in C1, 0.65% Mg in C3 and was found to be superior to all other treatments in terms of Mg content. TOF was on par with MC in C1 and C3 (0.58%, 0.52%) and in C2 VC was significantly higher (0.84%). Both TOF-F and TOF was having low shoot Mg content except in C3 TOF-F was on par with PM.

4.3.3.6 Shoot S

The treatment TOF-F had the highest S content in shoot tissue in all three crops when compared to other treatments is clear from Table 42. S content in the shoot was non-significant in C1 and C2s and TOF-F showed highest shoot S content. The treatment TOF-F was found significantly higher in C3 (164.62 mg kg^{-1}) compared to other treatments.

4.3.3.7 Shoot micronutrients

The Fe content in shoot tissue varied among the treatments and ranged from 992.56 mg kg^{-1} (MC in C2) to 240.12 mg kg^{-1}(C in C2). In C1 it was significantly higher in TOF-F (902.91 mg kg^{-1}) compared to other treatments. the MC (992.56 mg kg^{-1}) recorded significantly higher Fe content in C2 and TOF-F (976.45 mg kg^{-1}) was on par with it. In C3, TOF-F (952.46 mg kg^{-1}) had significantly higher Fe content in shoot tissue and MC (932.27 mg kg^{-1}) was on par with it. The TOF-F application recorded higher plant Fe content in shoot tissue compared to all other treatments except MC in C2 and TOF application recorded superior shoot Fe content than CC and FYM after all three seasons (Table 43).

The Mn content in shoot tissue varied significantly among the treatments as pointed out in Table 44. In all three crops TOF-F (108.40 mg kg^{-1}, 158.40 mg kg^{-1}, 145.22 mg kg^{-1}) showed significantly higher Mn followed by TOF (103.60 mg kg^{-1}, 158.40 mg kg^{-1}, 145.22 mg kg^{-1}). Lowest shoot tissue Mn content was recorded by FYM (38.00 mg kg^{-1}, 54.00 mg kg^{-1}, 40.00 mg kg^{-1}).

The Zn content in shoot varied among the treatments significantly as presented in Table 45. The TOF-F had the highest Zn content of 61.20 mg kg^{-1},

Table 41. Effects of treatments on Mg content of amaranthus shoot, %

Treatments	C1	C2	C3
FYM	0.16	0.44	0.61
PM	0.48	0.72	0.65
CC	0.32	0.80	0.48
VC	0.22	0.84	0.62
MC	0.32	0.40	0.40
TOF	0.28	0.40	0.50
TOF-F	0.32	0.40	0.63
C	0.08	0.16	0.31
SE m ±	0.06	0.062	0.01
CD (0.05)	0.10	0.18	0.04

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 42. Effects of treatments on S content of amaranthus shoot, mg kg^{-1}

Treatments	C1	C2	C3
FYM	131.39	139.37	140.4
PM	127.25	141.39	147.45
CC	139.37	143.41	147.45
VC	140.38	140.38	142.4
MC	131.29	139.57	143.21
TOF	142.3	144.52	145.40
TOF-F	146.44	187.85	164.62
C	130.28	130.31	124.22
SE m ±	3.02	5.04	2.05
CD (0.05)	NS	NS	14.02

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 43. Influence of treatments on Fe content of shoot sample, mg kg^{-1}

Treatments	C1	C2	C3
FYM	268.12	377.16	400.49
PM	680.15	538.37	521.46
CC	574.46	578.73	546.76
VC	341.76	804.19	564.19
MC	868.79	992.56	932.27
TOF	502.71	652.75	712.19
TOF-F	902.91	976.45	952.46
C	241.17	240.12	250.37
SE m ±	4.86	5.12	1.93
CD (0.05)	11.99	35.69	29.92

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 44. Effects of treatments on Mn content of amaranthus shoot, mg kg^{-1}

Treatments	C1	C2	C3
FYM	38.00	54.00	40.00
PM	60.40	92.00	60.45
CC	54.40	64.00	85.00
VC	72.80	97.60	81.55
MC	82.80	76.80	72.00
TOF	103.60	109.20	90.10
TOF-F	108.40	158.40	145.22
C	70.40	84.40	80.24
SE m ±	1.55	0.42	2.29
CD (0.05)	14.61	11.15	16.79

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

52.00 mg kg^{-1}, 62.00 mg kg^{-1} in all three crops followed by TOF 59.20 mg kg^{-1}, 48.80 mg kg^{-1} in C1 and C2 and VC (50.00 mg kg^{-1}) in C3. Control recorded lowest content (27.20 mg kg^{-1}, 25.60 mg kg^{-1}, 30.00 mg kg^{-1}) in all three crops.

As evidenced from Table 46 the Cu content in shoot tissue was found to have no statistical difference with all other treatments in all three crops. From Table 47, it is clear that no statistical differences existed among the treatments with regard to B. The treatment TOF-F had the highest B content (9.90 mg kg^{-1}, 9.70 mg kg^{-1}, 9.90 mg kg^{-1}) in all three crops.

4.3.4 Root nutrients

4.3.4.1 Root N

The N content in root varied among the treatments except in C1 as represented in Table 48. Significant difference was found in C2 and C3. The highest N content was recorded by the treatment PM (2.41%, 1.77%, 1.82%) at all three crops and the lowest by control C (1.96%, 1.10%, 1.00%). In C2 and C3 TOF-F had 1.71% N and 1.76% N respectively and it was on par with PM and differed significantly from other treatments. The TOF application recorded higher root N content than CC and FYM after all three seasons.

4.3.4.2 Root P

As presented in Table 49 the treatments differed significantly except in C2. The treatment TOF-F recorded 0.30% P in C1, 0.58% P in C3 and was found to be superior to all other treatments in terms of P content. MC was on par with TOF-F in C3 (0.57%).

4.3.4.3 Root K

As depicted in Table 50 TOF-F had the highest K content followed by TOF in all three crops. The TOF-F was significantly higher and TOF was on par with it compared to other treatments. The K content by TOF-F was reported as 4.94% K in C1, 5.48% K in C2, 4.90% K in C3 and the K content in TOF was reported as 4.56% K in C1, 4.00% K in C2, 4.57% K in C3.

Table 45. Effect of different organic manures on Zn content of amaranthus shoot, mg kg^{-1}

Treatments	C1	C2	C3
FYM	46.40	34.80	35.22
PM	49.60	26.00	48.20
CC	36.40	26.60	40.00
VC	41.20	40.40	50.00
MC	57.60	30.80	40.21
TOF	59.20	48.80	40.00
TOF-F	61.60	52.00	62.00
C	27.20	25.60	30.00
SE m ±	0.57	0.58	1.85
CD (0.05)	2.52	2.66	10.49

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 46. Effect of treatments on Cu content of amaranthus shoot, mg kg^{-1}

Treatments	C1	C2	C3
FYM	5.20	5.40	3.00
PM	6.40	5.40	5.00
CC	3.60	4.80	5.02
VC	2.40	4.80	3.11
MC	6.00	7.60	3.00
TOF	8.40	4.40	6.10
TOF-F	8.80	9.60	7.00
C	1.60	0.80	1.00
SE m ±	0.31	0.06	0.41
CD (0.05)	NS	NS	NS

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 47. Effect of treatments on B content of amaranthus shoot, mg kg^{-1}

Treatments	C1	C2	C3
FYM	8.41	7.20	7.40
PM	8.80	8.39	9.80
CC	7.40	8.50	6.43
VC	5.61	8.64	9.60
MC	8.70	8.10	8.70
TOF	8.72	8.05	8.77
TOF-F	9.90	9.70	9.90
C	4.04	6.70	6.05
SE m ±	0.31	0.02	0.01
CD (0.05)	NS	NS	NS

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 48. N content of amaranthus root as effected by different organic manures, %

Treatments	C1	C2	C3
FYM	2.00	1.34	1.25
PM	2.41	1.77	1.82
CC	2.00	1.40	1.20
VC	2.02	1.26	1.18
MC	2.10	1.32	1.40
TOF	2.10	1.60	1.32
TOF-F	2.24	1.71	1.76
C	1.96	1.10	1.00
SE m ±	0.09	0.07	0.07
CD (0.05)	NS	0.09	0.12

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 49. Effect of treatments on P content of amaranthus root, %

Treatments	C1	C2	C3
FYM	0.10	0.49	0.26
PM	0.11	0.51	0.52
CC	0.15	0.48	0.38
VC	0.14	0.49	0.44
MC	0.19	0.49	0.57
TOF	0.14	0.41	0.42
TOF-F	0.30	0.57	0.58
C	0.12	0.20	0.20
SE m ±	0.0	0.04	0.01
CD (0.05)	0.07	NS	0.06

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 50. Effect of treatments on K content of amaranthus root, %

Treatments	C1	C2	C3
FYM	3.08	3.18	3.65
PM	4.02	3.40	3.92
CC	3.1	2.84	3.68
VC	3.84	3.36	3.80
MC	3.66	3.14	3.98
TOF	4.56	4.00	4.57
TOF-F	4.94	5.48	4.90
C	3.12	3.76	3.01
SE m ±	0.21	0.26	0.12
CD (0.05)	0.63	0.57	0.55

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

4.3.4.4 Root Ca

The Ca content in root tissue varied significantly among the treatments in all three seasons as depicted in Table 51. The treatment TOF-F had the significantly highest levels of Ca in all three crops (3.26%, 3.12%, 2.96%). In C3 MC (2.76%) was on par with TOF-F. The TOF application recorded higher shoot Ca content than FYM in all three seasons.

4.3.4.5 Root Mg

The Mg concentration in root tissue in all three crops is presented in Table 52. It was non-significant in all three seasons. The treatment VC recorded 0.76% Mg in C1 and the treatment PM recorded 0.76% Mg in C2 and 1.25% Mg in C3. Both TOF-F and TOF was low in root Mg content compared to other treatments.

4.3.4.6 Root S

The treatment TOF-F had the highest S content in root tissue in all three crops when compared to other treatments as clear from the Table 53. S content in shoot was non-significant in C2 and here TOF-F showed the highest shoot S content. The treatment TOF-F was found to be significantly higher in C1 and C3 (127.15 mg kg^{-1}, 167.55 mg kg^{-1}) compared to other treatments.

4.3.4.7 Micronutrient content of Root

The Fe content in root tissue varied among the treatments and ranged from 1092.85 mg kg^{-1} (TOF-F in C2) to 150.74 mg kg^{-1} (C in C3). The TOF-F recorded significantly higher Fe content in all three crops (966.10 mg kg^{-1}, 1092.85 mg kg^{-1}, 952.48 mg kg^{-1}) and MC was on par with it in C1 and C2 (924.16 mg kg^{-1}, 1062.52 mg kg^{-1}). The TOF-F application recorded higher root Fe content compared to all other treatments and TOF application recorded superior root Fe content than PM, CC and FYM after all three seasons (Table 54).

The Mn content in root tissue varied significantly among the treatments as pointed out in Table 55. In all three crops TOF-F (85.60 mg kg^{-1}, 88.00 mg kg^{-1}, 105.22 mg kg^{-1}) showed significantly higher values followed by TOF (61.20 mg

Table 51. Influence of treatments on Ca content in amaranthus root, %

Treatments	C1	C2	C3
FYM	2.50	1.34	2.12
PM	2.64	1.82	2.50
CC	3.17	1.63	2.10
VC	2.98	1.34	2.05
MC	2.74	1.82	2.76
TOF	2.69	1.74	2.60
TOF-F	3.26	3.12	2.96
C	2.69	1.63	2.00
SE m ±	0.15	0.02	0.21
CD (0.05)	0.37	0.08	0.25

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 52. Effect of treatments on Mg content of amaranthus root, %

Treatments	C1	C2	C3
FYM	0.48	0.60	1.21
PM	0.64	0.76	1.25
CC	0.56	0.52	1.08
VC	0.76	0.46	1.22
MC	0.36	0.48	1.00
TOF	0.40	0.52	0.91
TOF-F	0.48	0.48	1.10
C	0.40	0.44	0.33
SE m ±	0.08	0.04	0.08
CD (0.05)	NS	NS	NS

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 53. Effect of treatments on S content of amaranthus root, mg kg^{-1}

Treatments	C1	C2	C3
FYM	119.07	137.25	142.3
PM	115.03	146.34	154.42
CC	113.01	127.15	147.35
VC	121.09	151.39	142.30
MC	112.00	136.24	123.11
TOF	116.04	141.29	142.30
TOF-F	127.15	160.48	167.55
C	118.06	139.27	124.12
SE m ±	4.02	0.073	2.02
CD (0.05)	10.07	NS	17.25

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 54. Influence of treatments on Fe content of amaranthus root, mg kg^{-1}

Treatments	C1	C2	C3
FYM	201.12	686.90	400.85
PM	379.24	732.50	521.89
CC	616.82	446.45	546.41
VC	646.45	895.55	564.41
MC	924.16	1062.52	752.41
TOF	759.18	826.65	712.15
TOF-F	966.10	1092.85	952.48
C	180.10	366.11	150.74
SE m ±	0.08	1.06	1.93
CD (0.05)	50.78	41.81	59.02

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

kg^{-1}, 65.20 mg kg^{-1}, 90.10 mg kg^{-1}). Lowest shoot tissue Mn content was recorded by FYM (43.60 mg kg^{-1}, 40.40 mg kg^{-1}, 40.00 mg kg^{-1}).

The Zn content in root varied among the treatments significantly as presented in Table 56. The TOF-F had the highest Zn content of 63.60 mg kg^{-1}, 50.40 mg kg^{-1}, 60.00 mg kg^{-1} in all three crops followed by TOF 55.60 mg kg^{-1}, 46.40 mg kg^{-1} in C1 and C2 and MC (50.21 mg kg^{-1}) in C3. Control recorded lowest content (30.80 mg kg^{-1}, 13.20 mg kg^{-1}, 16.00 mg kg^{-1}) in all three crops.

As evidenced from Table 57 the Cu content was found to have no statistical difference with all other treatments in all three crops. From the Table 58, it is clear that no statistical differences existed among the treatments in root B content. The treatment TOF-F had the highest B content (8.01 mg kg^{-1}, 7.51 mg kg^{-1}, 8.01 mg kg^{-1}) in all three crops.

