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REVIEW

Vermicompost acts as bio-modulator for plants under stress and non-stress conditions

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Abstract

Vermicompost is being used as a component of organic farming, making it imperative to study the role and impact of vermicompost on the growth of different plants species. The response of each plant species is unique at varied doses and application modes of vermicompost. Under normal non-stress conditions, many studies have been conducted to know the impact of various application doses and combinations with vermicompost. Compilation of studies in the foresaid arena is very tedious due to diverse experimental designs and plant species used. The main aim of this study is know the mechanisms of the impact of vermicompost on plant growth and other agronomic parameters with or without any environmental stress. An effort has also been made to demonstrate the role of vermicompost as bio-modulator on agronomics parameters under stress and non-stress conditions. The literature search was done from various databases using various keywords and appropriate studies were screened out and relevant ones were used. Studies that establish the role of vermicompost to alleviate the negative impact of stress on the plants have also been compiled. To understand the underlying mechanisms of vermicompost production, its interaction with soil and plants and after vermicompost application to plants has also been correlated. These interrelated mechanisms are otherwise scattered in the literature. The present study reveals the interaction and interplay of earthworm's gut microbes, soil microbes, and plants' growth regulators, humic acid and enzymatic actions in soil. It has been brought to light that vermicompost has the potential to positively impact most of the plant species and can be a dependable organic alternative to fertilizers.

Keywords Earthworm · Soil · Plant species · Plant growth · Stress and non-stress · Vermicompost

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1 Introduction

Intensive agricultural and animal husbandry practices across the globe is able to meet the demands of an exponentially increased population. Widespread use of chemicals and non-biodegradable materials in these practices has resulted in undesirable changes in an environment, especially in agricultural soil (Bhattacharyya et al., 2015; Hossain et al., 2021). There is an alarming requirement to use organic materials and practices in agriculture and farming. On the other hand, these agro-farming practices are generating huge quantities of organic refuse (Geethakarthi, 2021; Rout et al., 2014). These organic wastes, if not positively manipulated and disposed of on the Earth, can become a threatening source of soil, air and water contamination, thus presenting health risks for mankind. Excessive chemical usage in agriculture has also brought out the risk of damaged environment, poor economics and deteriorated human health (Nicolopoulou-Stamati et al., 2016; Toksha et al., 2021). To secure mankind from these risks, exploration to substitute the chemicals with other organic soil amendments like farmyard manure, green manure, compost or vermicompost has risen to a great extent.

Earthworm remains the key role player in vermicomposting. There exists a complex mechanism of interaction among earthworm, microbes and soil. Earthworms secrete the mucus in the surrounding medium which is a colloidal material and increases the water-holding capacity of the soil. Mucus also maintains the moisture by acting as an absorbent. Earthworms are important facilitators of nutrients flow in bio-geochemical cycles due to their fragmenting properties and adding casts to the surrounding soils (Ahmad et al., 2021). Increased soil macropores with vermicompost application have been reported in a corn field (Marinari et al., 2000). Vermicasts work as 'micro-dams' and store hygroscopic and gravitational water. An increase in water-holding capacity of soils improves productivity. The burrowing action of the earthworm also plays a significant role in altering the soil porosity and water-holding capacity of soil. During feeding, earthworms fragment the organic substrate; enhance microbial number and activity (Edwards et al., 2011); oxidize and decompose the substrate; add humification effect with their mucus to stabilize the organic matter; and pass as a rich product—vermicompost from gut (Ravindran et al., 2015). Earthworm mucus is believed to add nitrogen in vermicompost, responsible to overcome seed dormancy (Hilhorst & Karssen, 2000), thus reducing the germination time. During the ingestion and digestion in earthworm's gut, substrate is biodegraded uniquely with its gut's microbes and enzymes (Dadkhah et al., 2017). Earthworm's intestine inhabits certain microorganisms, specially bacteria, which produce polysaccharide gums which increase the entry of water into soil by constructing the cemented macro-pores (Munnoli et al., 2010). Earthworm's gut microbes and mastication process make it accelerated decomposition.

Vermicomposting is a greener agricultural practice which conserves energy by converting refuse to absorbable nutrients (Manikandan et al., 2018; Yuvaraj et al., 2021). Vermicompost is better than other fertilizers due to its more nutrient availability (Kumar & Gupta, 2018) to plants. Vermicompost proves to be a great economical enterprise and waste management (Baghel et al., 2018). The main aim of this study is the mechanisms of the positive impact of vermicompost on plant growth and other agronomic parameters with or without any environmental stress. An effort has also been made to demonstrate the role of vermicompost as bio-modulator on agronomics parameters under stress and non-stress conditions. This article is the first of its kind which explains the bio-modulatory role of vermicompost and its products on plant growth under stress and non-stress conditions. In this review article, the role of vermicompost on plant growth in terms of microbial activity, plant growth regulators, pest control mechanisms, etc. is explained under stress and non-stress conditions. The mechanism of action of humic acid and vermiwash from vermicompost is also explained.

2 Methodology and data assessing

The literature search was done from Science Direct (https://www.sciencedirect.com), PubMed Central https://www.ncbi.nlm.nih.gov/pmc/advanced/), Google Scholar (https://scholar.google.co.in) and SpringerLink (https://link.springer.com) using various keywords, viz. vermicompost, vermicomposting, role of vermicompost on plant growth, vermicomposting action mechanism, humic acid, vermicompost nutrient content, etc. and appropriate studies were screened out and relevant ones were used (Fig. 1).

3 Vermicomposting—an edge over composting

To regenerate organic nutrients from the organic refuse, composting and vermicomposting had always been well-accepted alternative procedures. In these practices, organic residues are transformed into suitable, simple and safer decomposed product. In vermicomposting, earthworms can convert organic and household wastes into high-quality manure (Amouei et al., 2017; Mashur et al., 2021). Vermicomposting dates much back than composting, but its application has started relatively later (Lazcano et al., 2008).

Technically, composting is a biological process of aerobic transformation of organic by-products into another suitable organic form that can be suitably added to the soil (Baca

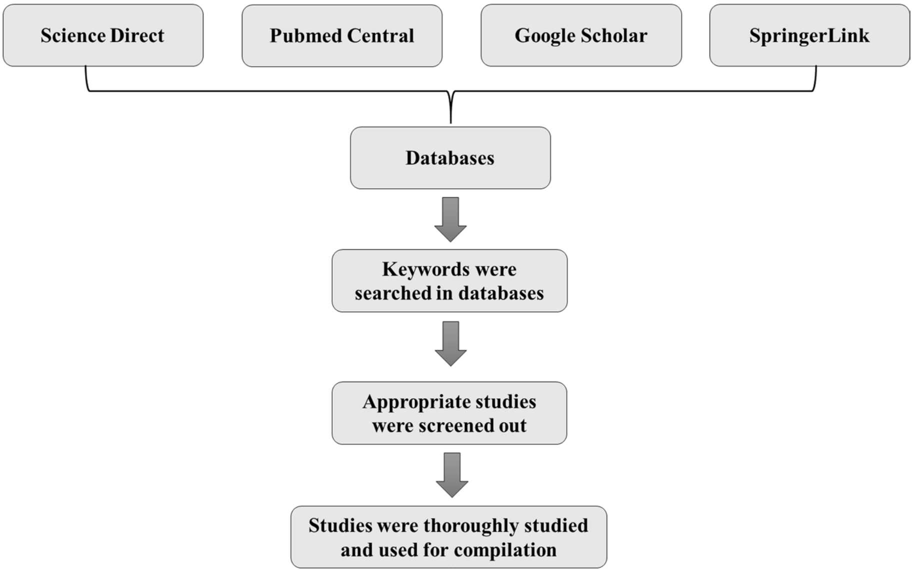

Fig. 1 Flow chart showing the methodology and data assessing of appropriate studies

et al., 1992; Chaher et al., 2021), whereas vermicomposting is a biotechnological extension of composting in which diverse species of earthworms are added to carry out the transformation of organic waste along with the natural microbial decomposition. It is a unique and complex process to get the decomposed organic end product (Edwards et al., 2011), i.e. vermicompost. During vermicomposting, a substrate is exposed to bacteria and enzymes present in earthworm gut, which provide the unique texture and property to vermicompost, making it superior to other composts. Vermicomposts can amplify the nutrient profile, being a superior organic fertilizer when compared to composts due to earthworm gut-borne microorganisms that provide biochemical alterations of nutritive elements (Soobhany, 2019; Soobhany et al., 2017). Vermicomposting is known to have an edge over composting as:

(a) It undergoes mesophilic stage with mesophilic fungi and bacteria at temperature 20–40 °C, as compared to composting process which passes through the thermophilic stage, i.e. 40–60 °C, and has a faster rate of bio-oxidation.
(b) The process of vermicomposting provides a better nutrient profile of the processed product and long-term nutrient availability (Duggan & Jones, 2016; Kumar et al., 2015). Making vermicompost is physically, nutritionally and biochemically superior (Gandhi et al., 1997).
(c) High composting and microbial activity in the presence of earthworm increases mineralization and humification (Doan et al., 2015).
(d) Vermicompost has unique bioactive molecules like humic acid, plant growth regulators and pest repellents. (Edward et al., 2011).
(e) Vermicompost has high porosity and water-holding capacity (Edward and Burrow, 1988) than the product obtained from the composting process.
(f) It has finer particle size and structure (Edward and Burrow, 1988), greater surface area for enhanced nutrient availability, better absorbability and retention of nutrients (Shiwei & Fu-zhen, 1991).

Foresaid influences have recently encouraged the researchers to be interested in the process of vermicomposting and the use of vermicompost to study its impact on soil (Aksakal et al., 2016) and plants. A lot of efforts are going on to use and stabilize diverse substrates using diverse earthworm species.