4.3.5 Soil biological properties after each crop harvest

4.3.5.1 Micro fauna: microbial load

The effect of organic manures on bacterial count is presented in Table 59. The peak level was noticed towards the C3. The treatment TOF-F had maximum bacterial number except in C1. In C1, MC (7.40 $\times 10^6$ cfu g^{-1}) exhibited significantly highest bacterial count and TOF (7.35 $\times 10^6$ cfu g^{-1}) as well as TOF-F (7.25 $\times 10^6$ cfu g^{-1}) were on par with it. In C2 and C3 TOF-F (7.69 $\times 10^6$ cfu g^{-1}, 7.72 $\times 10^6$ cfu g^{-1}) recorded significantly highest bacterial count followed by MC (7.56 v cfu g^{-1}, 7.58 $\times 10^6$ cfu g^{-1}) as well as TOF (7.44 $\times 10^6$ cfu g^{-1}, 7.55 $\times 10^6$ cfu g^{-1}).

The fungal population remained significant at all levels of sampling as shown in Table 60. A high population was recorded in MC in all three crops and was significantly different from all other treatments. increase. A gradual increase in fungal population was observed after each successive crop due to TOF-F and TOF application.

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Table 55. Effect of treatments on Mn content of amaranthus root, mg kg^{-1}

Treatments	C1	C2	C3
FYM	43.60	40.40	40.00
PM	50.80	41.60	60.45
CC	44.80	51.20	85.00
VC	48.00	41.60	81.55
MC	53.20	60.40	70.00
TOF	61.20	65.20	90.10
TOF-F	85.60	88.00	105.22
C	44.40	50.80	80.24
SE m ±	0.09	0.32	2.29
CD (0.05)	16.27	20.96	16.79

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 56. Effect of treatments on Zn content of amaranthus root, mg kg^{-1}

Treatments	C1	C2	C3
FYM	38.00	29.60	45.22
PM	34.80	23.20	48.20
CC	18.80	14.00	22.00
VC	45.20	22.80	40.00
MC	42.80	40.00	50.21
TOF	55.60	46.40	50.00
TOF-F	63.60	60.40	60.00
C	30.80	13.20	16.00
SE m ±	0.15	0.35	1.85
CD (0.05)	5.45	8.15	10.49

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 57. Effect of treatments on Cu content of amaranthus root, mg kg^{-1}

Treatments	C1	C2	C3
FYM	4.84	1.80	2.30
PM	2.56	2.92	2.50
CC	3.32	1.72	1.50
VC	2.24	1.16	2.70
MC	4.44	1.24	2.30
TOF	4.16	2.20	2.61
TOF-F	5.96	5.56	3.01
C	3.88	1.04	1.20
SE m ±	2.15	4.26	8.41
CD (0.05)	NS	NS	NS

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 58. Effect of treatments on B content of amaranthus root, mg kg^{-1}

Treatments	C1	C2	C3
FYM	7.51	7.31	7.51
PM	7.91	7.21	7.91
CC	7.51	6.71	7.51
VC	7.71	7.11	7.71
MC	7.81	7.41	7.81
TOF	7.81	7.41	7.81
TOF-F	8.01	7.51	8.01
C	6.11	6.01	6.11
SE m ±	0.01	0.09	0.81
CD (0.05)	NS	NS	NS

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 59. Effect of organic manures on bacterial count in three successive amaranthus crops, $\times 10^6$ number of cfu g^{-1} soil

Treatments	At harvest		
	C1	C2	C3
FYM	7.12	6.95	7.22
PM	7.17	6.85	7.25
CC	6.65	7.15	7.24
VC	7.19	7.37	7.48
MC	7.40	7.56	7.58
TOF	7.35	7.44	7.55
TOF-F	7.25	7.69	7.72
C	6.50	6.60	6.74
SE m ±	0.013	0.009	0.007
CD (0.05)	0.20	0.20	0.20

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 60. Effect of different organic manures on fungal colonies in field micro plot trial, $\times 10^4$ number of cfu g^{-1} soil

Treatments	At harvest		
	C1	C2	C3
FYM	4.28	4.20	4.00
PM	3.65	3.93	4.30
CC	4.03	4.33	4.39
VC	3.95	3.79	3.95
MC	4.36	4.47	4.44
TOF	3.86	4.00	4.10
TOF-F	3.88	4.04	4.07
C	3.89	3.90	3.83
SE m ±	0.008	0.005	0.003
CD (0.05)	0.20	0.20	0.10

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

A peak level in population of actinomycetes was recorded after C3 by all treatments except control as pointed out in Table 61. After C1 it was non-significant. FYM recorded the highest number after C2 and C3. A gradual increase in actinomycete population was observed after each successive crop due to TOF-F and TOF application.

4.3.5.2 Macro fauna: earthworm and microarthropod count

Earthworm count was almost equal in all treatments and a gradual increase in population was observed in each crop as pointed out in the Table 62. A steep increase in earthworm population was observed after each crop due to VC application. The population count recorded was 5, 8 and 11 number m^{-2} after C1 C2 and C3 respectively.

Results of microarthropod count estimated by Modified Berlese- Tullgren Funnel Extractor Method are shown in Table 63. Microarthropods count was significant in all three crops. A gradual increase in microarthropod count was observed after each and PM recorded significantly higher count in all three crops followed by TOF-F, MC and TOF.

4.3.5.3 Dehydrogenase activity

The variation in soil dehydrogenase activity among the treatments is evident from the Table 64. The activity increased progressively after each crop except control. It was clear that the MC was significantly highest in dehydrogenase activity after all three crops among all the treatments. After C1 dehydrogenase activity of TOF (49.90 μg of TPF g^{-1} soil 24 h^{-1}) was on par with MC (53.60 μg of TPF g^{-1} soil 24 h^{-1}). Both TOF-F and TOF were superior to FYM and CC in dehydrogenase activity after all three crops.

4.3.5.4 Microbial biomass carbon

The microbial biomass carbon among the treatments ranged from 189.55 μg g^{-1} soil (MC after C3) to 124.19 μg g^{-1} soil (C in C1) as pointed out in the Table 65. The MC was significantly highest after all three crops as compared to all the treatments. A gradual increase in microbial biomass carbon was observed after crop to crop due to TOF-F and TOF application.

Table 61. Effect of organic manures on actinomycete number, $\times 10^3$ number of cfu g^{-1} soil

Treatments	At harvest		
	C1	C2	C3
FYM	3.50	5.16	5.24
PM	3.65	4.72	4.80
CC	3.74	4.76	4.79
VC	4.09	4.34	4.79
MC	3.74	4.58	4.99
TOF	4.02	4.89	4.90
TOF-F	4.35	4.82	4.93
C	3.80	4.74	4.69
SE m ±	0.015	0.005	0.003
CD (0.05)	NS	0.20	0.10

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 62. Effect of organic manures on earthworm number, number m^{-2}

Treatments	At harvest		
	C1	C2	C3
FYM	2	3	4
PM	1	2	4
CC	2	3	4
VC	5	8	11
MC	2	3	3
TOF	2	3	4
TOF-F	2	3	4
C	2	1	2
SE m ±	0.49	0.46	0.41
CD (0.05)	1.44	1.37	1.21

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 63. Effect of treatments on microarthropod count, no. kg^{-1} soil

Treatments	At harvest		
	C1	C2	C3
FYM	22.75	30.00	38.75
PM	32.50	42.50	53.25
CC	20.50	28.00	35.25
VC	25.75	30.50	30.75
MC	30.50	36.50	48.50
TOF	27.50	32.50	45.25
TOF-F	31.50	40.50	50.25
C	20.50	25.00	27.00
SE m ±	1.87	3.94	1.01
CD (0.05)	4.45	7.68	4.84

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 64. Effect of organic manures on dehydrogenase activity, μg TPF g^{-1} soil 24 h^{-1}

Treatments	At harvest		
	C1	C2	C3
FYM	39.20	44.10	50.40
PM	46.80	51.20	58.80
CC	37.60	40.40	56.50
VC	40.80	52.50	62.20
MC	53.60	75.50	89.60
TOF	49.90	53.70	64.00
TOF-F	45.20	54.00	68.60
C	21.90	20.70	29.20
SE m ±	0.11	0.64	0.46
CD (0.05)	5.01	6.19	9.37

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

4.3.6 Shoot observations

4.3.6.1 Plant height

The effects of treatments on plant height of amaranthus was found to be significant as clear from Table 66. In C1 plant height was significantly higher in PM (56.0 cm) and it was on par with MC (52.3 cm) and TOF-F (49.0 cm). In C2 plant height was significantly higher in TOF-F (85.3 cm) and it was on par with PM (80.5 cm) and MC (70.0 cm). In C3 plant height was significantly higher in PM (85.0 cm) and it was on par with TOF-F (80.8 cm) and MC (79.5 cm). TOF application recorded higher plant height compared to VC, CC, FYM and C in all three seasons.

4.3.6.2 Primary branches per plant

Number of primary branches per plant was non-significant in all three crops, which is evident from the Table 67.

4.3.6.3 Shoot weight

The effects of treatments on shoot weight of amaranthus at three crops was found to be significant as clear from Table 68. In C1, shoot weight was significantly higher in PM (96.33 g plant^{-1}) and it was on par with TOF-F (92.65 g plant^{-1}) and MC (87.21 g plant^{-1}). In C2, shoot weight was significantly higher in TOF-F (160.58 g plant^{-1}) and it was on par with PM (140.58 g plant^{-1}) and TOF (113.07 g plant^{-1}). In C3, shoot weight was significantly higher in PM (156.97g plant^{-1}) and it was on par with TOF-F (143.06 g plant^{-1}), MC (138.00 g plant^{-1}) and TOF (98.03 g plant^{-1}).

4.3.6.4 Shoot dry weight

Table 69 showed the dry matter yield of amaranthus as influenced by different organic manures. The effects of treatments on shoot dry matter of amaranthus was found to be significant. In C1 shoot dry weight was significantly higher in PM (1331.67 kg ha^{-1}) and it was on par with MC (1115.21 kg ha^{-1}) and TOF-F (988.50 kg ha^{-1}). In C2 shoot dry weight was significantly higher in TOF-F (2293.75 kg ha^{-1}) and it was on par with PM (2037.08 kg ha^{-1}) and MC (1950.00 kg

Table 65. Effect of organic manures on microbial biomass carbon in amaranthus crop, µ g g^{-1} soil

Treatments	At harvest		
	C1	C2	C3
FYM	125.92	154.41	153.04
PM	151.68	174.12	172.88
CC	147.76	171.04	173.65
VC	126.08	153.65	176.72
MC	174.36	188.55	189.55
TOF	136.99	174.37	176.80
TOF-F	150.52	177.86	184.40
C	124.19	135.07	135.92
SE m ±	0.51	0.82	0.82
CD (0.05)	4.01	6.14	10.24

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 66. Plant height of amaranthus as influenced by different organic manures, cm

Treatments	C1	C2	C3
FYM	43.00	48.00	52.75
PM	56.00	80.50	85.00
CC	43.00	51.50	60.00
VC	45.38	59.75	70.00
MC	52.25	70.00	79.50
TOF	47.00	61.00	72.50
TOF-F	49.00	85.25	80.75
C	30.00	35.75	38.75
SE m ±	1.995	7.408	4.662
CD (0.05)	5.91	21.94	13.80

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

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Table 67. Effect of treatments on primary branches per plant

Treatments	C1	C2	C3
FYM	11.00	12.75	14.50
PM	11.50	12.00	17.00
CC	9.80	9.00	14.25
VC	8.80	10.25	12.75
MC	11.80	11.25	17.25
TOF	8.80	9.50	16.75
TOF-F	11.00	11.25	14.25
C	9.00	8.00	9.50
SE m ±	0.621	2.415	1.812
CD (0.05)	NS	NS	NS

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 68. Effect of treatments on shoot weight, g plant^{-1}

Treatments	C1	C2	C3
FYM	50.26	71.13	77.06
PM	96.33	140.58	156.97
CC	50.88	64.99	62.26
VC	53.68	105.99	88.02
MC	87.21	94.31	138.00
TOF	51.75	113.07	98.03
TOF-F	92.65	160.58	143.06
C	36.87	36.66	42.26
SE m ±	12.071	13.109	19.124
CD (0.05)	35.74	50.03	56.62

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

ha^{-1}). In C3 shoot dry weight was significantly higher in PM (2180.07 kg ha^{-1}) and it was on par with MC (1916.67 kg ha^{-1}) and TOF-F (1431.35 kg ha^{-1}).

4.3.7 Root phenomics

4.3.7.1 Number of primary and secondary roots

Amaranthus has a single primary root which develops into tap root. Number of secondary roots varied in different treatments non significantly. Highest number was observed in TOF-F in all three crops as shown in Table 70.

4.3.7.2 Root weight

The effect of treatments on root weight of amaranthus was found to be significant in all three crops as clear from Table 71. TOF-F had the highest root weight in all three crops (17.50 g plant^{-1}, 26.88 g plant^{-1}, 21.18 g plant^{-1}). It was on par with PM in all three crops (16.50 g plant^{-1}, 23.41 g plant^{-1}, 18.44 g plant^{-1}) with TOF in C2 and C3 (16.93 g plant^{-1}, 13.58 g plant^{-1}) and with MC in C1 and C3 (14.17 g plant^{-1}, 19.28 g plant^{-1}).

4.3.7.3 Root dry matter

Table 72 showed the dry matter yield of amaranthus root as influenced by different organic manures. The effects of treatments on root dry matter of amaranthus was found to be significant. TOF-F had the highest root dry matter in all three crops (211.21 kg ha^{-1}, 477.08 kg ha^{-1}, 488.40 kg ha^{-1}). It was on par with PM and TOF in all three crops and with MC in C1 and C3.

4.3.7.4 Root volume

As evidenced from Table 73, TOF-F had the highest root volume in all three crops (20.75 cm^3, 25.25 cm^3, 23.00 cm^3). It was on par with PM in all three crops (18.00 cm^3, 24.25 cm^3, 20.75 cm^3) and with TOF in C1 and C3 (17.50 cm^3, 12.75 cm^3).