3.1 Mechanisms of vermicomposting and its action

Organic refuse from agro-farming contains a rich pool of unavailable nutrients. These nutrients can be altered by oxidation used to improve the nutrient status of the soil. Earthworms are only natural bioreactors' converting this hazardous refuse to environmentally safer forms (Angin et al., 2012) with vermicomposting. Vermicomposting, its impact on soil and plant after its application is unique, complex and delicate mechanism (Fig. 2). This technology uses earthworms for the effective recycling of waste along with the action of soil microorganisms. Many mechanisms hypothesized are still not understood as far as the impact of vermicompost is concerned. There is also a need to compile and string the various underlying mechanisms hypothesized for vermicomposting and its interaction with soil and plants. Hardly, any experimental data are available on the mechanism of action of vermicompost at a molecular level. Still, an effort has been made to organize the little

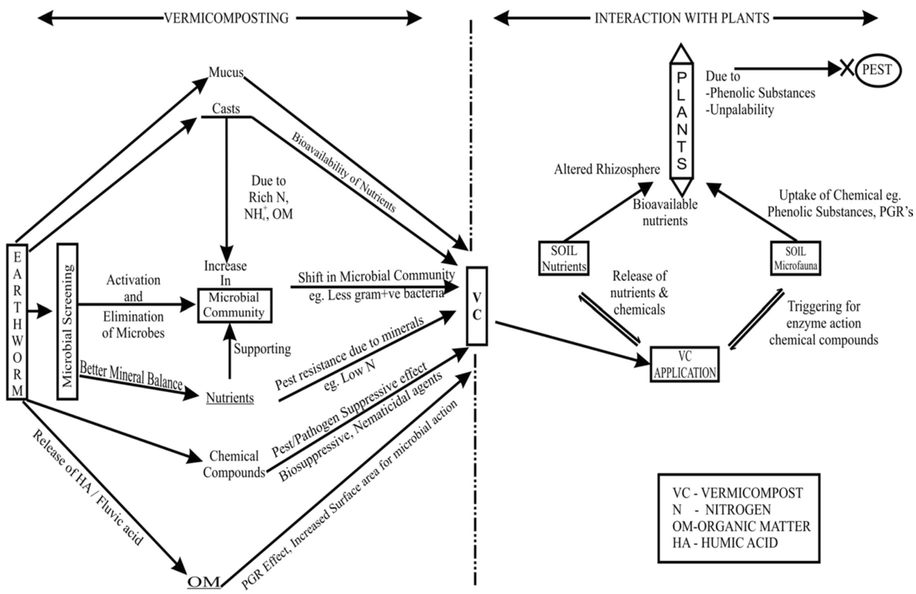

Fig. 2 Impact of vermicompost on soil and plants

available scattered data on mechanisms of interaction of vermicompost, soil and plant (Fig. 2).

The mechanism of vermicomposting and interaction of vermicompost with a plant is a multidimensional process. Though a variety of earthworm species, varied technologies and diverse substrates have been used in the preparation of vermicompost, certain core phenomena have been proposed to be operational, which are responsible for the positive effects of vermicompost on different plant species.

3.1.1 Synergistic effect of vermicompost and microbial activity on plant growth

Vermicompost has a unique and rich microbial community, that is, fungi, nitrogen fixers, actinomycetes, spore formers, bacteria, as compared to the substrate used for feeding earthworms (Zhang et al., 2002). The rhizosphere of plants supplied with vermicompost had a unique microbial community (Aira, 2007). Increased microbial biomass and enzymatic activities in vermicompost have been established in turmeric (Dinesh et al., 2010). Principal component analysis indicated the direct relationship between microbial activity and available mineralizable organic matter. Even one time application of vermicompost to *Fragaria* (strawberry) crop has increased soil microbial biomass when compared with, application of inorganic fertilizer (Arancon et al., 2006a, b). The richer microbial community has been traced in vermicompost of coconut leaf origin. The useful microbe such as bacteria and actinomycetes in vermicompost and vermiwash obtained from *Vigna mungo* leaf waste was significantly high (Esakkiammal et al., 2015). An increase in microbial population including fungi, actinomycetes and bacteria has been reported with vermicompost application. LV and Ma (2005) reported microbial increase by 108.2% with vermicompost application. In addition, to an increase in microbial number, change in the microbial community was also observed (Cai et al., 2003; Castillo et al., 2016). It is well established that vermicompost helps in aiding the microbe to function efficiently in soil (Singh et al., 2013; Rajiv et al., 2014). An increase in taxonomic and functional diversity of the bacterial community and metabolic capacity points out the role of bacterial succession in vermicomposting process and provides evidence of a microbial role in enhancing beneficial effects of vermicompost on soil and plants (Dominguez et al., 2019; Song et al., 2015). Vermicompost extract also affects the rhizosphere microbial populations. In a study by Canfora et al. (2015), vermicompost extract application on *Solanum lycopersicum* increased the microbial biodiversity specifically of Eubacteria. More operational taxonomical units of microbes were maintained till the end of the experiment (i.e. 50 days after transplanting). It also positively affected the root surface area, root dry weight and shoot dry weight. During vermicomposting, better mineral balance is achieved which also supports rich microbial community and plant growth. Vermicompost increased the magnesium levels when applied to wheat *(Triticum aestivum)* (Erdal & Ekinci, 2020).

Diverse and rich microbial community in vermicompost further plays a key role in increasing the rate of nutrient cycling in soil, production of plant growth-promoting materials, providing resistance to plants towards bacterial, fungal and nematode attacks (Arancon et al., 2003) and suppression of diseases caused by *Phytophthora, Fusarium, Plasmodiophora* in tomato (Chaoui et al., 2002). Enzyme activity and composition are improved due to microbial presence, which in turn positively affects microbial living conditions and further increase the number of microbes (Li et al., 2000). Adding microbes to vermicompost application in some studies has facilitated plant growth better than chemical fertilizers (Song et al., 2015) due to biological interactions between plant growth-promoting (PGPR) and mycorrhizal fungi which protect plants against environmental stress and improve rhizosphere.

3.1.2 Plant growth regulators: an added advantage of vermicompost

Vermicompost not only promotes nutrient cycling and contribution of critical microbial diversity but also influences the mechanisms that produce plant growth regulators materials. Earthworms and microbial diversity add plant growth hormone like molecules (e.g. fulvic acid or humic acid) to organic matter during vermicomposting (Sinha et al., 2011). The presence of plant growth regulators (PGR) in vermicompost has been suggested as one of the possible factor to contribute to increased plant growth and yield (Arancon et al., 2003; Muscolo et al., 1999).

It has been established that plant growth regulators are produced by microbes and are pre-contained in vermicompost (Frederickson et al., 2007). Nevertheless, some authors suggested that earthworms, and not microorganisms, are responsible for the production of PGRs. The production of PGRs by microorganisms or by earthworm is still debated by many researchers (Sinha & Valani, 2011). The growth of few ornamental plants showed growth patterns similar to as achieved by natural plant hormones—auxins, gibberellins and cytokinins, after adding aqueous extracts from vermicompost (Tomati et al., 1988), specially in *Begonia, Petunia* and *Coleus* supporting the fact that hormonal activity is caused by the earthworms. Earthworms secrete gibberellin, auxin and cytokinin during vermicomposting synergistically with microbes (Sinha et al., 2011). There can be a cumulative effect of direct secretions of PGRs by earthworm and microbial role for sustaining PGRs in soil (Atiyeh et al., 2002). Ravindran et al. (2015) reported high amounts of indole acetic acid, GA_3 and kinetin in vermicompost as compared to compost, which signifies the role of the earthworms and their gut microbes. The large microbial population in sewage sludge (Wen et al., 2015) which was processed by earthworms had been directly correlated with high amounts of plant hormones (Tomati et al., 1988). Organic manures are believed to have subtilin molecules which lead to the production of plant growth hormone and provide disease resistance (Perumal et al., 2006).

3.1.3 Mechanism of action of humic acid from vermicompost source

Humic acid and plant growth regulators show synergetic plant growth (Muscolo et al., 1999). Vermicompost application to plants shows hormone-induced growth responses, which is correlated with high contents of humates excreted by earthworms (Sahni et al., 2008). Humus is an integral part of plant growth as it enables plants to (a) make minerals bioavailable from organic matter, (b) absorb nutrients from the soil, (c) stimulate growth specially roots and (d) help in mechanism to overcome stress (Kangmin et al., 2010). Hussain et al. (2016) also reported the presence of alcohols, phenols and nitrogenous compounds in vermicompost made from *Ipomoea*.

The following mechanisms have been hypothesized with which humic acid affects plant growth.

- Pramanik (2010) reported that humic acid enhances the nutrient uptake by plants by increasing permeability of root cell membrane (Valdrighi et al., 1996) and stimulating root growth and increasing root hair proliferation (Tallini et al., 1991).
- Canellas et al. (2002) reported the enhanced formation of lateral roots in maize as an impact of humic acid application from vermicompost, thus promoting root elongation, and proposed that humic acid molecules adsorb the PGRs produced in vermicompost and act conjunctively with PGRs to enhance plant growth. They also reported an enhancement in proton (H^+)—ADP-ase activity in maize which was due to humic acid.
- Humates are compounds that can be depolymerized by microbes, especially by some bacteria (Sekhohola et al., 2013).
- Humates are recalcitrant carbon compounds, and Eubacteria and Archaea species can use these humates. Vermicompost extract with a high C/N ratio favours these bacteria (Dong et al., 2012).

4 Impact of vermicompost on plants under stress condition

In most of the studies, vermicompost has shown a positive effect when the plant is not facing any kind of stress. In some of the recent researches, role of vermicompost as a stress modulator has been reflected. In an experimental study on sodium salt stress in soil, vermicompost acted well as a soil conditioner and alleviated adverse effects of sodium in Na salt-stressed soils. Vermicompost treatments on varied salinity stress levels had positive effects on the physicochemical properties of soil. Vermicompost (5%) treatments while efficiently alleviating adverse effects of salinity also enhanced the soil quality. Vermicompost was proved to be efficient amelioration material for the reclamation of Na salt-effected soils (Demir, 2020). The recent studies on the role of vermicompost in promoting stress tolerance are compiled in Table 1. Vermicompost is known to alleviate the impact of other

Table 1 Various studies showing the role of vermicompost in alleviating the stress in plants

Test plants	Treatment details	Role of vermicompost under stress conditions	References
Combating Salinity stress			
Potato (*Solanum tuberosum*)	VC@300, 580, 860gm/plant; VW@5, 10, 15 ml/plant with salinity stress of 15, 20 and 25 mM of NaCl was used	VC and VW could combat the salinity stress on plant growth and tuber characteristics Greatest plant height and stem diameter were obtained with VC@580 gm/plant + VW @15 ml/plant produces greater plant height and stem diameter	Gomez et al. (2017)
Pomegranate (*Punica granatum*)	Salinity level of 0, 30, 60 mM NaCl was maintained with and without VC leachate	VC leachate improved growth parameters and physiological factors and is recommended to be used under salt stress	Bidabadi et al. (2017)
Medicago rigidula L.	VC@0, 10, 20, 30% were applied to salinity stress levels with 0, 50, 100 mM NaCl	Highest plant survival capacity was found with VC@30% and salinity@0 mM NaCl	Akhzari et al. (2015)
Sunflower (*Helianthus annus*)	In 45 pots, saline media with EC 0.5, 4.8, 8.6 dS/m was applied with or without VC. Treatments were compared with biogas slurry	VC could alleviate salt stress better than biogas slurry N-assimilating enzyme activities were enhanced with VC	Jabeen and Ahmad (2017)
Bean (*Phaseolus vulgaris*)	VC/soil was added as 75:25; 50:50; 25:75; 10:90; 0:100, with four salinity levels of 20, 40, 60, 80 mmol/L NaCl	VC application under drought stress enhanced photosynthetic rates In leaf, root tissues Ca and K concentrations were found to be high	Beykkhormizi et al. (2016)
Bean seedlings (*Phaseolus vulgaris*)	Five ratios of VC and sand (0:58; 100:59; 10:58; 90:59; 25:58; 75:59; 50:58; 50:75; and 58:25), with levels of salinity 30, 60, 90 and 120 m/Mol NaCl, with three replications	At low salinity levels, all vermicompost ratios and, at high salinity levels, high VC dose limit the negative effects of salinity	Khurmizi (2016)
Blessed thistle (*Silybum mairanum Gaertn.*)	0.5 kg vermiculite and 0.5 kg peat were used as potting media, substituted in various combinations of 5% or15% VC and 1% or 4% NaCl in different pot treatments	Decreased proline content with VC than inorganic fertilizer, under high stress VC reduced MDA content	Xu et al. (2016)

Table 1 (continued)

Test plants	Treatment details	Role of vermicompost under stress conditions	References
Peppermint *(Mentha haplocalyx Briq)*	0.5 kg vermiculite and 0.5 kg peat were used as potting media, substituted in various combinations of 5% or 15% VC and 1% or 4% NaCl in different pot treatments	Decreased proline content with VC than inorganic fertilizer, under high stress VC reduced MDA content	Xu et al. (2016)
Water deficit/draught stress			
Petunia	VC@0, 10, 20% w/w was applied; salicylic acid conc. 0, 50, 100, 200 ppm was applied with and without water stress	VC and salicylic acid improved plant pigments	Saberi et al. (2015)
Chick pea (*Cicer arietinum* L.)	VC@0, 10, 20, 30% with water stress levels of field capacity 100%, 75%, 25% was applied	VC@30% improved the Ca, K contents in leaf	Hosseinzadeh et al. (2017)
		It also improved morphological features of plant and soil biological activities	Amiri et al. (2017)
German chamomile (*Matricaria chamomilla*)	VC@0, 5 and 10 t/ha was applied to no stress, medium stress and severe stress	VC application improved nutrient content and chlorophyll content in leaf under moderate-to-severe drought stress	Salehi et al. (2016)
Vetiveria zizanioides	Irrigation@ field capacity (FC) of 30% and 60% with VC@0%, 40%, 60% and urea @0, 100, 200 mg/Kg/pot was applied	Maximum essential oil was obtained in 60% irrigation to field capacity, 60%VC and 200 mg/kg/pot urea	Akhzari and Pessarakli (2017)
Lentil (*Lens culinaris medik.*)	VC@15, 25% w/w applied under non-stressed, temperate and severe stress conditions	VC@25% w/w enhanced growth parameters, leaf Ca, K, and root Ca, at temperate and severe stress	Hosseinzadeh and Ahmadpour (2018)
Temperature and water-deficit stress			
Tomato seedlinTemperature and water-deficit stress g *(Solanum lycopersicum)*	VC leachate (1:10v/v) was used at different temperature regimes 10, 15, 20, 25, 30 and watering regimes 15, 30, 45 mL of Hoaglands nutrient solution	Physiological parameter improved under low water regime; weight of seedlings was maximum at 30℃	Chinsamy et al. (2014)

All the studies have correlated and compared with control

VC vermicompost, *VW* vermiwash, *FC* field capacity stress conditions in environment like water deficit, salinity stress, temperature stress, etc. The role of vermicompost under stress conditions has been studied in pots, fields, glasshouse, polyhouse, greenhouse, container media, etc.

4.1 Role of vermicompost during drought conditions

Recent studies reflect that with the application of vermicompost on plants under water-deficit stress, salinity stress and temperature stress, plant growth is enhanced. All the studies in this table have been correlated and compared with control. It has been established that during stress conditions plants accumulate amino acids like proline, sugar or other substances for osmotic adjustment (K'onigshofer and L'oppert, 2015). Vermicompost application is also studied to alleviate drought stress. In *Matricaria chamomilla* L. (German chamomile), vermicompost increased the nutrient uptake and leaf-soluble sugars. High sugar content in the leaf regulates the osmotic mechanisms in plants (Zhou & Yu, 2009) and reduces photo-oxidation of chlorophyll. After the application of vermicompost, proline content in chamomile plant did not increase, indicative of potential to combat drought stress (Agatonovic-Kustrin et al., 2015; Orsini et al., 2016). Vermicompost addition also increases microbial activity which forms weak acids and releases phosphate from minerals, as most phosphate in plants is defused from the soil in soluble form, and thus vermicompost shows a positive effect on plants even under stressed conditions. Vermicompost applications increase the potassium concentration in plant parts by enhancing nutrient uptake which may be responsible for better plant growth during drought resistance in *M. Chamomilla*. In drought stress, oxygen radicals, enzymes and phenols degrade chlorophyll pigments, but vermicompost application has always enhanced chlorophyll and other pigments by high end uptake (Salehi et al., 2016). Thus, vermicompost could compensate for irrigation interruptions, thus combating water stress effects (Aguilar et al., 2017).

4.2 Role of vermicompost during salinity stress

Plants treated with vermicompost become more tolerant to salinity (Table 1). Xu et al. (2016) studied that vermicompost had improved salinity tolerance in the *Cnicus benedictus* (Blessed thistle) and *Mentha piperita* (pepper mint). Under high salinity conditions, the malondialdehyde content is enhanced, but treatment with vermicompost significantly reduced malondialdehyde content, indicating their role of vermicompost in stress tolerance. The effect of reducing salinity stress has been dependent on the dosage of vermicompost (Ahmad et al., 2009). With 15% of vermicompost application, soluble proteins, ratio of potassium/sodium ions and calcium/sodium ions improved significantly. Vermicompost also reduced salt-induced crop loss (Chinsamy et al., 2013). Bidabadi et al. (2017) also studied the effect of vermicompost leachate in *Punica granatum* (pomegranate). The study elaborated that foliar spray of vermicompost leachate reduced the sodium ion accumulation in seedling, thus inducing salt tolerance. Salinity promotes chlorophyll loss and reduces photosynthesis, but the application of vermicompost extract could combat the losses as it has improved antioxidant enzyme activity and reduced oxidative stress. Vermicompost extract could alleviate the nutrient stress in tomato seedling caused due to deficiency of phosphorus and potassium. Vermicompost extract increased the leaf chlorophyll in plants under stress (Aremu et al., 2014; Chinsamy et al., 2013, 2014). Vermicompost extract reduced the chlorophyllase activity responsible for damage to chloroplast under salinity stress.

4.3 Improves plant growth, fruit qualities and yield under stress

Plants supplemented with vermicompost have shown an increase in shoot height, fresh/dry weight in *Zingiber officinale* (ginger) (Ahmad et al., 2009), *Solanum lycopersicum* (tomato) (Chinsamy et al., 2013), *Fragaria anana* (strawberry) (Keutgen & Pawelzik, 2008) and *Jatropha curcas* L. (Patel & Saraf, 2013). In green bean also, vermicompost reduced the negative effects of drought stress condition and enhanced the yield (Nouriyani, 2018). In another study by Hosseinzadeh et al. (2017), addition of 30% vermicompost to *Cicer arietinum* (chickpea) under water stress condition of moderate and severe level enhanced the morpho-physiological parameters and fruit quality (Table 1). In *Phaseolus vulgaris L.* (dry beans), application of 3% application of vermicompost increased seed number and biomass by 30%. Vermicompost leachate improved the morpho-physiological parameters in tomato seedlings as per American Society for Horticulture Science, 2014. Tomato seedlings were kept under different temperature and water conditions to create temperature and water stress. Vermicompost leachate enhanced the morpho-physiological and biochemical parameters (Chinsamy et al., 2014). Similar results have been found in maize as well; vermicompost and fertilizers have increased all of the morpho-physiological parameters of maize (Tejada et al., 2008; Tejada & Benitez, 2011), but foliar application of 6% vermi tea application revealed significant morpho-physiological growth in maize (Aslam & Ahmad, 2020).

5 Impact of vermicompost on plant under non-stress conditions

During integrated nutrient management (INM), vermicompost is added in combination with other manures, composts of different origins like cattle dung, litter, chemical fertilizers, plant growth regulators, microbes, humic acid, salicylic acid, vermiwash or other additives. Many studies indicated the enhanced performance of vermicompost with microbial additions like few bacterial strains, or arbuscular fungi or biofertilizers or biostimulants. Table 2 shows the impact of application of vermicompost alone (i.e. without any other nutrient component) on different types of plants when plants were grown under optimum conditions of water, temperature and soil (i.e. when no stress of water deficit, temperature stress or salt stress is there). Table 3 shows the impact of application of vermicompost as a component of integrated nutrient management (INM) (i.e. with additional nutrient components) on different types of plants when plants grow under optimum conditions of water, temperature and soil (i.e. no stress of water deficit, temperature stress or salt stress is there). The literature shows a great diversity in the application mode, application dose, plant species or varieties and conditions of growing the test plant because some are pilot studies, or under controlled conditions and a few are under field conditions. Comparative and conclusive study to know the effect of vermicompost on plants is a tedious task.

Response of the plant species or variety or cultivar has been specific for vermicompost due to genotypic differences (Makkar et al., 2018). Studies show the role of vermicompost, when used in combinations as INM on plants of utility as fruits, vegetables, cereal crops, leguminous plants, fodder plants, forage plants, plants of medicinal and horticultural value.

Most of the studies claim the positive conditioning of soil with vermicompost application; even if the vermicompost is one of the components of integrated nutrient management, plant growth parameters, plant nutrient uptake, plant pigment production and biomass, crop yield has been improved.