4.3.7.5 Root diameter

As evidenced from Table 73, TOF-F had the highest root diameter in all three crops (14.75 mm, 16.50 mm, 16.25 mm). It was on par with PM in all three

Table 69. Effect of treatments on shoot dry weight, kg ha^{-1}

Treatments	C1	C2	C3
FYM	622.08	1079.17	1070.21
PM	1331.67	2037.08	2180.07
CC	742.71	1167.50	864.65
VC	816.04	1612.92	666.98
MC	1115.21	1950.00	1916.67
TOF	656.85	1805.83	1361.56
TOF-F	988.90	2293.75	1431.35
C	568.33	402.50	586.98
SE m ±	165.08	43.687	265.609
CD (0.05)	488.77	417.60	786.42

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 70. Number of primary and secondary roots in amaranthus

Treatments	Primary roots			Secondary roots		
	C1	C2	C3	C1	C2	C3
FYM	1	1	1	65.75	41.25	37.50
PM	1	1	1	49.25	51.50	58.75
CC	1	1	1	60.00	26.50	41.25
VC	1	1	1	59.50	35.75	25.00
MC	1	1	1	44.00	37.50	70.00
TOF	1	1	1	53.00	42.75	40.00
TOF-F	1	1	1	66.75	52.25	62.50
C	1	1	1	33.25	18.50	26.25
SE m ±	-	-	-	12.071	10.798	6.866
CD (0.05)	-	-	-	NS	NS	NS

C1- First crop; C2- Second crop; C3- Third crop; NS- Non significant
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Absolute control.

Table 71. Effect of treatments on amaranthus root weight, g plant^{-1}

Treatments	C1	C2	C3
FYM	9.74	14.60	10.86
PM	16.50	23.41	18.44
CC	9.10	9.20	10.45
VC	8.41	13.26	7.61
MC	14.17	14.84	19.28
TOF	9.75	16.93	13.58
TOF-F	17.50	26.88	21.18
C	7.32	3.86	5.83
SE m ±	1.981	3.955	2.847
CD (0.05)	5.82	11.71	8.43

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 72. Effect of treatments on root dry matter, kg ha^{-1}

Treatments	C1	C2	C3
FYM	154.98	202.50	357.29
PM	189.31	457.08	412.15
CC	124.38	234.58	290.21
VC	140.52	285.42	211.39
MC	204.56	331.67	435.49
TOF	164.67	420.00	377.08
TOF-F	211.21	477.08	488.40
C	89.17	99.17	162.01
SE m ±	15.94	75.96	79.086
CD (0.05)	47.19	224.90	234.16

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

crops (12.75 mm, 11.00 mm, 15.00 mm) and with MC in C1 and C3 (12.50 mm, 12.25 mm).

4.3.7.6 Total root length

The effects of treatments on root length of amaranthus was found to be significant as clear from Table 74. TOF-F had the highest root length in all three crops (25.12 cm, 26.25 cm, 25.75 cm). It was on par with PM in all three crops (23.50 cm, 23.75 cm, 24.75 cm) and with MC in C1 and C2 (24.95 cm, 24.00 cm). TOF application recorded higher total root length compared to VC, CC, FYM and C in all three seasons.

4.3.7.7 Root: shoot ratio

Table 75 shows the root: shoot ratio of amaranthus as influenced by different organic manures. The root: shoot ratio of TOF-F was lower than FYM in C1 and C3 and PM in the C2. Highest root: shoot ratio was shown in FYM (0.34) in C3.

4.3.8 B:C ratio

The B:C ratio of different treatments per ha is presented in Table 76. The TOF-F was significantly higher in B:C ratio and it was on par with PM it in all three crops. The mean B:C ratio of different organic manures differed in the order TOF-F (1.75) > PM (1.72) > TOF (1.62) > MC (1.60) > FYM (1.35) > VC (1.31) > CC (1.22) > C (0.92).

4.3.9 Incidence of pest and diseases

C1 was infected with amaranthus leaf blight. About 100% disease incidence was observed. The percent disease index calculated using the disease scoring was - 15-26%. The spread of the disease was arrested by effective irrigation management and foliar application of 2% PGPR mix II, in C2 and C3.

Table 73. Effect of treatments on root diameter and root volume

Treatments	Root diameter (mm)			Root volume (cm^3)		
	C1	C2	C3	C1	C2	C3
FYM	10.75	10.25	10.25	16.00	16.25	18.25
PM	12.75	11.00	15.00	18.00	24.25	20.75
CC	9.75	5.75	8.25	14.00	10.25	17.75
VC	11.50	5.25	7.75	15.25	12.25	17.25
MC	12.50	8.75	12.25	16.50	14.00	14.50
TOF	9.50	10.75	10.00	17.50	21.00	20.75
TOF-F	14.75	16.50	16.25	20.75	25.25	23.00
C	8.75	3.75	5.50	6.75	6.25	5.25
SE m ±	1.059	1.228	1.784	1.227	0.42	1.57
CD (0.05)	3.14	3.04	5.28	3.63	2.17	4.65

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 74. Total root length of three successive crops of amaranthus, cm

Treatments	C1	C2	C3
FYM	20.85	21.75	18.50
PM	23.50	23.75	24.75
CC	20.12	18.25	16.25
VC	20.17	20.75	19.25
MC	24.05	24.00	21.25
TOF	22.17	22.50	20.50
TOF-F	25.12	26.25	25.75
C	15.50	11.50	10.75
SE m ±	1.99	1.12	2.19
CD (0.05)	5.00	3.31	2.85

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Table 75. Influence of treatments on root: shoot ratio

Treatments	C1	C2	C3
FYM	0.24	0.19	0.34
PM	0.16	0.22	0.19
CC	0.17	0.20	0.34
VC	0.17	0.18	0.32
MC	0.18	0.17	0.28
TOF	0.25	0.23	0.28
TOF-F	0.21	0.21	0.33
C	0.16	0.25	0.28
SE m ±	0.02	0.03	0.02
CD (0.05)	0.04	0.04	0.05

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer -Fortified; C – Absolute control.

Table 76. Effect of treatments on B:C ratio per ha

Treatments	C1	C2	C3	Mean
FYM	1.31	1.35	1.38	1.35
PM	1.68	1.76	1.71	1.72
CC	1.02	1.36	1.29	1.22
VC	1.41	1.28	1.24	1.31
MC	1.58	1.66	1.61	1.60
TOF	1.62	1.67	1.57	1.62
TOF-F	1.72	1.79	1.74	1.75
C	1.00	0.86	0.9	0.92
SE m ±	0.03	0.02	0.009	0.02
CD (0.05)	0.11	0.09	0.05	0.08

C1- First crop; C2- Second crop; C3- Third crop
FYM – Farmyard manure; PM – Poultry manure; CC – Conventional compost; VC – Vermicompost; MC – Microbial compost; TOF – Thermochemical Organic Fertilizer; TOF-F – Thermochemical Organic Fertilizer - Fortified; C – Absolute control.

Discussion

5. DISCUSSION

A study entitled "Root phenomics and soil biological activity in response to thermochemical organic fertilizer application" was conducted from October 2017 to April 2019 at the Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani with the objective of studying the root phenomics and soil biological activity in response to thermochemical organic fertilizer application as compared with conventional organic manures and its effect on growth and yield of Amaranthus. The results obtained are discussed in this chapter.

5.1 CHEMICAL CHARACTERISTICS OF ORGANIC MANURES USED IN THE EXPERIMENT

All manures had slightly acidic to neutral reaction (Table 7). Could be due to the acidic waste materials used as substrate (He *et al.,* 2018) and formation of humus and humic acids through polymerisation and condensation occurred during maturity stage (Fels *et al.*, 2014). Highest pH was recorded by MC. FYM has recorded the lowest pH, and this may be due to the low soluble salt content. All organic manures had safe limits of EC. Plant growth is supported by the mature composts with safer EC values and high EC causes negative effect on crop (Yang *et al.*, 2015). According to Mohee *et al.* (2015), the safe range of EC for the compost is <3.5 dS m^{-1}. Comparatively highest EC was noted in TOF-F followed by TOF, PM and MC. EC value of animal manure will be higher than organic waste composts and higher EC indicates the higher nutrient concentration (Ko *et al.*, 2008). In organic manures, the most significant property is the organic carbon content. During composting, TOC decreases due to degradation and mineralisation of organic substances to CO_2 by microbial action (Azim *et al.*, 2018). The TOF and TOF-F recorded higher TOC, as method of processing of waste is not dependent on biological activity for decomposition of organic matter. However, due to the impact of dilution due to fortification, the value in TOF-F is slightly lesser than TOF.

The N content of all organic manures remained significant. PM had highest content and it was on par with TOF-F. This was followed by TOF, MC, FYM, VC and CC. Generally, the total nitrogen is 1 to 4% of the total dry weight of compost, and is composed of at least 10% of available nitrogen (Brinton and Evans, 2000). Poultry manure is rich in nitrogen because solid and liquid excreta are excreted together and no urine loss occurs (Amanullah *et al.,* 2010). The higher N content of TOF-F is due to fortification. The P content was significantly different and PM was found to have the highest content. TOF-F and TOF were having comparably higher values compared to all other conventional organic manures. Fortification resulted in higher P content in TOF-F. Both TOF-F and TOF were having superior values for K content than other manures. It may be attributed to the addition of reagent during preparation of organic fertilizer (dilute KOH). TOF-F was significantly higher in K content than TOF due to fortification. The nutrient content of the conventional animal-based manures and other composts are in conformity with the average contents stated as per POP (KAU, 2016). The content of TOC and NPK in the thermochemically prepared organic fertilizer exceeds that of FYM indicating its superiority.

Highest Ca content was found in TOF-F which was on par with PM. Fortification resulted in higher Ca content in TOF-F. The PM recorded highest Mg content and it was significantly superior. The S content varied significantly among the manures with TOF-F registering the highest value followed by TOF and PM. Fortification of TOF with sulphates of Mg and Zn enhanced the S content in TOF-F.

The Fe content among different organic treatments was significantly highest in MC followed by TOF-F. Superior microbial activity in MC resulted in higher decomposition and release of nutrients. The TOF-F had the highest Mn content and CC was the lowest. The Zn content in manures differed significantly. The highest value was noticed for TOF-F. The TOF-F had the significantly higher Cu content and FYM, the lowest. The fortified nonconventional manure (TOF-F) recorded the highest B content followed by TOF. The fortification of TOF made TOF-F superior in Zn and B content. The fertility specifications of the thermochemical treatment based organic fertilizer are in accordance with that of city compost as per FAI, 2017. Though the nutrient content of TOF was less than that of TOF-F, it was statistically superior to FYM, CC and VC. The source of materials from which the organic manures have formed might have been devoid of heavy metal contamination. The absence of heavy metal pollution raffinose the suitability of TOF and TOF-F as a marketable organic fertilizer.

5.2 KINETICS OF PH, EC AND OC

In the pot culture trial with perlite based growing media with different organic manures, contrasting results were observed for pH and EC. The pH of the growing media, irrespective of the kind of organic manure, had an alkaline reaction initially but exhibited a general decline at harvest of the crop tending to neutrality. This is very well expected as decomposition of organic manures yields organic acids which will decrease the soil pH. The decomposition of carbohydrates in the glycolytic pathway results in carboxylic groups and several organic acids are produced that could have decreased the soil pH (Yan *et al.*, 1996; Gill *et al.*, 2016). Growing media with the compost based organic manures *viz.*, CC, VC and MC exhibited comparatively higher pH in the initial stage owing to the inherently higher pH of respective manures. The pH of the growing media with TOF exhibited a higher magnitude of decrease by 0.67 units at the time of harvest of amaranthus which is an indication of the steady rate of decomposition that is taking place in TOF. However, the same trend is not reflected in the fortified TOF because lime was added as a source of Ca during fortification. Growing media with VC too exhibited a similar pattern of lower magnitude (0.07 units) of pH decline. As vermicomposting proceeds, it results in production of alkaline substances which balances the effect of organic substances produced during decomposition (Zupancic and Grilc, 2012). In the field micro plot trial, the soil reaction which was strongly acidic (5.26) at the start of the trial recorded a higher pH in all treatments at harvest of the first crop. A steady progressive decrease was then observed at harvest of the consecutive second and third crops and finally attained near initial values except for the control treatment. This is a clear indication of the buffering capacity of the soil imparted by the different organic manures which reiterates the importance of addition of organic matter to the highly weathered acidic Ultisols.

Contrary to the decreasing trend in soil pH, soil EC registered a general increase in the growing media with different organic manures at harvest stage. No significant difference in EC was noticed in the initial phase between the growing media with different manures. As organic manure decomposition proceeds, it might have released soluble salts also into the soil along with the degradation products. Composting results in increase of concentration of salts due to the decomposition of complex organic matter and formation of mineral salts such as ammonium ions and phosphates via transformation of organic matter. So decomposition and mineralization of organic matter may contribute soluble salts to increase soil EC (Chan *et al.*, 2016). The growing media with PM and TOF-F were superior in electrical conductivity at harvest stage. Since bird excreta occurs in combination with urine (Amanullah *et al.*, 2010), the higher soluble salt content might have contributed to high EC levels. The progressive increase in soil EC subsequent to each of the three crops was also apparently observed in the field micro plot trial also. The TOF-F and TOF was superior in electrical conductivity. Sequential soil electrical conductivity measurement was efficient in the identification of dynamic modifications in the accessible soil N as influenced by organic manure (Eigenberg *et al.*, 2002). A high EC indicates the higher nutrient concentration (Ko *et al.*, 2008). Lowest EC was observed in growing media with FYM is might be due to volatilisation losses of ammonia and precipitation of salts (Chan *et al.*, 2016).

A general decrease in soil OC content was evident throughout all treatments at the harvest stage as compared to the preliminary phase. Depletion of soil organic carbon stocks is due to the activity of soil micro and macro fauna. Soil organic carbon addition stimulates the soil microbial population. Carbon serves as the source of energy for the growth and metabolism of the microorganisms. They cause the mineralization of organic matter by the release of CO_2 through respiration (Kumar *et al.*, 2010). The inherently higher OC content of TOF-F rendered it superior at both initial and final stages. The highest organic carbon mineralisation of 1.36% (Fig. 2) in TOF-F may be attributed to the predominance of the labile carbon pool, which is the carbon fraction having the least residence time and undergoes decomposition comparatively easily (Leno, 2017).

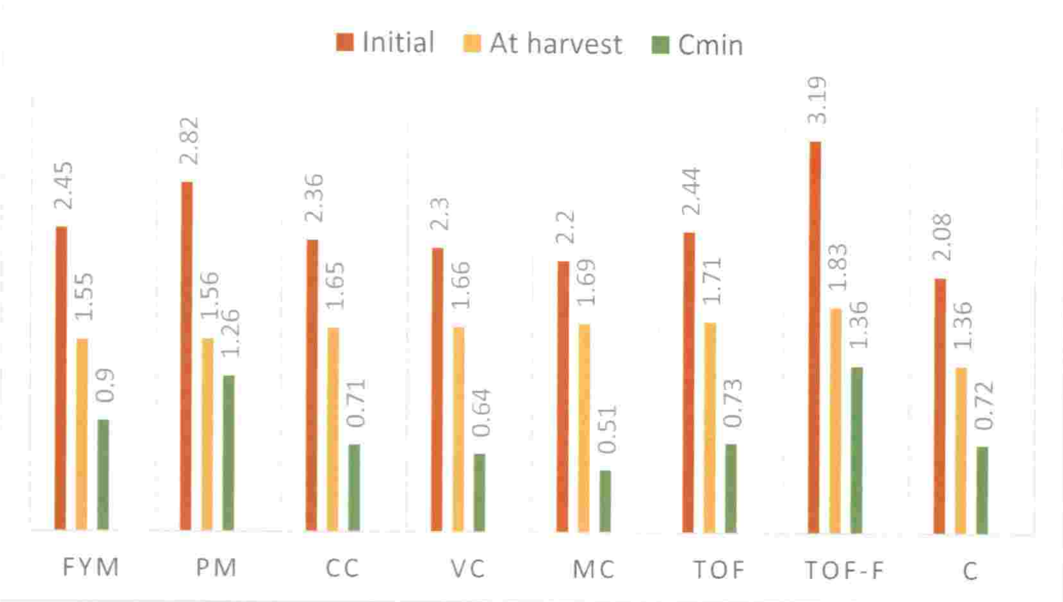

Fig. 2 OC content (%) in growing media at initial and harvest stages and the content of carbon mineralised (C_{min})

The OC content of the field plot which had a medium content of 1.16% exhibited a gradual progressive increase in the soil organic carbon status consequent to organic manure additions consecutively over three seasons except in the control treatment which largely remained without much change in the OC content. This is a pointer towards the priming effect imparted by addition of organic manures favouring the rhizospheric microorganisms. The superiority of the thermochemically decomposed organic fertilizer, with and without fortification, over the compost based and animal/bird based manures was explicitly evident (Fig. 3). The thermochemical organic fertilizer has a comparatively high carbon pool index also which is indicative of the carbon sequestration potential acquired by virtue of the thermochemical decomposition process (Leno, 2017).

5.3 NUTRIENT DYNAMICS IN THE GROWING MEDIA AND IN FIELD MICRO PLOTS

A general decline of all plant available major and micronutrients in the growing media was observed at the harvest stage as compared to the preliminary stage of sampling at the start of the pot culture trial. Preliminary sampling of growing media revealed the superiority of inherently N rich manures TOF-F and PM. A decline in N content of growing media was observed in all treatments. Ionic absorption by plant roots, immobilisation by soil microbial population and losses of the nutrient by volatilisation and leaching are the various modes of depletion of the nutrient. Addition of organic manures in the open micro field plots served to replenish the organic nitrogen stock in the soil from the initial low status of 125.44 kg ha^{-1} (Fig. 4). The organic carbon content of the manures exerted a positive influence on mineralisation of nitrogen. Among the three crop cycles, C3 harvest suggested there is a positive temporal variation in the mineralization of organic N and P (Maerere *et al.*, 2001). In field trial TOF-F, PM and MC application resulted in higher soil N enrichment compared to other treatments. Though MC was low in initial N content, rich biological properties enhanced N mineralisation. FYM recorded lowest soil available N season after season compared to other treatments except no manure control. A progressive depletion of soil N levels in the control plot which was deprived of both C and N sources, was evident after the harvest of each crop. Bauwa *et al.* (2016) reported a strong positive correlation between soil N and its organic matter content. The thermochemical based fertilizers and the poultry manure with a comparatively higher N content and lesser C: N ratio are capable of N release at a steady rate. Organic manures with elevated levels of N and low levels of C: N ratio mineralize N in adequate amounts for plant use (Eldridge *et al.*, 2017).

P content in the growing media was superior in treatments TOF-F and PM at the initial phase of sampling. A decline in P content in pot study might be due to initial immobilization or plant uptake from the isolated closed system. Significantly high P content in PM alone at harvest stage might have resulted due to a higher nutrient release and crop uptake in case of TOF-F. The initial high soil P status (94.78 kg ha^{-1}) was enhanced by the P content of organic manures in the field plots (Fig 5). The P dynamics exhibited a temporary immobilisation at the harvest of the first crop. This may be due to the fact that as organic P accumulates in soil, extra cellular phosphatase enzyme production slows down and mineralisation gets suppressed (McGill and Cole, 1981). However release of P showed an increasing trend during the subsequent two seasons attaining more than initial values for all treatments except for control, where the P status remained almost static. The increased availability may be attributed to the P release from Fe and Al compounds by the chelating action of organic anions (Reddy *et al.*, 2015). Among different treatments TOF-F and PM recorded high available P in soil throughout all seasons since they had higher P levels. The enhanced P release dynamics of TOF-F has also influenced the formation of desirable root phenomic characters and root architecture in this treatment.

At the end of the crop season in pot trial, the availability of K in all treatments was lower than the initial level due to crop uptake. Giusquiani *et al.* (1988) reported that even at low rates of application municipal solid waste composts increased the soil K concentrations. But the availability at the end of the experiment was lower than the initial in all treatments due to plant uptake. The thermochemical OF based treatments maintained the superiority of K content in the growing media both in the initial stage as well as at harvest stage. In the field trial, there was a progressive mineralisation of K at harvest due to manure application at all seasons raising the K status from an initial low level of 93.8 kg ha^{-1} to a medium K status in all treatments except control (Fig. 6). The content of all major primary nutrients were higher in thermochemical based manures than CC and FYM both in the initial phase as well as at harvest stage.

Among the secondary nutrient contents of growing media, the thermochemical organic fertilizer with fortification was significantly higher with regard to Ca and S contents. As soil was initially deficient in Ca and S contents the application of organic manures gradually increased the content and in case of Ca, TOF-F and PM treatments attained near sufficiency values whereas S was sufficient in all treatments. The supplementary addition of lime on fortification may have led to a higher content of Ca in the TOF-F treatment. The release of Mg was more prominent in PM at both stages of sampling in the growing media. Initially soil in the micro plot was sufficient in Mg content. Though PM and TOF-F were superior in Mg content, the soil samples after the crop were rich in available Mg content only in PM. The steady release of K from the TOF-F and TOF might have resulted in slower Mg mineralisation in that treatment. Available S content in growing media was initially high in TOF-F and PM whereas at harvest it was significantly superior in PM. The sulphur deficiency in soil is replenished by application of organic manures and it exhibited a gradual increase. TOF-F was superior in available S content at harvest of the third crop. The comparative superiority of TOF-F in the TOC and N contents might have contributed to the higher content of S initially in the growing media. Mineralisation of S is closely associated with N as both nutrients are present in the organic pool in the soil (Ali *et al.*, 2015).

There was no significant variation in the release of micronutrients in the growing media with different manure types. While MC dominated in Fe content, TOF-F dominated in Mn content at harvest. MC was rich in Fe content, which was reflected in soil from micro plots. Initial soil was sufficient in Fe, Mn, Zn and Cu content and it increased gradually due to continuous application of organic manures. TOF-F enhanced all micronutrients to great extent compared to other manures in soil. The formation of stable complexes by chelation between functional groups of organic compounds in the thermochemically produced fertilizer and metals might have blocked their sorption and increased their concentration in soil solution (Madrid *et al.*, 2003). The application of organic manures reclaimed the soil B content to sufficient range except C which was still deficient. Among the different organic manures TOF-F greatly enhanced the soil B content.

Content of heavy metals Pb and Cd in the growing media were below detectable limits irrespective of the treatment because the degradable solid wastes used for the preparation of composts was devoid of heavy metal content.

5.4 SHOOT AND ROOT NUTRIENT CONCENTRATION

The content of nutrient elements in the shoot and root tissue almost followed a trend similar to that of the growing media. It was observed that the concentration

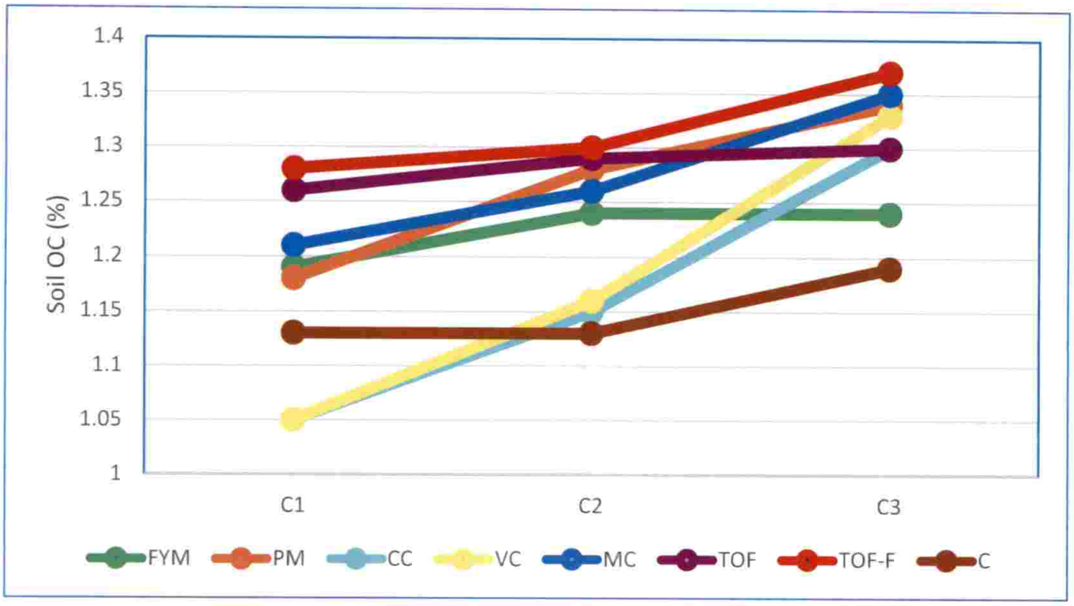

Fig. 3 Soil OC as influenced by different treatments in three successive crops

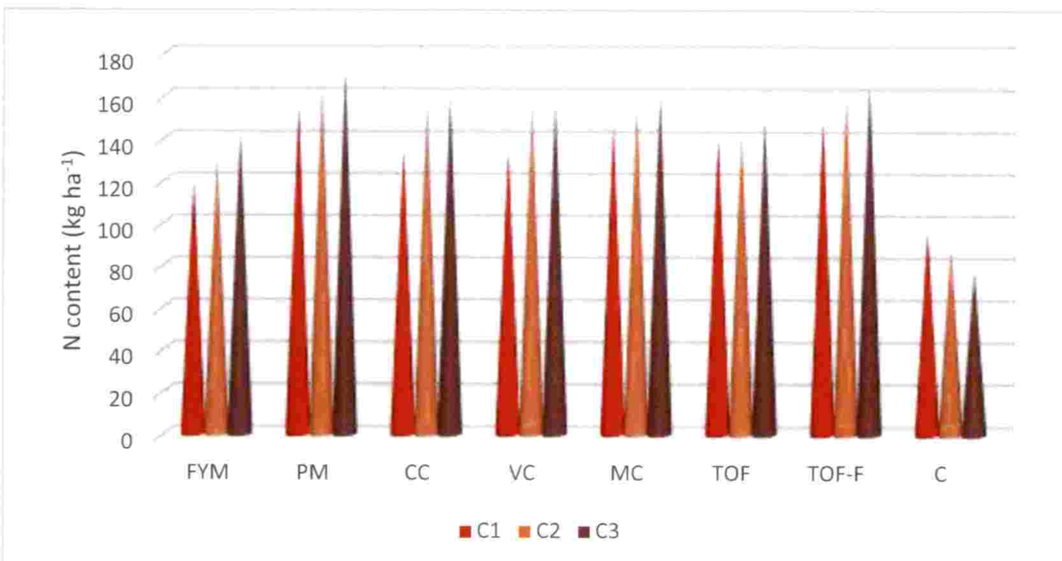

Fig. 4 Effect of treatments on soil available N content

of the major primary elements in the shoot tissue was comparatively higher than in the root tissue. Though the magnitude of nitrogen release in the growing media was comparatively higher in the compost based manures and FYM treatments, the concentration of N in the root and shoot tissue of the thermochemical based and poultry manure applied treatments were found to be higher than the other treatments. This is indicative of the sustenance effect and capability of these manures manifested by a steady supply of N over a period of 30 days with fair degree of retention and minimal leaching loss, thereby preventing environmental pollution. The N content in TOF-F is higher than other manures as a result of fortification and it is able to release higher amounts of N for plant uptake (Leno *et al.*, 2017). The N content was the lowest in FYM, because of the low N content. Baral *et al.*, (2017) reported that the plants treated with cattle manure showed low nitrogen use efficiency.

Root and shoot P concentration was also found to be higher in the PM followed by TOF-F and TOF. The root and shoot tissue concentrations of P followed the same order of the magnitude of P release from different manures in the growing media. No preferential advantage for a particular kind of manure could be observed for availability of P released nor its absorption through roots and uptake to the shoot tissue in the pot culture trial. The concentration of K was the highest in plants treated with both fortified and non-fortified organic fertilizer. The high content of K in this manure might have contributed to a higher plant uptake (Jayakrishna and Thampatti, 2016). The K mineralised from the thermochemical based treatment was subjected to amaranthus root absorption and subsequent shoot uptake in an efficient manner as compared to PM and CC over the crop growth period.