In a greenhouse study on tomato, vermicompost improved fruit yield by 74%, soluble sugars by 71% and vitamin C by 47%. Soil quality was improved with high pH and low soil electrical conductivity (Nguyen & Wang, 2017). This experiment was done in plastic pots using urea, chicken manure compost, vermicompost treatment as soil fertilizer and compared with control (Nguyen & Wang, 2017; Wang et al., 2017). Treatment with autoclaved vermicompost with plant growth-promoting rhizobacteria (PGPB) promoted overall better performance in *Gladiolus* cultivation in terms of diameter of flowers for number of leaves per plant, number of florets per spike and diameter of corm (Karagoz et al., 2019). Vermicompost increased soil carbon, nitrate, phosphate or other plant nutrients (Jindo et al., 2016). In chilli, six treatments in various combinations of inorganic fertilizer, vermicompost and phosphobacteria were applied (Densilin et al., 2011). Enhanced nutrients in chilli fruits were obtained with a combination of vermicompost and inorganic treatment. In red cabbage, *Brassica oleracea* var. *capitata* F. *rubra*, vermicompost in doses of 0, 100, 200, 400, 800 kg/da (1da = 0.1 hectare) was applied in combination with NPK 400 kg/da of vermicompost with NPK yielding the highest quality parameters (Maltas et al., 2017). Vermicompost and drum compost in combination with NPK was used in five treatments to check the growth of tomato and cabbage plants. Vermicompost in combination with NPK had high yield, pericarp thickness and shelf life (Goswami et al., 2017). In chicory, *Chicorium intybus* L, four humic acid treatments (0, 0.3, 0.6, 0.9 kg/ha) were added to vermicomposts of 0, 5, 7.5 and 10 t/ha, and highest dry aerial parts were obtained from vermicompost 10t/ha with 0.9 kg/ha humic acid (Gholami et al., 2018). Vermicompost has also affected specific increase in primary and secondary metabolites, i.e. caffeic acid, phenols, flavonoids, ellagic acid in chichory (Gholami et al., 2018). Strong effect of vermicompost was observed by Blouin et al. (2019) on plant growth with proportion of vermicompost ranging between 30 and 50% of the volume of the growing medium. Knowing the positive influence of vermicompost, it becomes essential to compile the application dose and mode studied on various plants so that finer and plant specific research can be done in near future. It will help to conserve the research effort, resource and will also alleviate uncertainty about vermicompost application, if any.

6 Vermicompost influencing plant growth by adding nutrients in soil

Vermicompost provides all macro- and micro-nutrients (Fe, Cu, Mg, N, P, K), growth hormones and regulators (auxin, gibberellin) and enzymes (protease, lipase), also supporting the solubilization of phosphorus and zinc (Rehman et al., 2020). Vermicompost increased the sustained release of nitrogen from soil and also increases the availability of phosphorus to the plants due to better decomposition of the organic matter releasing weak organic acids responsible for phosphorous solubility and availability (Herenica et al., 2007; Guo et al., 2016). Singh et al. (2012a, b) reported an immediate increase in NH^{4+}-N and NO^{3-}-N with vermicompost application. Vermicompost increased nitrogen availability in soil by increasing the number of nitrogen-fixing microorganisms in the rhizosphere (Mackay et al., 1982). Soil treated with vermicompost had greater contents of nitrogen as ammonia and nitrates;

Table 2 Application of vermicompost alone (i.e. without any other nutrient component) on different types of plants under non-stress condition

Plant studied	Treatment	Conditions	Inference	References
Effect of vermicompost on fruits/vegetables				
Strawberry (*Fragaria* sp.)	VC was mixed with soil as 10, 20, 30, 40, 50%	Pot studies in greenhouse	Enhanced growth and yield of fruit soluble sugars and vitamin C	Zuo et al. (2018)
Groundnut (*Arachis hypogea*)	Soil, vermicompost and NPK were mixed (17:35:50). *Parthenium*-mediated zinc oxide nanoparticles@200, 300, 400 ppm sprayed with 0.03% adjuvant were added at 35 and 70 DAS	Pot culture	High zinc increased the crop yield, 25 g of *Parthenium*-based vermicompost and 300 ppm zinc oxide nanoparticles increased the yield component	Rajiv and Vanathi (2018)
Lettuce (*Lactuca sativa*)	VC@0, 1%w/w; PGPR bacteria with or without inoculation; four levels of phosphate sources (0, RP powder, tricalcium phosphate, triple superphosphate @25 mg/Kg) were applied	Greenhouse studies in pot	VC increased shoot dry matter and nutrient uptake except copper. Co-application of all decreased dry shoot weight due to toxic levels of phosphate, so is not recommended	Khosravi et al. (2018)
Okra (*Abelmoschus esculentus*)	Vermicompost made from cattle dung and *E. fetida* species. Okra was grown using cattle dung, chemical fertilizers, vermiwash, vermicompost and vermiwash + vermicompost	Pot experiments	Better performance of plant using the combination of vermiwash and vermicompost	Ansari and Sukhraj (2010)
Chilli (*Capsicum annum* L. var, Serrano)	Conventional nutrient solution, VC, cow manure (solarized) and poultry manure (solarized) were applied	Greenhouse studies	Highest fresh yield and ascorbic acid were obtained with VC, competitive with nutrient solution	Castellanos et al. (2017)

Table 2 (continued)

Plant studied	Treatment	Conditions	Inference	References
Honeydew melon (*Cucumis melo*)	VC@20, 30, 40, 50% was added to spent mushroom substrate@40, 50% with cattle manure compost and coconut fibre in four different treatments@10, 20, 30% with sulphur@1gm/kg substrate	Pot studies	Growth and yield parameters were highest at 30%VC, 50% spent mushroom substrate, 20% coconut fibre and 1 gm sulphur /kg substrate	Nguyen and Wang (2017)
Basil (*Ocimum basilicum* L.)	Soil/sand of 3:1, with 0, 10, 20, 30, 40, 50% VC v/v and washed and unwashed spent mushroom compost was applied	Pot studies	VC and 50% washed spent mushroom compost increased concentration of myrsine; 1,8-cineol and sabinene in essential oil up to 116%	Esmaielpour et al. (2017)
Spinach (*Spinacia oleracea*)	VC@5, 10% v/v was added, and VC extract was separately added@40 ml to the soil	Greenhouse studies	VC enhanced the morpho-physiological growth parameters, photosynthetic efficiency and pigment, electron transport rate, leaf succulence and amino acid content	Xu and Mou (2016)
Corn (*Zea mays*)	VC@0, 5000, 10,000, 20,000 kg/ha was added to 2 kg soil in pots	Pot studies in growth chambers	Plant nutrient uptake was maximum at 10000 kg/ha.VC also improved soil nutrient properties	Erdal and Ekinci (2017)
Okra (*Abelmoschus esculentus*)	Vermicompost of crop residue, garden work and cow dung application at a rate of 5 ton/ha^{-1}	Field experiment	Increased seed germination, emergence speed index, homogeneity of seed germination, morphological parameters, Dickson quality index, when compared with the same dose of FYM and biochar	Sarma and Gogoi (2015)

Table 2 (continued)

Plant studied	Treatment	Conditions	Inference	References
Brinjal (*Solanum melongena*)	VC of macrophytes was applied@0, 2, 4, 6 t/ha	Field studies	VC@ 6t/ha increased seed germination, plant growth and fruit yield parameters	Najar et al. (2015)
Okra (*Abelmoschus esculentus*)	VC of *Salvinia* was applied as 2.5, 3.75 and 5t/ha	Field studies	Increased seed germination, plant growth and yield. Quality of fruits was enhanced	Hussain et al. (2017a)
Okra (*Abelmoschus esculentus*)	VC of *Parthenium* as 2.5,3.75 and 5t/ha	Field studies	Increased seed germination, plant growth and yield were obtained	Hussain et al. (2017b)
Cluster bean (*Cyamopsis tetragonoloba*)	Vermicompost of *Punica granatum balasta* and *Citrus sinensis*	Pot experiment	Rich growth of leaves and plant height occured	Chellachemy and Dinakaran (2015)
Tomato (*Lycopersicum esculentum*)	VC treatment to loamy sand, silt loamy, silt clay, at different rates	Pot experiment in greenhouse	With 0.5–0.6 g/g VC resulted in higher plant growth, chlorophyll, leaf and flower number, plant biomass in sandy soils	Zucco et al. (2015)
Pea (*Pisum sativum*)	Vermicompost of cow dung and oak leaves applied at the rate of 6t/ha showed the best results, compared with FYM	Field study	Improved seed germination, seedling growth, stem and root biomass, flowering, fruiting Leaf litter manure and vermicompost of cow dung and pine leaves	Bhaduria et al. (2014)
Cucumber (*Cucumis sativus*)	Seeds germinated in VC containing peat @ 0, 20, 40, 60, 80, 100%	Greenhouse studies	VC@40% enhanced the yield	Atmaca et al. (2014)
Cuminum cyminum	Treatment with Vermicompost from municipal solid waste at the rate 5, 10, 15 and 20t ha^{-1}	Controlled growing conditions	Increased vegetable growth and higher yield in plants	Mohammad (2012)

Table 2 (continued)

Plant studied	Treatment	Conditions	Inference	References
Chilli (*Capsicum annum* L)	VC@ 0, 15, 30, 45, 60% was added to perlite v/v. Steiner solution was used as control	Greenhouse studies	As VC concentration is increased, plant growth increased, and also dry weight, plant weight and fruit weight	Lopez-Gomez et al. (2012)
Tomato (*Lycopersicum esculentum*)	Five treatments were applied combining vermicompost and soil in proportions of 0:1, 1:1, 1:2, 1:3, 1:4 and 1:5 (v/v). Growth and yield parameters were measured 85 days and 100 after transplanting	Greenhouse	Addition of sheep manure vermicompost decreased soil pH, titratable acidity and increased tomato yields and soluble, insoluble solids and carbohydrate concentrations in fruits	Gutierrez micelle et al. (2007)
Tomato (*Lycopersicum esculentum*)	Treatment of three tomato varieties with vermicompost 0, 20, 40, 80, 100% (v/v)	Potting media in greenhouse	Stimulatory effect on emergence, growth, biomass allocation of tomato seedling and better fruit quality	Zaller (2007)
Peppers (*Capsicum annum*)	Vermicompost substitution 0%, 10%, 20%,40%, 60%, 80%, 100% proportion	Greenhouse	Commercial vermicompost produces 45% and 17% greater mean number of fruits at 40% substitute	Arancon et al. (2004)
Radish (*Raphanus sativus*)	VC@ 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100% v/v was mixed with sand	Pot studies	VC@10% improved seed germination	Buckerfield et al. (1999)
Effect of vermicompost on cereal crops				
Maize (*Zea mays*)	Vermicompost at a rate of 0, 4, 8, 12 t/ha	Field treatments	Higher seed yield harvest index and protein content were obtained at an application of 12 t/ha	Nasab et al. (2015)
Wheat (*Triticum aestivum*)	VC@ 0, 5, 10, 20 t/ha was mixed to soil	Field studies	Enhanced plant growth, fruit and yield parameters with vermicompost	Joshi et al. (2013)

Table 2 (continued)