There was not much variation in the concentration of the major and secondary nutrients Ca, Mg and S in the root and shoot tissue of amaranthus in the pot culture trial. Ca and S concentration in shoot and root tissue was highest in TOF-F. Concentration of shoot Mg was highest in TOF-F whereas PM was found highest in root Mg content. This may be attributed to the preferential absorption of

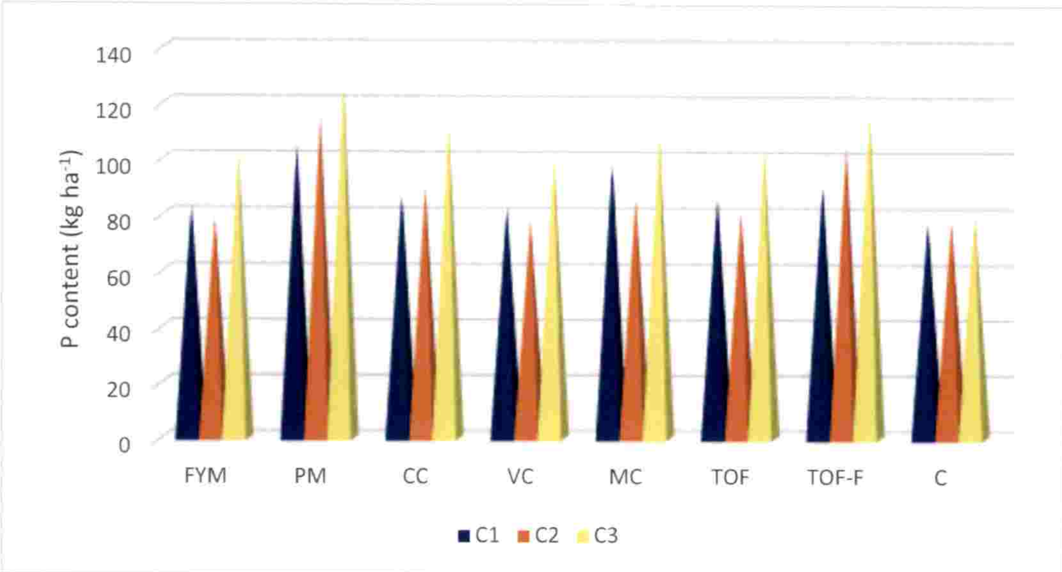

Fig. 5 Effect of treatments on soil available P content

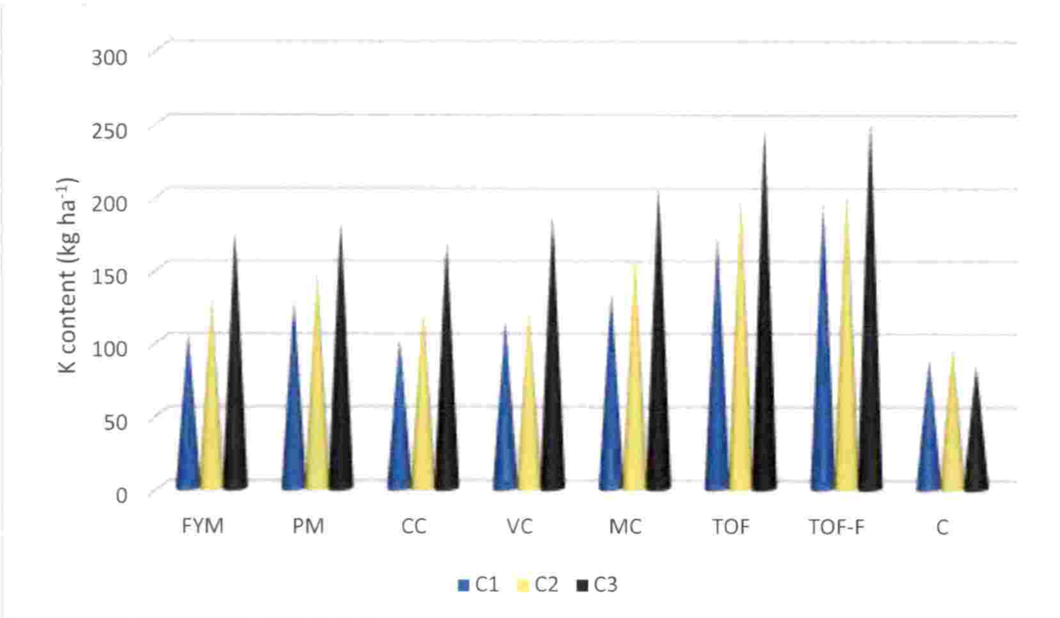

Fig. 6 Effect of treatments on soil available K content

K^+ ions in the TOF-F treatment as compared to mineralised Mg^{2+} ions in the absorption sites of the plant roots.

The magnitude of concentration of micronutrients in the shoot and root tissue of amaranthus was in accordance with the extent of mineralisation in the different growing media treatments. The high inherent level of Fe content in MC was reflected in the shoot concentration of Fe in amaranthus. However it was on par with TOF-F in the root concentration. Compost based treatments accumulated more Fe in the amaranthus root than FYM whereas a reversal in the trend was noticed in the shoot concentration. Mn, Zn and Cu contents in root and shoot tissue were dominant in the TOF-F treatment. Concentration of these micronutrients were considerably higher in the root and shoot tissue in the compost based treatments as compared to FYM treatment. Variation in B content in both the root and shoot remained insignificant.

5.5 SOIL BIOLOGICAL ACTIVITY IN POT CULTURE AND IN THE FIELD MICRO PLOT

Studies revealed that there was a proliferation of the microbial population consequent to addition of organic manures both in the pot culture trial as well as in the open micro field. The addition of organic matter enhances both microbial diversity and population (Albiach *et al.*, 2000).

The bacterial, fungal and actinomycetes count in the growing media in the pot culture trial recorded an increase for all manure types at harvest stage of the crop from the initial stage of start of the trial, with the highest being registered by MC treatment. However the bacterial count registered an increase of 17.47% in the thermochemical based treatment, which was the highest magnitude of count increase. The bacterial count in the soil also consistently increased after each crop of amaranthus in the open field with the highest values after the second and third crop seasons (Fig. 7). The magnitude of enhancement in fungal population also in the TOF treatment was higher than FYM and compost based treatments in the growing media at harvest. The build-up of the soil fungal population after the first crop season was sustained even after the harvest of the second and third crops in the micro plots, with respective applications of the organic manures. The highest extent of increase from the initial levels in actinomycetes was observed in animal, bird and earthworm based manures as compared with the compost based and thermochemical based manures in the growing media of the pot culture trials. This trend was sustained in the micro plots of the field with the soil applied with FYM registering the highest actinomycetes count after the second and third crop seasons.

Food waste compost are comprised of the remains of fruit and vegetables and rich in carbohydrate. It is an easy source of carbon, nitrogen and energy for microorganisms. This resulted in increased soil microbial populations and soil microbial biomass (Chitravadivu *et al.*, 2009). MC was enriched with microbes during preparation. So obviously it shown higher biological activity.

Microbial count proliferated due to application of organic manures. Bacterial count was predominant over fungi and actinomycetes. Initially TOF-F and TOF were low in bacterial number due to sterilization of microbes during thermochemical process. So low count was obtained before crop in pot trial. But at harvest, there is more increase in bacterial count and comparable to MC. The reason might be due to the ample supply of easily soluble nutrients in this organic fertilizer (Sudharmaidevi *et al.*, 2017). Also, higher organic carbon content might be contributed. The amount of increase of microbial load is attributed to an increase in soil organic carbon content due to manure application (Yanardag *et al.*, 2017).

Fungal colonies gradually increased due to organic manuring. Fungi colonies were significantly superior in MC due to innate microbial population. Fungi population of TOF-F and TOF was almost similar colonies to MC. In pot trial actinomycetes population was superior in MC and also comparable colonies are obtained in FYM and TOF-F. It is reported that organic materials with a high C/N ratio attracted fungal and actinomycetes population and whereas bacterial population is favoured those with low C/N ratio (Leite *et al.*, 2017). Actinomycetes are responsible for decomposition of resistant fraction of organic matter, so their population might be higher in FYM than TOF-F and TOF which were having higher C/N ratio.

The pot culture study, being an isolated system, presence of earthworms were detected only in pots filled with VC based growing media after the harvest of the crop. Unlike in the pot culture study, presence of earthworms were observed in most of the open field micro plots applied with different manures. Plots applied with VC exhibited higher number of earthworms after each crop.. VC was applied after sieving so it may not contain adult worms but it can contain earthworm eggs. Vermicompost can enhance soil fertility biologically through growth in soil microbes and earthworm population (Lim *et al.,* 2015). Soil micro arthropods were abundant in MC but non-significant. In consonance with the observations for earthworms in the pot culture study, there was no significant difference between manures in the micro arthropod count. However in the open system, soil micro arthropods were abundant in PM followed by TOF-F and MC. Soil micro arthropods increased by immediate food supply rather than soil chemical parameters (Kautz *et al*., 2006). Eo and Nakamoto (2007), reported that increased population densities of micro arthropods in organically fertilized plots were apparently associated with increased microbial activity. A gradual rise in population was observed after all three crops due to rise in nutrient availability.

Dehydrogenase is an oxidoreductase enzyme that exists only in viable cells and are indicators of overall microbial activity (Taylor *et al*., 2002). MC was superior in dehydrogenase activity in the pot culture trial. But it needs to be noted that the dehydrogenase activity of the thermochemical based OF applied growing media registered a doubling of the dehydrogenase activity at harvest. This trend of sequential increase in dehydrogenase activity ahead of other compost based and FYM treatments was sustained even after the crop harvest in all three seasons. A steep increase in dehydrogenase activity was found at harvest in TOF-F and population is comparable to MC.

The microbial biomass carbon in the different treatments in the pot culture as well as field trials closely followed the trends observed in dehydrogenase activity. There is correlation between dehydrogenase activity and microbial biomass carbon. Higher microbial activity in MC resulted in higher microbial biomass carbon (Fig 8). It was increased gradually after each crop due to organic manure application. The microbial biomass and soil enzyme activities were increased by the long-term manure and fertilizer treatments (Mandal *et al.*, 2007). In TOF-F and TOF initially it was low after C1 then gradually increased after C2 and C3, even more than all other treatments and in par with MC.

The extremely low value of the dehydrogenase activity and the microbial biomass carbon in the control treatment is a pointer towards the inevitability of addition of organic manures to maintain soil health sustainably.

5.6 EFFECT OF ORGANIC MANURES ON SHOOT AND YIELD CHARACTERS

The superior effects of the poultry manure, microbial compost and the fortified thermochemical organic fertiliser was quite evident in the plant biometric characters like plant height, primary branches per plant, shoot weight and dry matter content in the pot culture trial. The same trend was retained in the field micro plot trials throughout all the three seasons of crop growth. However there was no significant variation in the number of primary branches between treatments in the micro plots.

Manures are applied based on nitrogen equivalent basis, yield varied due to different bio-chemical properties of different organic sources (Bashir *et al.* 2015). All PM, TOF-F and MC recorded higher plant height compared to all other treatments consistently in the pot culture as well as in the open field over three seasons (Fig. 9). TOF was superior in plant height than VC, FYM, CC and C (Plate 7 and 9). The plant height was higher in pot culture as compared to field condition irrespective of treatments indicating effective utilisation of the mineralised nutrients from the organic manures. Number of primary branches per plant was significant

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in pot trial and TOF-F followed by MC recorded highest number. Though plant height was highest in PM, shoot yield was more in TOF-F followed by PM in pot trial. Among the different organic manures, the shoot yield was poorest in FYM and CC (Fig. 10) due to low availability nutrients particularly secondary and micronutrients. Higher shoot dry weight was found in PM followed by TOF-F. Shoot dry matter also varied exactly similar to shoot weight. PM, TOF-F and MC recorded higher shoot dry weight compared to other treatments.

The steady supply of essential nutrients at a constant rate reflected in their higher concentration in root and shoot particularly of N and P recorded in the root and shoot of amaranthus in poultry manure, microbial compost and the fortified thermochemical based fertiliser treatments might have contributed to the highest plant height and shoot yield and dry matter content. The significant effect of poultry manure in promoting plant biometric characters is well established. Poultry manure is the most appropriate organic fertilizer currently available for organic vegetable cultivation, whether processed or unprocessed (Vimala *et al.,* 2001). Kahu *et al.* (2019) stated that application of poultry manure at 10 t ha^{-1} shown highest plant height, number of leaves, leaf length, leaf width, leaf area and leaf area index in Amaranthus. TOF was superior in plant height during all seasons than VC, FYM, CC and C. An increase in crop growth and yield as a result of TOF-F application has been stated by Sudharmaidevi *et al.* (2017).

5.7 EFFECT OF ORGANIC MANURES ON ROOT PHENOMICS, NUTRIENT ACQUISITION AND UTILISATION

The framework of spatial arrangement of the root system which constitutes the root architecture is of vital significance and critical for rhizosphere resource mobilisation, nutrient acquisition, plant interactions and nutrient cycling. Variations in the root architectural fabric profoundly influences the capacity of plants to take up nutrients. The major fluxes of elements in the plant shoot system is largely influenced by the root system architecture. Root characteristics affecting the acquisition of mineral elements determine the concentration of essential

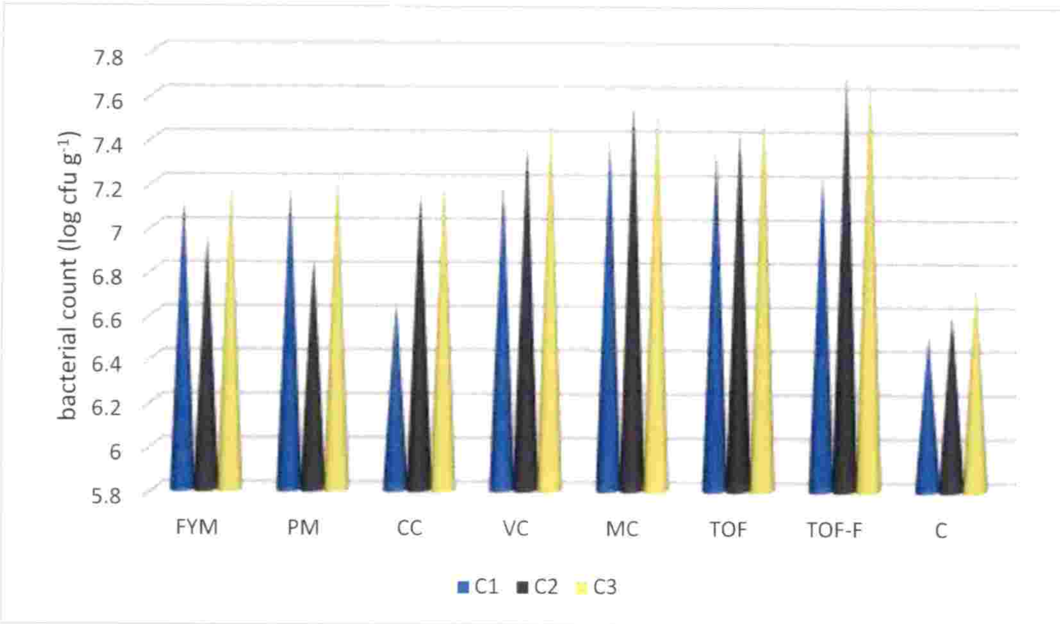


Fig. 7 Effect of organic manures on bacterial count in field micro plot trial

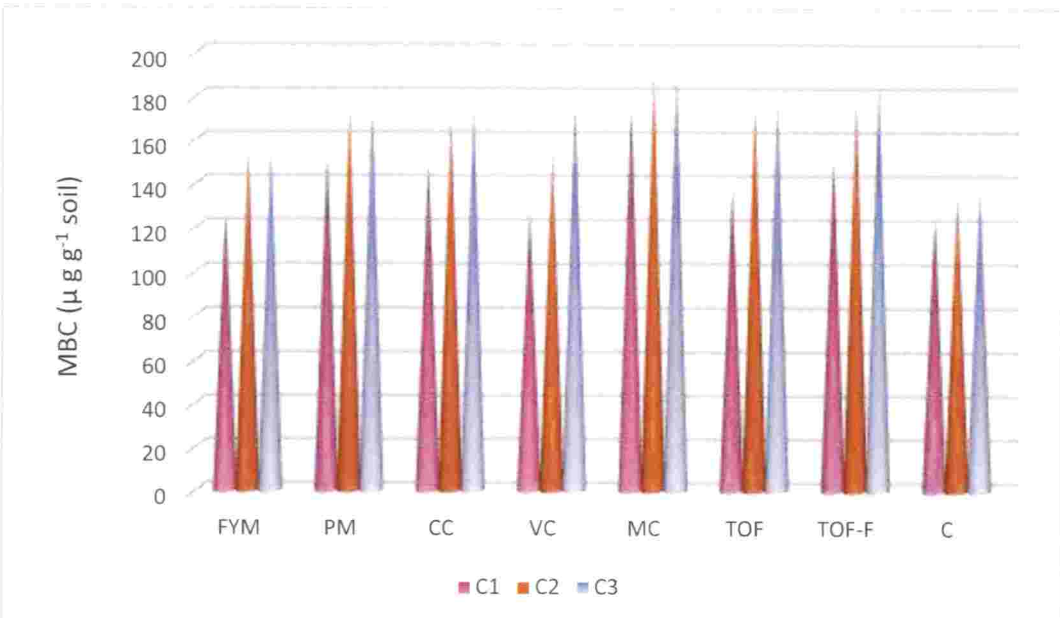


Fig. 8 Effect of organic manures on microbial biomass carbon in field micro plot trial

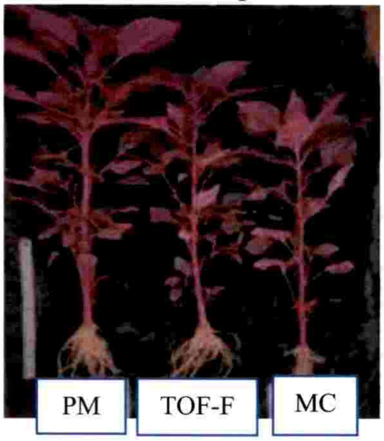
nutrients in the root and thereby to the shoot. The bioavailability of nutrients in the rhizospheric environment has a profound bearing on root growth and proliferation.

Domination of the growing media prepared from the thermochemical based treatment, with and without fortification, in the expression of various root phenomic characters like number of secondary roots and total root length was explicitly clear in the pot culture experiment (Plate 8). This trend was consistently carried forward through the entire three seasons in the field micro plot trials (Plate 10). Amaranthus has a single primary root which develops into tap root. Number of secondary roots varied in different treatments non-significantly. Highest number was observed in TOF-F in all three crops. In the field micro plots TOF-F recorded significantly superior root length followed by PM and MC (Fig. 11). Organic fractions like humic acid, fulvic acid and humin have high potential to increase root length. Among them humic acid has a high potential compared to humin and fulvic acid. Humic acid treatment favours cell differentiation and new lateral root induction. The number of lateral roots increased by 22 to 111% in maize treated with different humic acid. The humic acid treatment clearly induced the proliferation of root mitotic sites with respect to control plants (Jindo *et al.*, 2012). The humic acid produced through the composting process enhances the principal root length. The thermochemical decomposition based fertiliser was found to have a higher labile carbon content as compared with FYM based treatments (Leno, 2017). A high labile carbon content is suggestive of a shorter turn over time favouring the conversion of organic matter to humic acid. The high number of bacterial count and fungal population in the field trial as well as pot trial is suggestive of the formation of humic acids from the labile carbon fraction of TOF-F. The high N content in amaranthus shoot in the thermochemical treatment with fortification particularly in the second (3.44%) and third crop (3.76%) seasons bear testimony to the efficient acquisition and utilisation of mineralised and leached N by deep foraging of the long principal root. The 'steep, cheap and deep' roots favour improved N acquisition to harness the highly soluble nitrate which gets leached down which demands a higher root length (Lynch, 2013). The treatment that received additions of vermicompost, though with

Plate 7. Comparison of plant height in pot culture trial

Plate 8. Total root length obtained under different treatments in pot culture trial

First crop



PM TOF-F MC

Second crop

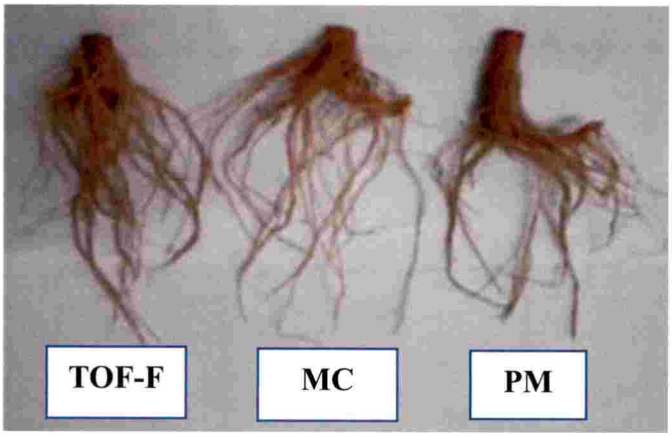
TOF-F PM MC TOF VC CC FYM C

Third crop

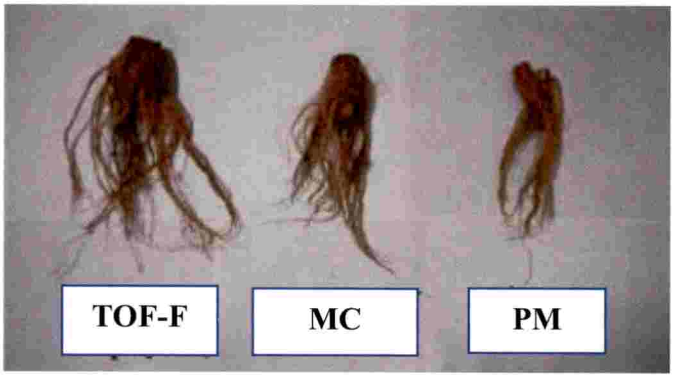
PM TOF-F MC TOF VC CC FYM C

Plate 9. Variation in plant height under different organic manures in the field micro plot trial during the three seasons

First crop



Second crop



Third crop

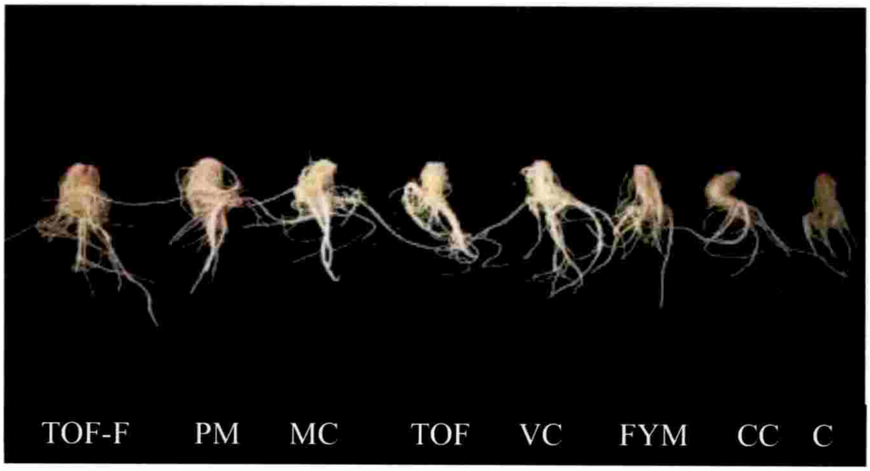


Plate 10. Comparison of root system in field micro plot trials during the three seasons

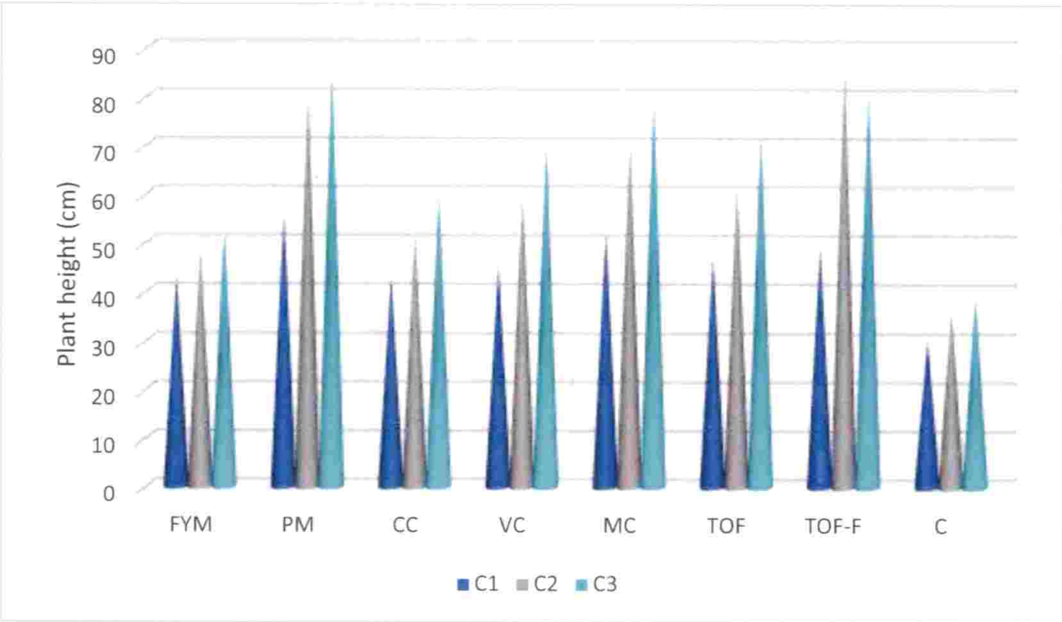


Fig. 9 Plant height influenced by different organic manures in field micro plot trial

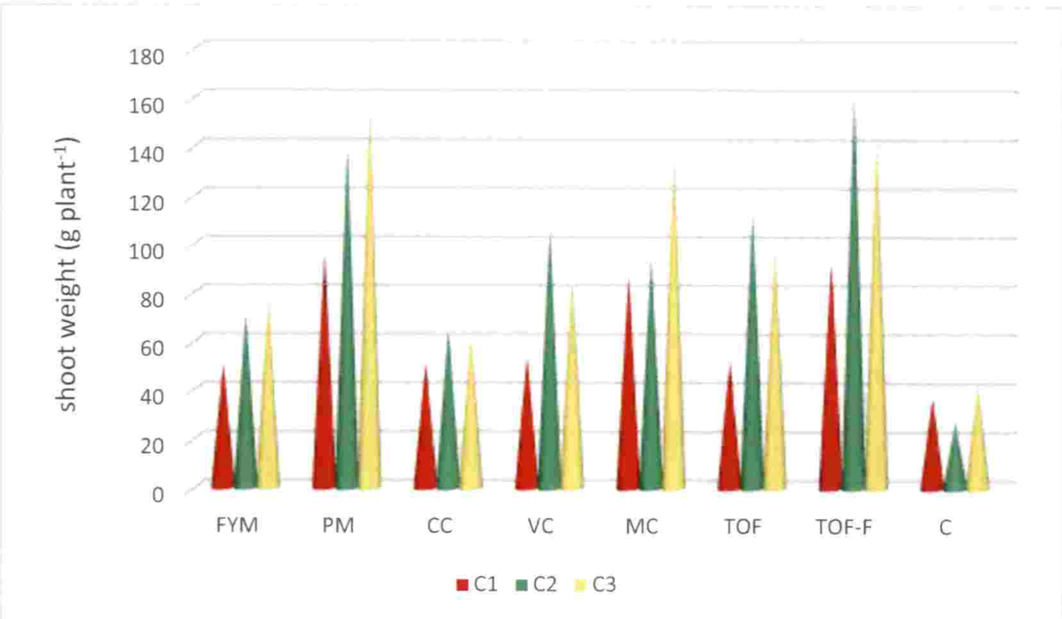


Fig.10 Effect of treatments on shoot weight in field micro plot trial

a higher count of earthworms in the soil, exhibited comparatively lower levels of root length, secondary roots and root diameter in the present study. While earthworms often improve the soil structure and nutrient availability, Arnone and Zaller (2014) reported decreasing grass root length densities under increasing earthworm densities. Root phenomics of the thermochemically processed fertilizer thus has a better nutrient acquisition efficiency than those under vermicompost application. In addition, root dry weight in seedlings treated with humic acid from composted material was increased generally by 25 to 30% with respect to non-composted humic acid fractions (Jindo *et al.*, 2012). The substantially high root dry weight attained in the TOF and TOF-F treatments in the present experiment is in perfect justification of this fact.