Plant studied	Treatment	Conditions	Inference	References
Maize *(Zea mays)*	VC of Lantana leaves and cow dung @ 0, 20, 40, 60, 80% was mixed with soil	Pot and laboratory studies	Germination index was maximum in 80:20 of lantana and cow dung	Suthar and Sharma (2013)
Thyme (*Thymus vulgaris)*	VC@ 20, 25, 50, 75% was applied to soil	Pot studies	VC@ 25% enhanced seed germination, whereas 59%VC improved morpho-physiological parameter, leaf pigment, photosynthetic efficiency and oil yields	Amooaghaie and Golmohammadi (2017)
Effect of vermicompost on medicinal plants				
Lemon grass (*Cymbopogan flexuosus*)	VC@ 0, 2, 4, 6, 8, 10 gm per plant was applied	Field studies	VC@ 10 gm/plant maximally enhanced the plant height, herb yield and oil content	Sasikala et al. (2016)
Plantago ovata	Treatment with vermicompost from municipal solid waste at the rate 5, 10, 15 and 20t ha^{-1}	Field studies	Increased vegetable growth and higher yield in plants	Asgharipour (2012)
Stevia rebaudiana	Vermicompost applied at rate of 0.7 kg/plant and compared with compost, liquid vermicompost	Inside and outside greenhouse	Compost and vermicompost showed comparable enhancement of plant height, diameter, dry matter	Giuffre et al. (2015)
German chamomile *(Matricaria recutita L.)*	Vermicompost of cow manure applied at 0, 2, 4, 6, 8% w/w	Pot experiment	Application of 8% VC significantly enhanced shoot height, fresh and dry weight, flower number and dry weight	Niloofar et al. (2014)
Peppermint (*Mentha piperita L.)*	VC of cow manure was applied @ 7 Mg/ha, its VW, leachates VC and VW, MSW @50 Mg/ha and compared with chemical fertilizer	Field studies	VC treatment affected plant height, pigment content, essential oil yield, branching and morpho-physiological parameters	Ayyobi et al. (2014)

Table 2 (continued)

Plant studied	Treatment	Conditions	Inference	References
Huizache (*Acacia farnesiana*)	VC@ 10, 20, 30, 40, 50% v/v was applied	Studies under shelter	VC@ 10%when mixed with sand yielded maximum plant growth and weight	Moreno-Resendez et al. (2014)
Dragonhead (*Dracocephalum modavica*)	VC@ 0, 15, 30% was applied	Pot studies	VC@ 30% enhanced plant growth, seed weight and oil yield	Mafakheri et al. (2013)
Lemongrass (*Cymbopogan citrates*)	VC@ 0, 5, 10 gm/plant was added to sand and soil mixture	Pot studies	VC application@ 5 gm and leachate @ 20% increased the essential oil content. Leachate increased myrcene concentration. 2.0 g *Glomus mosseae*, 5.0 g vermicompost and 20% worm-bed leachate yielded 0.797% essential oil of which 62.6% was citral	Leon-Anzueto et al. (2011)
Effect of vermicompost on leguminous plants				
Pea (*Pisum sativum*)	VC@ 9 gm/kg soil was applied and compared to chemical treatment of NPK @ 37.5, 60, 50 kg per ha, respectively	Field studies	VC enhanced the morpho-physiological parameters in comparison with control and chemical fertilizers	Maji et al. (2017)
Chickpea (*Cicer arietinum*)	VC@ 10,20% was applied	Pot studies	Plant growth, fruit yield and photosynthetic pigments were enhanced	Yadav and Garg (2015)
Glycine max	Vermicompost applied at 0, 20, 40, 60, 80, 100%. Optimum dose was 20%	Pot studies	Enhanced seed germination parameters	Batham et al. (2014)
Phaseolus vulgaris	VC was supplemented equivalent to 0, 50, 75, 100% of recommended dose of nitrogen	Pot studies	VC enhanced the seed germination, morpho-physiological parameters, fruit yield and weight	Kadam and Pathade (2014)

Table 2 (continued)

Plant studied	Treatment	Conditions	Inference	References
Chickpea (*Cicer arietinum)*	VC@ 5, 10, 25% v/v was used for seed germination	Pot studies	10% temple waste, VC water extract showed stimulatory effect on germination percentage	Singh et al. (2013)
Effect of vermicompost on fodder plants				
Buckwheat (*Fagopyrum* sp.)	VC@ 0, 1, 1.5, 2.5 t/ha was applied to soil on two cultivars	Field studies	VC@ 2.5 t/ha yielded the highest value of plant growth, weight and grain yield	Babu et al. (2016)
Alfa alfa (*Medicago sativa)*	VC@ 0, 25, 50, 75 and 100% was added to sandy soils	Greenhouse studies	Enhancing VC dose enhanced the plant growth parameters	Alwaneen (2016)
Effect of vermicompost on oilseed plants				
Flax (*Linum usitatissimum*)	VC@ 0, 20, 40, 60, 80, 100% v/v applied to soil as well as commercial potting media (perlite + coconut coir)	Pot studies in polyhouse	VC enhanced the seed germination in two varieties. VC @40–60% improved morpho-physiological parameters	Makkar et al. (2017)
Rye (*Secale cereale*)	VC of municipal sewage sludge @ 0, 10, 20, 30, 40, 50% v/v substituted sand	Container studies in growth chamber	VC inhibited seed germination	Karlsons et al. (2016)
Effect of vermicompost on horticultural plants				
Vinca rosea (*Catharanthus roseus*)	VC@ 0, 25, 50, 75 and 100% was added to sandy soils	Greenhouse studies	Increasing VC dose enhanced the plant growth parameters	Alwaneen (2016)
Marigold (*Tagetes patula*)	Treatment of VC from cow dung and household waste with C/N ratio less than 20 was used	Pot experiment	Plant height was more up to 2.3 times with VC treatment. It enhanced the growth, plant height, biomass, buds and flowers	Gupta et al. (2014)
Ivy morning glory (*Pharbitis nil*) and Chilli (*Capsicum frutescens*)	VC@ 0, 10, 20, 30% v/v was added to soil and was compared with unamended soil	Pot experiment	VC@ 20% enhanced the plant growth, dry weight of both species	Xu et al. (2014)

Table 2 (continued)

Plant studied	Treatment	Conditions	Inference	References
Lettuce (*Lectuca sativa)*	VC@ 0, 50% v/v was applied and was compared with unamended soil	Greenhouse experiment	VC enhanced the plant growth and anatomo-physiologically more chlorenchymatous layers were observed in lettuce seedlings	Arguello et al. (2013)
Lettuce *(Lectuca sativa)*	VC@ 0, 10, 20% w/w was added to soil. Treatments were compared with unamended soil and inorganic fertilizer separately	Greenhouse experiment	VC enhanced the plant growth and biomass yield and photosynthetic efficiency was enhanced	Papathanasiou et al. (2013)
Petunia hybrid—Dreams Neon Rose	Vermicompost of animal manure was applied @ 20, 40, 60% and compared with *Sphagnum* peat media of same dose	Glasshouse experiment	Enhanced leaf growth, fresh and dry shoot weight, flower number and increased macronutrients in plant tissues at the rate of 20% application	Chamani et al. (2008)
Petunia (*Petunia hybrida)*	VC @ 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100% v/v was substituted to commercial bedding container media	Greenhouse studies	VC enhanced the germination in petunia seeds	Arancon et al. (2008)

VC vermicompost, *FYM* farmyard manure, *VW* vermiwash, @ application at the rate of, *t* tonnes; *Ha* hectares, *Mg* megagrams, *v/v* volume by volume

Table 3 Application of vermicompost as a component of integrated nutrient management (i.e. with additional nutrient components) on different types of plants under non-stress condition

Plant studied	Treatment	Conditions	Inference	References
Effect of vermicompost as a component of INM on fruits/vegetables				
Strawberry *(Fragaria ananasa,* var. Chandler)	Vermicompost application of 5 or 10 t ha^{-1} supplemented with inorganic fertilizers to balance recommended fertilizer	Field studies	Increased microbial biomass and dehydrogenase activity	Arancon et al.(2006a, b)
	Vermicompost from recycled paper supplemented with inorganic fertilizer		Plant parasitic nematodes are reduced	
Strawberry *(Fragaria ananasa,)*	VC@ 0, 10, 25% w/w was added to peat, perlite mix and sand soil. Chemical fertilizer @ 150 mg NPK/L was applied biweekly	Pot studies	VC enhanced the plant biomass in strawberry as compared to chemical fertilizers	Broz et al. (2017)
Pomegranate *(Punica granatum)*	Vermicompost at the rate of 20 kg/tree in combination with biofertilizer (80 g/ tree), FYM, green manure as *Crotolaria, Juncea* L. and 75% of N.P.K	Field experiment	Enhanced rhizosphere of soil, microbial mass in soil, increased leaf micro- and macro-nutrients were obtained. Maximum fruit set and yield was obtained	Mir et al. (2015)
Pomegranate *(Punica granatum)*	Application of FYM, VC, poultry manure, green manure and inorganic treatments was done in recommended doses	Field studies	Performance of VC was not more than poultry manure and farmyard manure for fruit yield	Marathe et al. (2017)
Cucumber (*Cucumis sativus)*	VC@ 3000 kg/ha was used to substitute 150 kg/ha of inorganic fertilizer and compared to inorganic treatment and control	Greenhouse studies	Highest fruit quality and yield were obtained when substituted with VC under continuous cropping system	Zhao et al. (2017)

Table 3 (continued)

Plant studied	Treatment	Conditions	Inference	References
Beetroot (*Beta vulgaris*)	VC@ 5 t/ha, FYM @ 25 t/ha and biofertilizers @ 2 kg/ha was applied. After every 10 days, biostimulants were used as foliar spray	Field studies	VC and biofertilizers enhanced the plant growth and yield compared to FYM	Indikumari et al. (2016)
Chilli pepper (*Capsicum annum*)	VC was applied separately and along with inorganic fertilizer (half dose), equivalent to NPK as 120:80:80	Field experiments	VC enhanced fruit yield and quality by increasing soluble sugar, protein and pigments	Das et al. (2016)
Coriander (*Coriandrum sativum*)	VC@ 100%, 66.6% and 33.3% was used, making up with inorganic treatment	Field experiments	VC in combination with urea enhanced the plant growth	Dinani et al. (2014)
Passiflora curtis	Vermicompost application up to 20% with Arbuscular Mycorrhizal fungi *Glomus albida*	Greenhouse Potting experiment	Increased production of primary and secondary metabolites as foliar biomolecules specially flavonoids	Oliveira et al. (2015)
Tomato (Solanum lycopersicum)	Vermicompost applied with rice husk, ash and coconut fibre as 1:1:1	Greenhouse studies	Enhanced seedling emergence and elongation	Truong and Wang (2015)
Radish (*Raphnus sativus*)	VC and peat were mixed in the ratio 1:1; 1:2; 1:4; and 1:8. control was peat containing inorganic fertilizer 250 gm/m.^{2}	Greenhouse studies	VC and peat @ 1:1 enhanced the plant growth and root dry weight	Alsina et al. (2013)
Swiss chard (*Beta vulgaris*)	VC:coir mix was mixed as 1:1; 1:2; 2:1 (w/w)	Container grown experiment	VC:coir mix ratio of 2:1 enhanced plant growth and productivity	Abbey et al. (2012)