The trend in variations in root diameter and root volume were almost similar. Root diameter and root volume were significantly higher in TOF-F followed by MC and TOF (Fig. 12). A two to three fold increase from that of the FYM was observed in the TOF and TOF-F treatments with regard to the root diameter, root fresh weight, dry matter and root volume. Root volume is a key determinant of acquisition efficiency which is the quotient of soil volume depleted to total root volume (Fitter *et al.*, 1991). While P depletion zones are only a few millimetres in diameter, it may be 10- 100 times larger for nitrate due to the 1000 fold difference between phosphate and nitrate in effective diffusion coefficients (Barber, 1984). Top soil foraging was proved to be important for P acquisition in maize and common bean (Lynch and Brown, 2008). The elevated concentration of P in the shoot tissue in the third crop (0.52%) of amaranthus is in true reflection of the effective top soil foraging. P acquisition by roots is thought to be through 'topsoil foraging' (Richardson *et al.*, 2011) which has been made efficient by the high number of secondary roots and root diameter recorded in the thermochemical based treatments. Higher P uptake by amaranthus in TOF-F treatment may have in turn contributed to the superior root phenomics characters as P is highly essential nutrient for root formation and growth especially during the third crop season when the rate of P mineralisation was substantially higher. Hence the two to four fold increase in root volume obtained with the TOF and TOF-F treatments prudently

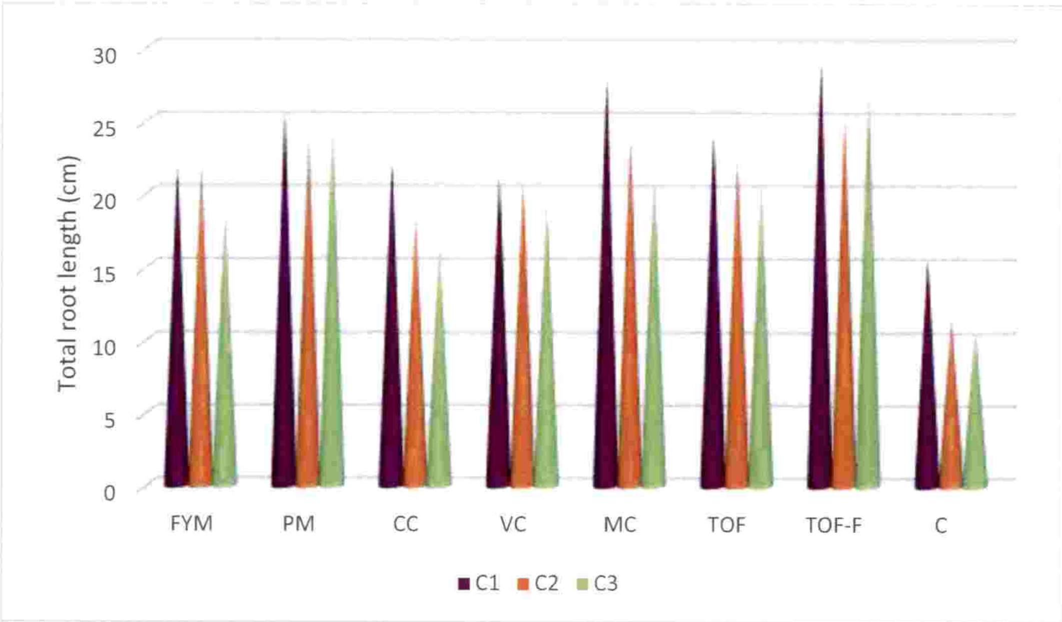


Fig.11 Total root length of three successive crops of amaranthus

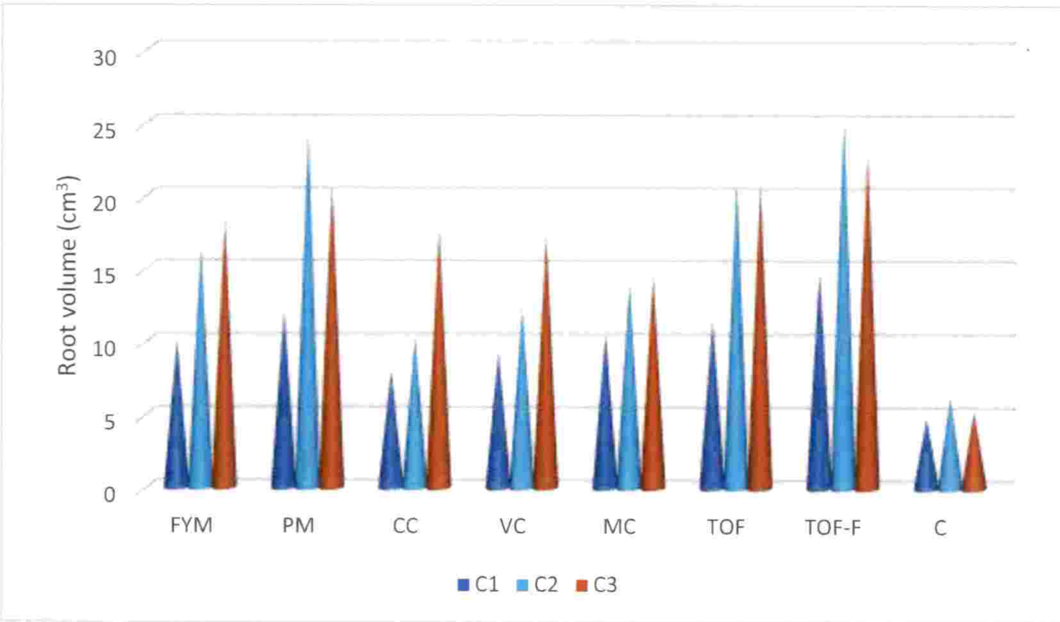


Fig. 12 Root volume of three successive crops of amaranthus

justifies the nutrient acquisition efficiency of these treatments which has resulted in the elevated concentration of secondary nutrients Ca, S and micronutrients Fe, Mn, Zn, Cu, B in the root tissue. The relatively high tissue concentrations of Ca (3.50%), S (187.85 mg kg^{-1}), Fe (902 mg kg^{-1}), Mn (158.40 mg kg^{-1}), Zn (62.00 mg kg^{-1}) and Cu (9.60 mg kg^{-1}) indicates a proportionate and effective translocation of these nutrients to the shoot tissue of amaranthus.

Significant difference existed in the root weight of amaranthus due to application of different organic fertilizers. Root weight in TOF-F treatment registered an increase of 46 % from that of the FYM treatment and 73 % from that of control in the pot culture trial. A similar trend was observed in the open micro plot trials where the root weight increased up to 49 % than FYM and 74 % than control. Enhanced root weight with application of TOF-F was reported in a pot culture study. The root weight in TOF-F was 2.5 to 4 times more than that of other manure treatments and 8.3 times than that of no manure control treatment (Jacob, 2018). Root dry weight followed the similar trend as root weight.

Apart from the root weight, the allocation of biomass between the root and shoot is also a factor which demands due consideration. Plant root responses to nutrients supplied locally to the root system and the plasticity that exists in biomass allocation between the roots and shoots is of prime concern while assessing the root phenomic characters. The general prediction is that plants should decrease the root: shoot ratio in response to increased soil fertility. The comparatively lower root: shoot ratio of the animal/ bird based manures and thermochemically processed manures observed in the pot culture trial using perlite based growing media are in conformity of this view (Table 20). However Chapin (1980, 1988) reasons that a high, inflexible root: shoot ratio not only maximises nutrient uptake from infertile soil but also allows luxury consumption and subsequent storage during nutrient flushes. Such nutrient flushes in the rhizospheric environment, especially in low nutrient soils shifts the allocation to exceed potential benefits gained in nutrient acquisition. The ability to quickly adjust allocation in this manner during nutrient flushes is of particular advantage in a seasonal crop like amaranthus, which has a low investment in expensive lignin and phenol rich structural tissue. It is also of particular interest to note that several investigators have observed that the root:shoot ratio decreases with an increased supply of nutrients like nitrogen or phosphorus only up to a certain level beyond which it plateaus or increases (Fichtner and Schulze,1992; Redente *et al.*,1992). These findings are in perfect corroboration with the results obtained in the present field micro plot trial study. The TOF treatment recorded the highest root: shoot ratio after the first and second crops and the TOF-F treatment after the third season. This manner of biomass allocation favouring an enhanced partitioning in the root tissue might have been facilitated by the nutrient flushes occurring in the rhizosphere of the field micro plot soil which was inherently low in the major nutrients N (125.44 kg ha^{-1}) and K (93.8 kg ha^{-1}) and deficient in Ca (263.75 mg kg^{-1}) and S (4.06 mg kg^{-1}). The nutrient flushes may have resulted due to enhanced mineralisation of these nutrients effected by the high population of rhizosphere bacteria and fungi, which was amply evident in the thermochemical based fertilizer applied treatments. Reynolds and Antonio,1996 has reported similar findings in an elaborate study on plasticity of root: shoot ratio under differing N conditions. K acquisition is also favoured by a large root biomass allocation with a high root/shoot ratio (White *et al.*, 2013). The high concentration of K in the shoot tissue of amaranthus ranging from 4.00% to 5.48% obtained in the thermochemical organic fertilizer treatments with and without fortification in present study reiterates this finding. The highest plant height (85.25 cm), shoot weight (160.58 g $plant^{-1}$) and shoot dry weight (2293.75 kg ha^{-1}) attained by the TOF-F treatment is due to the efficient utilisation of the mobilised nutrients in the build-up of the shoot biomass. The root perception of the rhizospheric environment informs the regulation of shoot growth (York *et al.*,2013).

Economic analysis revealed that TOF-F followed by PM were economically superior than other organic manures. The TOF-F was significantly higher in B:C ratio followed by PM and TOF.

Summary

6. SUMMARY

A study entitled "Root phenomics and soil biological activity in response to thermochemical organic fertilizer application" was conducted from October 2017 to April 2019 at the Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani with the objective of studying the root phenomics and soil biological activity in response to thermochemical organic fertilizer application as compared with conventional organic manures and its effect on growth and yield of Amaranthus. A summary of salient results of the study are presented.

Characterization of organic manure

- All manures had slightly acidic to neutral pH and safe limits of EC. Highest EC was noticed in TOF-F indicating higher nutrient concentration. The TOF and TOF-F recorded higher TOC as method of processing of waste is not dependent on biological activity for decomposition of organic matter. However, due to the impact of dilution due to fortification, the value in TOF-F is slightly lesser than TOF.
- PM had highest N content (2.38%) followed by TOF-F (2.18%) and TOF (2.02%). Poultry manure is rich in nitrogen because solid and liquid excreta are excreted together and no urine loss occurs. The higher N content of TOF-F is due to fortification.
- TOF-F and TOF registered considerably higher P content as compared to all other conventional organic manures except PM. Fortification resulted in higher P content in TOF-F.
- Both TOF-F and TOF were having superior values for K content than other manures. It may be attributed to the addition of reagent during preparation of organic fertilizer (dilute KOH). TOF-F was significantly higher in K content than TOF due to fortification.
- Highest Ca content was found in TOF-F which was on par with PM. The PM recorded highest significantly superior Mg content (0.62%).

- The S content varied significantly among the manures with TOF-F registering the highest value followed by TOF. Fortification of TOF with sulphates of Mg and Zn enhanced the S content in TOF-F.
- The Fe content of organic manures was significantly different and MC (4398.53 mg kg^{-1}) recorded the highest value followed by TOF-F (4296.56mg kg^{-1}). The TOF-F had the highest Mn content and CC had the lowest. Manure Zn content also differed significantly. The highest value was noticed in TOF-F followed by TOF. The TOF-F had significantly higher Cu content and FYM, the lowest. The fortified nonconventional manure (TOF-F) recorded the highest B content of 5.08 mg kg^{-1} B followed by TOF with 2.63 mg kg^{-1}.
- All organic manures are environmentally safe to use since heavy metal content is below detectable level. The source of materials from which the organic manures have formed might have been devoid of heavy metal.

Pot culture trial (to study the root phenomics and soil biological activity)

- A decrease in pH of the growing media at harvest from the initial stage is very well expected as decomposition of organic manures yields organic acids which will decrease the soil pH. EC increased at harvest than at the start of the crop. Decomposition and mineralization of organic matter contribute salts to increase soil EC.
- Decrease in OC was observed at harvest compared to initial. A significantly higher OC content was found in TOF-F in both initial and final stages (3.19%, 1.83%) and it was on par with TOF at harvest (1.81%). The highest organic carbon mineralisation of 1.36% in TOF-F may be attributed to the predominance of the labile carbon pool, which is the carbon fraction having the least residence time and undergoes decomposition comparatively easily.
- A decline in N content was observed in growing media due to crop uptake. N content of initial samples were on par in all PM, TOF-F and MC. Final sample showed significantly higher N content in PM.

- A decline in P content in pot trial might be due to initial immobilization or plant uptake from the isolated closed system. TOF-F was on par with PM in initial sample for P content and significantly high P content in PM alone at harvest stage might have resulted due to a higher nutrient release and crop uptake in case of TOF-F.
- The availability K content at the end of the experiment was lower than the initial in all treatments due to plant uptake. It was superior in TOF-F both before and after the crop.
- Significantly higher Ca content was observed in TOF-F initially and at harvest. PM was superior in Mg content before and after the crop. The steady release of K from the TOF-F and TOF might have resulted in slower Mg mineralisation in that treatment. S content showed significantly higher value for TOF-F in initial and for PM at harvest.
- TOF-F was superior in Mn, Zn, Cu, B and MC in Fe initially and at harvest. Heavy metals Pb and Cd were below detectable limits.
- Shoot N content of TOF-F (2.85%) and MC (2.46%) were on par with PM (2.91%). The treatment PM had the highest P content in shoot tissue. It was on par with TOF-F and TOF. TOF-F (2.56%) had the highest K content in shoot sample followed by PM (2.26%) and TOF (1.98%). Shoot nutrient content of TOF was higher than FYM and CC.
- The treatment TOF-F had the highest levels of Ca. PM (0.52%) was on par with TOF-F (1.08%) in shoot Mg concentration. The treatment TOF-F had the highest S content when compared with other treatments.
- The Fe content of shoot tissue was significantly different and MC recorded the highest value. TOF-F had the highest Mn (80 mg kg^{-1}), Zn (81.20 mg kg^{-1}), Cu (6.20 mg kg^{-1}) and B content (2.30 mg kg^{-1}) in shoot tissue.
- The highest N content in root tissue was recorded by the PM followed by TOF-F, VC and TOF. TOF-F was on par with PM in root P content. TOF-F had the highest K content in root sample followed by PM and TOF. Root nutrient content of TOF was higher than FYM and CC.