Table 3 (continued)

Plant studied	Treatment	Conditions	Inference	References
Cucumber with Arbuscular Mycorrhizal (AM) colonization	Applied vermicompost of bovine manure prepared with *Eisenia foetida*. Levels were $V_0=0\%$, $V_1=10\%$, $V_2=20\%$, $V_3=30\%$ using four treatments and three replications	Greenhouse studies	Significantly increased dry matter yields of cucumber. Addition of vermicompost also increased Olsen-P and other mineral elements in soil and shoot P, Ca, Mg, Cu, Mn and Zn concentrations.	Azarmi et al. (2009)
Onion (*Allium cepa*)	VC@ 10 Mg/ha; recommended dose of inorganic fertilizer were applied separately and in combination	Field studies	Combination of VC and inorganic fertilizer enhanced the plant growth, bulb yields, plant pigments, sugars and proteins	Srivastava et al. (2012)
Red clover with arbuscular mycorrhizal (AM) colonization	Amendment of soil with 10 or 50 % vermicompost + AM fungi	Controlled growing conditions	Amendment of soil with 10 or 50 % vermicompost significantly increased dry matter yields of red clover plants. Application of high amounts of vermicompost from composted urban wastes to soils might cause a significant reduction in activity of AM	Sainz et al. (1998)
Effect of vermicompost as a component of INM on cereal crops				
Sweet corn (*Zea mays*)	VC@ 0, 10, 15, 20, 25 Mg/ha was applied, liquid fertilizer was applied @ 0, 25, 50, 75 and 100%	Field studies	VC enhanced the fruit size and weight along with morpho-physiological parameters due to better NPK uptake	Muktamar et al. (2017)
Wheat (*Triticum aestivum*)	Treatment of vermicompost of rice straw and animal waste (2:1) at levels of 5gm/kg soil was effective	Field experiment	Increased straw weight and grain yield	Ibrahim et al. (2015)

Table 3 (continued)

Plant studied	Treatment	Conditions	Inference	References
Barley (*Hordeum aestivum)*	VC@ 5, 10 gm/kg soil; VC mixed equally and double to water treatment residual was added to saline sodic soil	Pot studies	VC double than water treatment residual yielded the highest grain weight	Mahmoud and Ibrahim (2012)
Maize (*Zea mays*)	VC@ 5gm/plant was added to the commercial potting media	Pot studies	VC improved the N and P content of leaves	Baldotto et al. (2012)
Rice (*Oryza sativa*)	VC was inoculated with consortium of strains *Azotobacte*r, *Azospirillum, Pseudomonas*	Pot studies	VC enriched with *Azotobacter* maximally increased the nutrient availability and plant yield	Mahanta et al. (2012)
Maize (*Zea mays*)	VC@ 1, 3, 6, 9% were applied alone and in combination with iron fertilizers. Compost and vermicompost were also compared. Hoagland solution was used for control	Pot studies	VC@ 3% and Fe sulphate combined together performed better	Kalantari et al. (2011)
Sorghum *(Sorghum bicolor)*	Vermicompost of rice straw with microbial inoculum was applied	Glass house conditions	Application of microbial inoculants along with high concentration of vermicomposts Vermicompost does not have synergistic effect for plant growth	Hameeda et al. (2007)
Effect of vermicompost as a component of INM on medicinal plants				
Fenugreek (*Trigonella foenum-graceum*)	Various fertilizers, i.e. VC, FYM, poultry manure, neem cake, inorganic fertilizer, were applied separately and in combination equivalent to 40 kg/ha of nitrogen	Field experiments	VC in combination with inorganic fertilizers increased the growth and yield	Shivran et al. (2016)

Table 3 (continued)

Plant studied	Treatment	Conditions	Inference	References
Basil *(Ocimum sp.)*	VC and tannery sludge @ 5t/ha were added to sodic soil. Two bacterial strains were also added	Field buried cement barrels	Combination of VC, tannery sludge, microbial inoculations enhanced the growth parameters, yield and oil quality	Trivedi et al. (2017)
Sweet basil *(Ocimum basilicum)*	VC@ 5t/ha with or without bio-inoculants was added. NPK was added as 80: 60: 60 kg/ha in separate treatments	Field studies	Combination of VC and bio-inoculants improved the plant biomass and yield of essential oils	Verma et al. (2016)
American Aloe (*Agave americana*)	VC@ 0, 10 gm/plant, rock phosphate @ 0, 1gm/plant and inoculated with spores of *Penicillium* sp. (10^6/plant) and *Glomus fasciculatum* (10^9/plant)	Pot studies in greenhouse	VC enhanced the dry weight of plant. Nutrient contents in stem *A. Americana*; and mycorrhization of the roots increased	Zacarías-Toledo et al. (2016)
Areca nut (*Areca catechu)*	VC equivalent to and twice to nitrogen in recommended dose of inorganic fertilizer was added	Field studies	VC enhanced the leaf nitrogen, potassium and fruit yield	Sujatha and Bhat (2016)
Sahendi savoury (*Satureja sahendica*)	VC@ 4t/ha, inorganic fertilizer NPK-100:50:25 kg/ha was used separately in treatments and in combination with micro-nutrients and vermi tea @ 40 L/ha	Field studies	VC and vermi tea enhanced the quality of essential oil. VC improved the thymol content	Hossaini et al. (2016)
Japanese mint (*Mentha arvensis*)	VC@ 15 Mg/ha, FYM @ 30 Mg/ha and poultry manure @ 7.5 Mg/ha was added and compared with separate treatments	Field studies	Combination of VC, FYM and poultry manure enhanced the plant growth and yield attributes	Bajeli et al. (2016)

Table 3 (continued)

Plant studied	Treatment	Conditions	Inference	References
Coffee (*Coffee arabica)*	VC was applied at the rate of 1000, 1500, 2000 and 2500 kg/ha with basin weeding	Field studies	With 2500 kg/ha of VC, soil scuffing and surface basin weeding (thrice), plant height, stem girth, number of leaves and canopy were promoted	Govindappa et al. (2015)
Chicory *(Cichorium intybus* L.)	VC@ 0, 5, 7.5, 10 t/ha with four humic acid treatments@ 0, 0.3, 0.6, 0.9 kg/ha was applied	Field studies	VC@ 10t/ha with 0.9 kg/ha Humic acid yielded the highest dry aerial parts but VC @ 7.5% enhanced phytochemical properties, i.e. level of phenols and flavonoids	Gholami et al. (2018)
Patchouli (*Pogostemon cablin*)	VC@ 0, 25, 50, 75, 100% was added to recommended dose of NPK @ 100, 75, 50, 25, 0%	Nursery conditions	VC alone as well as on combination enhanced the plant growth, herb and oil yield	Singh et al. (2015)
Matricaria chamomilla	Treatment of vermicompost (cow dung) and foliage application of amino acids	Field studies	Stimulatory effect on growth, flower yield and increased essential oil (34%—49%) content with vermicompost treatment	Hadi et al. (2011)
Turmeric *(Curcuma longa)*	Short-term incorporating of vermicompost and biofertilizers	Field studies	Improved soil quantity, i.e. soil microbial mass is greater by 31% and 29% inorganic and integrated nutrient management	Dinesh et al. (2010)
Effect of vermicompost as a component of INM on leguminous plants				
Pea (*Pisum sativum*)	VC@ 9 gm/kg soil, with or without humic acid was applied	Field studies	VC with humic acid increased the mycorrhiza and root nodulation in plant	Maji et al. (2017)

Table 3 (continued)

Plant studied	Treatment	Conditions	Inference	References
Soybean (*Glycine max*)	VC@ 0, 5% of soil weight was added. Treatments with and without Arbuscular Mycorrhiza were applied. $CdCl_2$ as contaminant was applied @ 0, 20, 40, 80, 160 mg/ kg of soil	Pot studies	Combination of VC and Mycorrhiza could decrease the toxicity of cadmium chloride. It also enhanced the morpho-physiological parameters, fruit number, size, weight, seed oil and photosynthetic rate	Pireh et al. (2016)
Mustard (*Brassica campestris*)	Vermicompost of cow dung and *Eichhornia* as 3:1 applied at the rate of 2.5 t/ha and compared with NPK treatments	Field experiment	2.5% of NPK when substituted by vermicompost enhanced the crop yield, sugars and proline content	Mondal et al. (2015)
Black gram (*Vigna mungo*)	VC and earthworm's coelomic fluid were added separately and in combination	Field studies	VC as well as combination with coelomic fluid enhanced the growth of black gram	Packialakshmi and Mahalakshm (2014)
Pe *(Pisum sativum)*	Vermicompost of cow dung and oak leaves applied at the rate of 6t/ha showed best and compared with FYM, results. Leaf litter manure and vermicompost of cow dung and pine leaves	Field studies	Improved seed germination, seedling growth, stem and root biomass, flowering, fruiting	Bhaduria et al. (2014)
Phaseolus vulgaris	VC was supplemented equivalent to 0, 50, 75, 100% of recommended dose of nitrogen with combination to urea	Pot studies	VC of tendu leaves along with urea yielded maximum grain. Best suited combination was 25%N from VC and 75%N from Urea	Kadam and Pathade (2014)
Phaseolus vulgaris	VC of wastewater sludge was applied and compared with biosolid, limed biosolid and fertilizers	Greenhouse studies	VC supplemented trial showed greater dry weight of pods, plants, number of flowers, nodules, pods and leaves	Pérez et al. (2011)

Table 3 (continued)

Plant studied	Treatment	Conditions	Inference	References
Phaseolus vulgaris	VC@ 0, 1.25, 2.5, 3.75, 5t/ha along with NPK 100, 75, 50, 25, 0 was applied to the soil	Field studies	VC@ 3.75 t/ha along with NPK of 25% had maximum shoot length and shoot weight	Singh et al. (2011)
Effect of vermicompost as a component of INM on fodder plants				
Green forages	Beet vinasse co-composted with vermicompost	Field studies	Decreased soil loss upto 31.2% Increased plant cover up to 68.7%	Tejada et al. (2009)
Effect of vermicompost as a component of INM on oilseed plants				
Flax (*Linum usitatissimum)*	Foliar application of VW along with VC was applied fortnightly to plants in VC, soil mix as well as commercial potting media (perlite + coconut coir)	Pot studies in polyhouse	VW enhanced the seed germination with 50% VC in two varieties. VW strengthened morpho-physiological parameters and enhanced yield	Makkar et al. (2017)
Effect of vermicompost as a component of INM on horticultural plants				
Rose (*Rosa indica Thory, Rosa chinensis, Rosa damascene Dieck*)	VC of tea waste, twigs and food waste was separately applied to sand in ratios of 1:1, 1:2, 1:3 each v/v	Pot studies	VC increased the plant growth but source of VC had a significant effect on plant growth	Alhajhoj (2017)
Marigold (*Tagetes sp.)*	VC@ 0, 25, 50, 75, 100% was added to media containing pine bark compost. Also, chemical fertilizer was added to one treatment	Pot studies in greenhouse	VC@ 75% enhanced seed germination	Mupambwa et al. (2016)