- Ca, S and micronutrient concentration in root was highest in TOF-F while Mg was highest in PM.
- Microbial load of bacteria, fungi and actinomycetes showed an increasing trend. The treatment MC had maximum bacterial number at both initial and final samples and TOF-F was found to be on par with it at harvest.
- Fungi colonies were significantly superior in MC due to innate fungal population. Fungi and bacteria were significantly higher in TOF than FYM and CC. Actinomycetes population was superior in MC and also comparable colonies were obtained in FYM and TOF-F.
- Earthworm count was observed at harvest with application of VC. Micro arthropod count increased at harvest than initial but it was non-significant. MC was significantly highest in dehydrogenase activity before and after the crop and was on par with TOF-F at harvest. Higher microbial activity in MC resulted in higher microbial biomass carbon.
- PM had the highest plant height followed by TOF-F and MC, but all the three were on par. TOF-F had the highest number of primary branches per plant (20) followed by MC (18). The maximum shoot weight was recorded by TOF-F. The PM and TOF-F were on par for shoot dry matter.
- Amaranthus had a single primary root which develops into tap root. No significant variation in the number of secondary roots could be observed.
- Highest total root length, root weight and root dry matter were observed in TOF-F. The TOF-F (10.50 mm) had highest root diameter and it was on par with TOF (7.75 mm). The maximum root volume was recorded by TOF-F. Root: shoot ratio of TOF-F was lower than VC and MC.

Field micro plot trial (to study the root phenomics and soil biological activity)

- Soil of the experimental site had strongly acidic pH, safe limits of EC, medium OC, low N, K and high P. Ca, S and B were deficient.
- The pH had a decreasing trend after all three crops. The soil EC showed an increasing trend but was in safe limits. The treatment TOF-F had the highest values for EC after C1 and C2. Lowest EC was observed in growing media

with FYM is might be due to volatilisation losses of ammonia and precipitation of salts.

- The OC content of the field plot which had a medium status of 1.16% exhibited a gradual progressive increase in the soil organic carbon status consequent to organic manure additions consecutively over three seasons except in the control treatment which largely remained without much change in the OC content. The significantly highest soil OC was recorded by TOF-F (1.28%) after C1 and it was on par with TOF (1.26%).
- The available nitrogen content of the soil progressively increased after each crop. The TOF-F was on par with PM (149.10 kg ha^{-1}, 159.52 kg ha^{-1}, 165.79 kg ha^{-1}) and TOF had higher soil available N content than conventional FYM after all seasons.
- Among different treatments TOF-F and PM recorded high available P in soil throughout all seasons since they had higher P levels. The enhanced P release dynamics of TOF-F has also influenced the formation of desirable root phenomic characters and root architecture in this treatment.
- In the field trial, there was a progressive mineralisation of K at harvest due to manure application at all seasons raising the K status from an initial low level of 93.8 kg ha^{-1} to a medium K status in all treatments except control. The treatment TOF-F marked the highest K content and TOF was on par with it after every individual crop.
- Available Ca content increased after each successive crop. After C2, TOF-F (290.80 mg kg^{-1}) had significantly higher soil available Ca content and was on par with PM after C3. In the field trial, PM recorded the highest Mg content and TOF-F was on par with it after all three crops while TOF was on par with PM after C1. The TOF-F (21.75 mg kg^{-1}) recorded significantly higher soil available S content after C3.
- After all three crops MC recorded the highest value for Fe content and TOF-F was on par with it after C2 and C3. The TOF application recorded higher Fe content than CC and FYM after all the three seasons. After C2 and C3, TOF-F recorded highest soil available Mn while TOF and MC were on par.

- The highest Zn content after all three crops was observed in TOF-F (17.02 mg kg^{-1}, 19.84mg kg^{-1}, 20.34 mg kg^{-1}). The highest Cu content after all three crops was observed in TOF-F (2.00 mg kg^{-1}, 2.45 mg kg^{-1}, 2.95 mg kg^{-1}). The TOF application recorded higher Cu content than conventional FYM after all three seasons.
- The status of B was sufficient in all the treatments except control after all the three crops. After C2 significantly higher content was found in TOF-F (1.63 mg kg^{-1}) and it was on par with MC (1.60 mg kg^{-1}).
- Plant N of TOF-F was on par with PM in C2 and C3. TOF was superior to FYM in plant N. Shoot P in TOF-F was on par with MC after C1 and C3. Shoot K was consistently highest in TOF-F (4.74%, 5.04%, 4.90%).
- The treatment TOF-F had the significantly highest levels of Ca in C1 and C2 (3.50%, 2.97%). The treatment PM was superior to all other treatments in terms of Mg content and TOF-F showed highest shoot S content. In shoot samples concentration of all micronutrients except Fe were higher in TOF-F due to higher availability.
- Higher root N concentration was observed in PM and TOF-F. TOF was superior to FYM, CC and VC in root N. TOF-F and TOF exhibited higher root P uptake than PM. The concentration of K was the highest in plants treated with both fortified and non-fortified organic fertilizer
- Ca and S concentration in root sample was highest in TOF-F. Mg was highest in PM. In root samples all micronutrient concentration was higher in TOF-F due to higher availability.
- Microbial count proliferated due to application of organic manures. Bacterial count dominated over fungi and actinomycetes.
- Initially TOF-F and TOF was low in bacterial number. Bacterial count was highest in TOF-F after C2 and C3 (7.72 log cfu g^{-1}, 7.69 log cfu g^{-1}). Bacteria in TOF was significantly higher than FYM and CC after all three crops. A high fungi population was recorded in MC in all three crops. Actinomycetes were highest in TOF-F after C1 whereas FYM recorded the highest number after C2 and C3.

- Uniform growth in earthworm population was observed in the field in case of application of different organic manures, but a steep rise in earthworm population is observed in VC. Soil micro arthropods were abundant in PM followed by TOF-F and MC.
- MC was superior in dehydrogenase activity. In field trial both TOF-F and TOF application resulted in higher dehydrogenase activity compared to other manures except MC. Higher microbial activity in MC resulted in higher microbial biomass carbon. Dehydrogenase activity and microbial biomass carbon of TOF were significantly higher than FYM and CC.
- All PM, TOF-F and MC recorded higher plant height compared to other treatments. Number of primary branches per plant was non-significant in all three crops. PM, TOF-F, MC and TOF recorded higher shoot weight compared to other treatments. Shoot dry matter also varied exactly similar to shoot weight. Plant height and shoot yield in TOF was superior to FYM, CC and VC.
- Though shoot characters of TOF-F were on par with PM, all root phenomic characters were significantly higher in TOF-F. Total root length and root weight of TOF was superior to FYM, CC and VC. The root: shoot ratio of TOF-F was lower than FYM in C1 and C3 and PM in C2.
- B:C ratio was highest for TOF-F (1.75) which was on par with PM. B:C ratio of TOF (1.62) was superior to MC, FYM, VC and CC.

Thus, it can be concluded that thermochemical organic fertilizer enhanced soil organic carbon and possessed comparable fertility value as conventional organic manures and is environmentally safe since heavy metal content is below detectable level. Fortification of thermochemical organic fertilizer facilitated efficient root phenomic characters coupled with proliferation of rhizospheric microorganisms, which favoured enhanced mineralisation of soil available nutrients and root nutrient acquisition. Thermochemical organic fertilizer is an effective and efficient substitute for conventional organic manures and its fortification with nutrients helped for realising higher productivity and profitability in amaranthus.

Future line of Work

- Tomographic studies to comprehend the micro morphological features of root architecture can be done.
- Microbiological and biochemical modes of action in the rhizosphere needs detailed investigation.
- Root phenomic characters and microbial responses with regard to other cultivated crops can be studied.

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Abstract

ROOT PHENOMICS AND SOIL BIOLOGICAL ACTIVITY IN RESPONSE TO THERMOCHEMICAL ORGANIC FERTILIZER APPLICATION

by

RAMESHA G K
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ABSTRACT

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ABSTRACT

A study entitled 'Root phenomics and soil biological activity in response to thermochemical organic fertilizer application' was conducted from October 2017 to April 2019 at the Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani with the objective of studying the root phenomics and soil biological activity in response to thermochemical organic fertilizer application as compared with conventional organic manures and its effect on growth and yield of amaranthus.

Characterization of farmyard manure (FYM), poultry manure (PM), conventional compost (CC), vermicompost (VC), microbial inoculant compost (MC), thermochemical organic fertilizer (TOF) and TOF fortified (TOF-F) with N (1.5%), P (1%), Ca (1%), Mg (0.5%), Zn (50ppm) and B (5ppm) were done. Manures had slightly acidic to neutral pH and safe limits of EC. TOF had the highest TOC. N and P of TOF-F and PM were on par. K, Ca, S, Mn, Zn, Cu and B were highest in TOF-F. Though the nutrient content of TOF was less than that of TOF-F, but statistically superior to FYM, CC and VC. Heavy metals (Pb, Cd) were below detectable limits.

A pot culture trial of Amaranthus (*var.* Arun) was done using growing media comprises of perlite: coir pith compost: organic manure for 30 days in CRD with a no manure control. The pH of the growing media decreased slightly at harvest but EC increased. OC and K were highest in TOF-F while PM had the highest N and P. Dehydrogenase activity (DA) and microbial load of TOF-F were on par with MC. While the N content in TOF-F (2.85 %) was on par with PM in the shoot, P content was on par in shoot and root. The highest root and shoot K was in TOF-F. Shoot Ca, S, Mn, Zn, Cu, B were highest in TOF-F while Mg was highest in PM and Fe in MC. Shoot and root nutrient contents of TOF were higher than FYM and CC. TOF-F was superior in shoot weight and number of primary branches whereas plant height and shoot dry matter content were on par with PM. Shoot yield was significantly higher in TOF than in FYM and CC. Total root length (34.75cm), root weight (30.31g $plant^{-1}$), root volume (11cm^3), root dry weight (3.37g $plant^{-1}$) and root diameter (10.5 mm) were highest with TOF-F. TOF had significantly higher root characters than FYM and CC. Root: shoot ratio of TOF-F was lower than VC and MC.

Field micro plot trial with amaranthus (*var.* Arun) was conducted successively for three seasons (C1, C2, C3) in RBD at the Model Organic Farm, Vellayani. Treatments were FYM (organic POP) and PM, CC, VC, MC, TOF and TOF-F on nitrogen equivalent basis. Site soil had strongly acidic pH, safe EC, medium OC, low N, K and high P. Ca, S and B were deficient. Soil pH progressively decreased whereas EC and OC increased. N, P and Mg contents of TOF-F were on par with PM whereas K, Zn, Cu and B were highest in TOF-F. Soil available nutrients except Mg were higher in TOF than FYM. Plant N of TOF-F was on par with PM in C2 and C3. TOF was superior to FYM in plant N. Shoot P in TOF-F was on par with MC after C1 and C3. Shoot K was consistently highest in TOF-F. Root P, K, Ca, S and micronutrients were highest in TOF-F. TOF was superior to FYM, CC and VC in root N. Bacterial count was highest in TOF-F after C2 and C3. Bacteria in TOF was significantly higher than FYM and CC. Actinomycetes were highest in TOF-F after C1. DA and microbial biomass carbon (MBC) of TOF-F after C2 and C3 were on par with MC. DA and MBC of TOF were significantly higher than FYM and CC. Plant height, shoot weight and shoot dry weight of TOF-F were highest after C2 whereas plant height and shoot yield in TOF was superior to FYM, CC and VC. Total root length, root volume and root diameter were highest in TOF-F. Total root length and root weight of TOF was superior to FYM, CC and VC. Root weight and root dry matter were highest in TOF-F in C1 and C3 and on par with PM after C2. The root: shoot ratio of TOF-F was lower than FYM in C1 and C3 and PM in C2. B:C ratio was highest for TOF-F (1.75) which was on par with PM. B:C ratio of TOF (1.62) was superior to MC, FYM, VC and CC.

The thermochemical organic fertilizer enhanced soil organic carbon and possessed comparable fertility value as conventional organic manures and is environmentally safe since heavy metal content is below detectable level. Fortification of thermochemical organic fertilizer facilitated efficient root phenomic characters coupled with proliferation of rhizospheric microorganisms, which favoured enhanced mineralisation of soil available nutrients and root nutrient acquisition. Thermochemical organic fertilizer is an effective and efficient substitute for conventional organic manures and its fortification with nutrients helped for realising higher productivity and profitability in amaranthus.

APPENDICES

Appendix I

Weather data from November, 2018 to April, 2019
Weekly averages of temperature, relative humidity and weekly sum rainfall

Standard weeks	Rainfall (mm)	Temperature (^0C)		Relative Humidity (%)	
		Maximum	Minimum	Maximum	Minimum
Nov 5-11	125	31.10	24.30	93.60	78.70
Nov 12-18	73	31.70	23.80	92.10	73.30
Nov 19-25	74	31.60	24.10	93.00	74.00
Nov 26-02	40	31.90	23.70	93.30	72.40
Dec 03-09	25	31.90	23.70	92.90	73.90
Dec10-16	37	32.20	23.80	94.30	73.90
Dec 17-23	3	32.00	22.90	92.40	71.90
Dec 24-31	9	31.90	23.50	92.70	71.70
Jan 01-06	0	31.97	19.60	92.00	66.60
Jan 07-14	0	31.57	20.70	92.00	68.50
Jan 15-20	0	32.20	20.85	90.86	68.14
Jan 21-27	4	32.15	21.93	92.90	66.97
Jan 28-03	0	32.79	23.47	89.55	66.25
Feb 04-10	5	31.90	24.30	92.00	66.60
Feb 11-17	0	32.20	23.80	92.00	68.50
Feb 18-24	0	32.00	24.10	90.86	68.14
Feb 25-03	0	31.90	23.70	92.90	66.97
Mar 04-10	0	32.00	23.70	89.55	66.25
Mar 11-17	0	31.90	23.80	92.00	66.60
Mar 18-24	0	31.97	22.90	92.00	65.00
Mar 25-31	0	31.90	23.50	90.86	65.00
April 01-07	0	32.20	19.60	92.90	64.00
April 08-14	59	32.00	20.70	89.55	64.00
April 15-21	64	33.00	24.30	88.00	63.00
April 22-30	5.00	33.00	24.30	89.00	64.00

Appendix II

Nutrient media composition for estimation of microbial count

1. Nutrient Agar - Bacterial Count

Peptone	-5g
Sodium chloride	- 5g
Beef extract	- 3g
Agar	-20g
Distilled water	-1000ml

2. Rose Bengal Agar – Fungal Count

Dextrose	-10g
Peptone	-5g
Potassium dihydrogen Phosphate	-1g
Magnesium sulphate	-0.5g
Agar	-20g
Distilled water	-1000ml

3. Ken knights Medium- Actinomycetes count

Glucose	- 1g
Potassium dihydrogen Phosphate	- 1g
Sodium nitrate	- 0.1g
Potassium chloride	- 0.1g
Magnesium sulphate	- 0.1g
Agar	- 20g
Distilled water	-1000ml