Table 3 (continued)

Plant studied	Treatment	Conditions	Inference	References
Lilium asiatic hybrid var. Navona	Vermicompost prepared from cow dung by employing *Eisenia foetida* (0, 4, 8 and 12 t/ha) and nitrogen fixing bacteria, mixture of *Azotobacter Chroococcum and Azospirillum lipoferum* were used	Pots in natural light	Plants had increased the number of leaves, leaf dry mass, fresh stem, dry weight, stem height and diameter, root length. Observed increased contents of gibberellic acid in root tissues	Moghadam et al. (2012)
Lettuce (*lectuca sativa)*	Different grades of VC and compost were used at base growing media @ 0, 10, 20, 50, 75% v/v	Pot studies in glasshouse	Plants with high mean shoot and dry weight were obtained. VC yielded larger plants and reduced conductivity stress as compared to control	Duggan and Jones (2016)
Lettuce (*lectuca sativa)*	VC, rice husk, basalt powder and sand were applied as 50:25:15:10, 60:15:10:15 and 60:15:15:10 was applied w/w, with commercial substrate as control	Field studies	All the combinations enhanced plant growth in lettuce	Castoldi et al. (2014)
Geranium (*Pelargonium graveolens*)	VC @ 5t/ha was added to soil separately and in combination with inorganic fertilizers	Field studies	VC and inorganic fertilizer, when applied together enhanced plant height, canopy and biomass. Also the oil yield was enhanced	Verma et al. (2014)
Blue mink (*Ageratum hustonianum)*	Soil, pine, sawdust, coconut fibre and VC in the ratio 25:50:75:100; 100%VC and unamended soil were taken as control	Container studies	VC@ 100% enhanced the maximum growth	Acosta Duran et al. (2014)

Table 3 (continued)

Plant studied	Treatment	Conditions	Inference	References
Petunia (*Petunia hybrida)*	Soil, pine, sawdust, coconut fibre and VC in the ratio 25:50:75:100; 100%VC and unamended soil were taken as control	Container studies	VC@ 100% enhanced the maximum growth	Acosta Duran et al. (2014)

orthophosphates; and high dehydrogenase activity. Thus, vermicompost sustains soil fertility even after the years of agriculture (Zhang et al., 2009). Vermicompost holds the nutrients over longer periods without adversely affecting the environment (Pawlin, 2019).

There is a need to study and understand the role of vermicompost on the content and quality of specific biochemicals or nutritional ingredients or active compounds found in the plant parts useful to mankind. Few studies have been done to investigate the deeper and minute role of vermicompost at molecular level. Though there is still lot of scope to understand the role of vermicompost on nutritional quality of plants. Table 4 shows the effect of vermicompost on nutritional status or quality parameters of useful plant part, as revealed from biochemical studies.

7 Role of vermicompost to improve the nutritional quality of plants

Table 4 shows the increased sugars, starches, phenols, flavonoids, carotenoids, proteins, oils, fatty acids and vitamins in different plants with vermicompost application. Essential oil of rosemary plant was analysed and compared with or without vermicompost using GC–MS (Ganjali & Kaykhaii, 2017). With hydrodistillation, essential oil yield of 1.7% (w/w) was obtained and 32 major compounds in essential oil were analysed, five of them being phenols. Vermicompost addition enhanced the ability of phenolic production. Javanmardi and Ghorbani (2012) found the effect of chicken manure tea and vermicompost tea on phenols, flavonoids and antioxidant activity of lemon basil (*Ocimum* × *citriodorum* Vis.) in a field experiment. Highest phenol content and antioxidant activity were obtained at 1:5 dilution of vermicompost tea. Organic-based compost tea could enhance the secondary metabolites in aromatic medicinal plants. In American aloe, content of fructan, glucose and fructose increased in the stem when rock phosphate and spores of certain fungi were added along with vermicompost (Zacarías-Toledo et al., 2016). Vermicompost increased the leaf chlorophyll content in *Allium cepa* L. (Hawkins & Lewis, 1993). In most of the studies, chlorophyll content of the plant increases with vermicompost addition which leads to enhanced photosynthesis by plant and thus the stored chemicals which may be primary or secondary metabolite are also enhanced.

Aslam et al. (2020) studied that the nutrients deficiency in *Vigna radiata* (mung bean) can be treated by vermicompost, vermi- tea and chemical fertilizers. They studied the various morphological parameters of seed, root, shoot and leaves, and physiological parameters, like relative water contents (RWC), and membrane stability index (MSI) were enhanced. They also reported a significant impact of natural and chemical fertilizers on morpho-physiological characters of *Vigna radiata*, but foliar application of 4% vermi tea application showed maximum growth enhancement on *Vigna radiata*.

8 Biological pest control mechanisms with vermicompost

Vermicast or other secretions of earthworm not only alter and shift the microbial community to be more suitable for plant growth but also provide direct pest resistance, pathogen-suppressive effect and nematicidal effect. Resistance to pathogen has been directly linked to the concentration of vermicompost (Ersahin et al., 2009; Hussain & Abbasi, 2018). The proposed underlying mechanisms for the pest suppression could be the activities of useful microbes in rhizosphere or due to an increase in contents of secondary metabolites in plants (Arancon et al., 2005; Cardoza, 2011; Singh et al., 2013; Xiao et al., 2016; Yardim et al., 2006). Rich microbial community with vermicompost application enhances the enzymatic activities and release of some specific bioactive molecules like phenol or phenolic substances or PGR-like molecules which provide pest and nematode resistance. Vermicomposting of tannery waste had significant values of phytohormones (IAA, kinetin). Maximum phytohormones were recorded in plants with vermicompost applications (Ravindran, 2015). Major mechanisms that have been hypothesized for the effective pest suppression are as follows:

(a) The presence of microbial population and microbial activity in plant rhizosphere has been reported to suppress *Rhizoctonia solani* (Ersahin et al., 2009) and *Aphis gossypii* in cucumber (Razmjou et al., 2012); *Helicoverpa zea* in *Arabidopsis* (Cardoza, 2011) in corn (Cardoza & Buhler, 2012); *Botrytis cinerea* in strawberry (*Fragaria sp.*) (Singh et al., 2008); and *Fusarium oxysporum* in tomato (Szczech, 1999).
(b) Vermicompost increases the soluble phenolic uptake by plants for pest resistance (Asami et al., 2003; Koul, 2008). Feeding deterrent effect has been observed due to the presence of phenolic compounds in the vermicompost extract. Phenols are bioactive molecules produced with enzyme phenol oxidase. Accumulation of phenolic compounds in plants decreases the palatability of the plant, thus altering the pest (specially arthropods) feeding response and reduction in the number of pests (Mohamadi et al., 2017). Amooaghaie and Golmohammadi (2017) reported the presence of gallic acid and chlorogenic acid in *Thyme*, believed to suppress *Fusarium oxysporum* and *Phytophthora infestans*. The presence of antimicrobial compounds such as humic acid and certain flavonoids has been reported in *Cyamopsis tetragonoloba* to control *Xanthomonas campestris*, *Bemisia tabaci* and *Alternaria sp.* (Karthikeyan et al., 2014).
(c) Role of 'N' metabolism plays a major role in the pest control. Vermicompost and its extracts give better and slow release of nutrients, specially nitrogen. Low levels of nitrogen in plants decrease the feeding response of the pests and thus provide pest resistance.
(d) Secondary metabolites produced at higher levels also decrease the palatability of plants and reduce the pest numbers. Xiao et al. (2016) reported the gene expression for secondary defence compounds in tomato against *Meloidogyne incognita*.
(e) Addition of vermicompost leads to slow release of mineral nutrients, making the ambience non-conducive for pathogens (Yardim et al., 2006).
(f) Soils amended with organic source of nutrients have better buffering capacity and mineral balance which creates the uncongenial ambience for the pests. Singh et al. (2013) reported the same in *Pogostemon cablin* (patchouli).
(g) Pathogen-destroying microbes have been reported in vermicompost formed from *Salvinia* and *Parthenium* applied to *Abelmoschus esculentus* (ladyfinger) (Hussain et al., 2017a, b).
(h) Release of allelochemicals has been considered responsible for managing root rot disease complex in *Coleus forskohlii* against *Fusarium chlamydosporum* and *Ralstonia solanacearum* (Singh et al., 2012a, b).

Aqueous vermicompost extracts reduced the damage by pests by reducing their numbers (Edwards et al., 2009) when studied on various plants, like tomatoes and cucumbers. The rate of pest suppression has been linearly correlated with the dosage of application of vermicompost extract. Vermiwash can kill or repel pests (George et al., 2007) and thus

Table 4 Effect of vermicompost on nutritional status or quality parameters of useful plant part as revealed from biochemical studies

Authors	Plant studied	VC application to know impact on quality/nutritional status	Biochemical studied	Impact on biochemical studied
Ganapathi and Dharmatt (2018)	Banana cv. Grand Naine	VC as a component of INM @ 24.2 t/ha applied with urea @ 537.73 kg/ha, green manure-Sunhemp @ 8.88 t/ha with *Azospirillum* @ 30.86 kg/ha and PSB @ 30.86 kg/ha was most effective	Total sugars, reducing sugars, non-reducing sugars Starch in fruit	Increased to maximum Decreased
Hosseinzadeh et al. (2017)	Chick pea (*Cicer arietinum*)	VC@ 30% in growth media was most effective in biochemical synthesis even under moderate and severe stress conditions	Proline-soluble proteins	Increased by 39% Increased by 28%
Ganjali and Kaykhai (2017)	Rosemary *(Rosemarinus officinalis)*	Comparison was made to examine the with and without fertilization of VC to study the effect on quantity of essential oils with GC–MS	Phenolic compounds	Increased
Das et al. (2016)	Pigeon pea (*Cajanus cajan*)	VC improved anti-oxidants and anti-bacterial properties of leaves	Crude proteins, soluble carbohydrates, total flavonoids in leaves	Increased
Goswami et al. (2017)	Cabbage and tomato	VC and water hyacinth compost in combination improved vegetable quality		
Maie Mohsen et al. (2016)	Marjoram (*Majorana hortensis* L.)	Percentage components of essential oils were enhanced with vermicompost as compared to control	Sabiene, α-phyllandrene, limonene, linalool, terpinen-4-ol	Increased
Sasikala et al. (2016)	Lemon grass (*Cymbopogon flexuosus*)	VC@ 0, 2, 4, 6, 8, 10 gm per plant was applied and 10 gm/plant maximally increased oil content	Lemon grass essential oil	Increased
Xu and Mou (2016)	Spinach (*Spinacia oleracea)*	VC@ 5% v/v and 10% v/v increased the content, thus reducing antioxidant capacity	Carotenoids, proteins, amino acids, flavonoids	Increased Decreased
Salehi et al. (2016)	German chamomile (*Matricaria chamomilla* L.)	VC@ 10 t/ha was most effective on biochemical studied in leaves	Proline	Increased

Table 4 (continued)

Authors	Plant studied	VC application to know impact on quality/nutritional status	Biochemical studied	Impact on biochemical studied
Pandey et al. (2016)	Basil (*Ocimum basilicum* cv. CIM-Saumya)	VC and poultry manure increased the level by 3%. Also, the components of basil oil were affected	Vitamin C, methyl chavicol, linalool, chavicol, β-caryophyllene, α-cadinene, β-farnesene, γ-muurolene	Increased
Hossaini et al. (2016)	*Satureja sahendica* L	VC@ 2t/ha along with 40 L of vermi tea showed the relative superiority of essence. Plots with application of 4t/ha were most suitable for thymol content	Thymol	Increased
Bajeli et al. (2016)	Peppermint (*Mentha piperita* L.)	VC@ 5 Mg/ha along with poultry manure 2.5 Mg/ha and FYM 10 Mg/ha produced maximum of 77.5% menthol	Menthol	Increased
Xu & Mou (2016)	Spinach (*Spinacia oleracea)*	VC@ 5, 10% v/v was added, and VC extract was separately added @ 40 ml to the soil	Carotenoids, proteins, amino acids, flavonoids	Increased
Ayyobi et al. (2014)	Peppermint (*Mentha piperita* L.)	VC treated plants had highest essential oil (24.21 ml/m^2)	Menthol and menthone	Increased
Singh et al. (2014)	Basil (*Ocimum basilium*)	VC@ 5 Mg/ha enhanced oil yield by 69.9%.VC application @10 Mg/ha produced maximum biochemicals. Combining VC with inorganic fertilizer further improved qualities	Linalool, methyl chavicol	Increased

Table 4 (continued)

Authors	Plant studied	VC application to know impact on quality/nutritional status	Biochemical studied	Impact on biochemical studied
Manivannan and Selvamani (2014)	Banana cv. Poovan (syn. Mysore AAB)	VC@ 3 kg with 12.5 kg FYM,1 kg neem cake, 100 gm VAM and 50 gm phosphobacteria and azospirillum with 50% inorganics showed superior biochemicals and low acidity. 100% organics improved quality parameters	Total soluble solids, total sugars	Increased
Singh et al. (2008)	Strawberry (*Fragaria x ananassa* Duch.)	VC leachate alone and in combination with cattle dung leachate improved biochemical content	Ascorbic acid, TSS of fruits	Increased
Lujan-Hidalgo et al. (2015)	Chincuya (*Annona purpurea* Moc & sesse ex Dunal)	VC enhanced the flavanones but decreased the total phenols.VC also decreased antioxidant addition	Flavanones, total phenols	Increased
Singh et al. (2015)	Patchouli (*Pogostemon cablin*)	VC@ 75% with 25% NPK increased oil yield by 6%, whereas no effect on yield quality	Oil quality/components	No effect
Mafakheri et al. (2016)	Lemon balm (*Melissa officinalis)*	VC@ 30% v/v per pot yielded most significant essential oil components Main constituent citronellal was obtained at VC@30% vv per/pot with biophosphate and without chemical fertilizer	Citronellal, β-caryophyllene, geranial, geranyl acetate	Increased
Khan et al. (2015)	*Andrographis paniculata*	VC@ 5t/ha with *Pseudomonas monteilii* and *Bacillus megaterium* produced the highest active compound biochemicals, 3.09% and 2.96%, respectively	Andrographolide content	Increased

Table 4 (continued)

Authors	Plant studied	VC application to know impact on quality/nutritional status	Biochemical studied	Impact on biochemical studied
Oliveira et al. (2015)	*Passiflora urtis* seedlings	VC @ 0.15 and 0.2 kg/kg of soil was most suited for mycorrhizal seedlings	Flavonoids in seedlings	Increased
		In seedlings with 0.2 kg VC/kg soil and mycorrhization was most effective for foliar biochemical studied	Orientin in leaves	
Pandey et al. (2015)	Marigold *(Tagetes sp.)*	Aroma components of Tagetes oil components were ameliorated with organic and chemical fertilizers	Limonene, E-ocimenone, Z-ocimenone, Z-ocimene dihydrotagetone, Z-tagetone, thujene, pinene epoxy ocimene	Increased
Abduli et al. (2013)	Tomato (*Solanum lycopersicum)*	VC addition @ VC:soil = 4:1 was most effective for biochemicals	Vitamin C, total sugars	Increased
Omar et al. (2012)	*Cassava (Manihot esculenta)*	Total flavonoids and phenols were 39% and 38% high in vermicompost-treated plants. Medan variety showed better nutritional quality reflecting the effect of VC on genotypes	Flavonoids, phenols	Increased
Hadi et al. (2011)	*Matricaria chamomilla.* L	VC@ 20t/ha yielded the highest essential oil, i.e. up to 0.49% as compared to 0.34% in control		
Zhang et al. (2011)	Watermelon *(Citrullus lanatus)*	Increased fructose, sucrose, lycopene and soluble proteins. Increasing vermicompost reduced the quality parameters	Fructose, sucrose, lycopene, soluble proteins	Increased

Table 4 (continued)

Authors	Plant studied	VC application to know impact on quality/nutritional status	Biochemical studied	Impact on biochemical studied
Leon-Anzueto et al. (2011)	Lemon grass (*Cymbopogon citrates*)	VC and worm-bed leachate significantly improved oil yield. Maximum essential oil contents were obtained using VC@5% and 20% worm-bed leachate	Myrcene	Increased
Singh et al. (2010)	Tomato (*Solanum lycopersicum*)	VC@ 7.5t/ha in combination of 50% dose of NPK yielded better quality of tomatoes. It showed the highest total soluble solids	TSS	Increased
Wang et al. (2010)	Chinese cabbage (*Brassica rapa*)	VC significantly enhances the contents of biochemicals when VC:soil was 4:7. The same treatment increased soluble sugars 62%, soluble proteins 18%, vitamin C 200%, phenols 25%, flavonoids 17% as compared to control. Also, the contents of 16 amino acids increased	Vitamin C, phenols, flavonoids, soluble sugars, soluble proteins, amino acids	Increased
Manivannan et al. (2014)	Beans (*Phaseolus vulgaris)*	VC@ 5t/ha improved the yield to 1.6 times, protein 1.05 times and sugar 1.01 times in clay loam soil than sandy loam soil	Proteins sugars	Increased
Coria-Cayupan et al. (2009)	Lettuce (*Lactuca sativa* L.)	VC of cattle manure and agro-industrial wastes increased lettuce pigments contents	Pigments	Increased
Peyvast et al. (2008)	Spinach (*Spinacia oleracea*)	VC@ 10% when added to soil enhances the biochemicals in leaves and petioles	TSS, iron, copper, manganese, zinc in leaves N, P, K, Ca, Mg and nitrate N in petioles	Increased

can reduce disease incidence (Al-Dahmani et al., 2003; Sobha et al., 2003). Vermiwash reduced the pest population and leaf curl index in *Capsicum annum* (chilly) plants (Giraddi et al., 2003). When soil was soaked with vermiwash, it reduced hornworms (Edwards et al., 2009). Vermiwash is believed to have heat-resistant metabolites causing pest inhibitory effect. Aghamohammadi et al. (2016) used sterilized vermiwash in his study to control *Tetranychus urtical* (two spotted spider mite) on *Phaseolus vulgaris* L. (bean plant); vermiwash can reduce application dose of acaricide (azocyclotin), protecting from fungi pathogens (Szcezch, 1999, Guterez- Miceli et al., 2007). Compost tea prepared by suspending vermicompost in 1:10 in water and then aerated for 12 hours, suppressed the plant parasitic nematodes (*Rotylenchulus reniformis and Meloidogyne spp*.) in *Zucchini* plants (Wang et al., 2014). Many studies have so far established the effect of vermicompost application on pest/pathogen suppression.

9 Role of vermiwash

Vermiwash as foliar spray rapidly provides nutrients to plants than soil applications (Pathak & Ram, 2004). Tejada and Gonzalez (2008) suggested that during vermicomposting about 70% moisture is maintained in substrate which leads to compulsory production of by-product i.e vermiwash or vermicompost leachate, which otherwise had been of no use in agricultural practices. Composition of vermiwash will depend on substrate and vermicomposting conditions. According to Varghese and Prabha (2014), vermiwash plays an important role in organic agricultural systems, i.e. sustainable, eco-friendly farming, nutrient availability, pest protection, soil fertility improvement. Some other recent studies have exploited the potential of vermiwash as foliar spray for the following reasons: (a) plant protection from pathogens, (b) increasing crop yields by increasing the photosynthetic efficiency due to enhancing chlorophyll content (Akhzari et al., 2015; Ayyobi et al., 2014; Srivastava et al., 2012), (c) presence of soluble substances which are easily absorbable and do not plug the sprayers, (d) low salt content and so does not adversely affect the physiology of stomata opening and closing in leaf, (e) compensation of time lag between fertilizer application and absorption by the plants and (f) improving the micro-nutrient levels in the soil (Jaikishun et al., 2014).

10 Conclusion

The research on the effect of vermicompost on vegetables and cereals was done by various researchers and described its beneficial role to most of the plant species. Vermicompost helps improve soil structure, texture, porosity, water-holding capacity, drainage and aeration along with a reduction in its erosion. Vermicompost enhances the soil's microbial activity, adds beneficial microbes and lowers the pest and disease incidence in plant. It also contains several micro and macro-nutrients, vitamins, enzymes and hormones like auxins and gibberellins. But specific plant species and varieties respond in unique way to vermicompost in terms of morphological, physiological and biochemical parameters. Depending on the plant species, recommended application doses vary for vermicompost and vermiwash. The present study also showed the positive impact of vermicompost, when applied alone or when applied in combination with microbes, plant growth regulators or biofertilizers as a part of integrated nutrient management (INM). Farmers must be educated and made aware about the positive impact of vermicompost on soil and plants species. There is a future scope to further explore the effectiveness of vermicompost on other plants from varied geographical origin, which have not been studied so far.

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