The Role of Vermicompost and Vermiliquer in Conferring Tolerance to Biotic and Abiotic Stresses in Organic Farming System: A Critical Review

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Abstract

Biotic and abiotic stresses negatively affect plant growth. Application of vermicompost and vermiliquer ameliorates the negative effects of these stresses on plants. Vermicompost as a result of organic wastes digestion by earthworms, is very low cost process allowing biomass recycling which its increasing use could be due to their numerous beneficial effects on plant growth promotion and development. The vermicompost and vermiliquer application increase the plant growth and yield under either biotic or abiotic stresses and also increased photosynthesis, nutrient uptake, and suppress plant diseases and pests. Vermicompost and vermiliquer -mediated increase in biotic and abiotic stress tolerance of plants is associated with improvement in soil properties, increasing plant water status, reduction of Na^+ uptake, increasing uptake of minerals, and regulation of stomatal conductance and phytohormones. This review highlights both the potential of vermicompost and vermiliquer in alleviating biotic and abiotic stresses in plants and future prospect of the role of these environmentally friendly under biotic and abiotic stresses in organic farming system.

Keyword: Abiotic stress, Antioxidant system, Biotic stress, Oxidative stress, Vermicompost

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1. Introduction

Excessive use of chemical fertilizers as well as chemical pesticides in conventional agriculture has had a very negative impact on the ecosystem, resulting in soil and water pollution, which ultimately poses a very serious challenge to food security for the world's growing population. Furthermore, food production and waste management are two very important concerns due to the increase in world population. Recycling of organic residues to improve the food production cycle seems to provide some opportunity to address the above mentioned challenges. Therefore, vermicomposting as a non-thermophilic process whereby earthworms transform organic residues into compost that can be used as a substrate for plant growth is an eco-friendly sustainable management method for both agronomic production and management of biodegradable organic wastes which have been considered by researchers (Edwards and Burrows 1988; Quailk and Hakimi Ibrahim 2013; Blouin et al. 2019). Historically, the use of earthworms in the decomposition of organic wastes was first reported in Germany in 1980 and then continued in the United States (Kiyasudeen et al. 2016). Vermicompost as a result of organic wastes digestion by red earthworms *Eisenia fetida*, is very low cost process allowing biomass recycling which its increasing use could be due to their numerous beneficial effects on plant growth promotion and development (Singh et al. 2008; Hernandez et al. 2015; Shirani Bidabadi et al. 2016, Rupani et al. 2018; Zarei et al. 2018; Churilova and Midmore 2019) such as amendment of soil properties (Yang et al. 2015), mitigation of nutrient deficiency, biotic and abiotic stresses (Sarma et al. 2010; Chinsamy et al. 2013; Aremu et al. 2014; Joshi et al. 2015; Shirani et al. 2017; Benazzouk et al. 2019; Zhang et al. 2019). In vermicomposting process, the main product is the worm casts, but the leachate obtained from it, known as vermiliquer or vermicompost leachate (VCL), is an organic liquid produced from earthworm digested material and earthworm feces during the vermicomposting process. It contains proteins, vitamins, and mineral nutrients such as nitrogen, phosphorous, potassium, calcium, and magnesium as available resources which improves plant growth and yield (Chaoui et al. 2003; Sinha et al. 2009; Chinsamy et al. 2014; Gutierrez-Miceli et al. 2016; Shirani Bidabadi 2018). Therefore, in general, it can be stated that vermiliquer have great deal of potential for crop production and protection in sustainable farming systems (Simsek-Ersahin 2011).

On the basis of the collected recent evidences, this review aims to present the role of vermiliquer in inducing tolerance against biotic and abiotic stresses in crop plants. The potential mechanisms of vermiliquer -induced tolerance to biotic and abiotic stresses are also described. However, the growth, physiological and biochemical responses of plants to vermiliquer under biotic and abiotic stresses have not yet been fully studied, and the mechanisms by which vermiliquer can mitigate the negative effects of biotic and abiotic stressors should be addressed in the future.

2. Design of a vermiliquer production unit: a practical example based on the author's experiences

Fig 1 schematically shows the design of a vermiliquer production unit. In order to prepare vermiliquer, first a container with two parts (upper and lower part) is prepared (Fig 1). The upper part of the container has several layers. Several stopcocks are installed at the bottom of the upper part of the container, so that when the leachate is ready, they can be easily directed to the lower part of the container. Then a layer of rubbles having thickness of around 5 cm with pore size of 2 cm are placed. Over this layer, another layer of sand possessing thickness of 2.5 cm is placed. Then a 20-30 cm thick layer of the organic solid wastes is placed over two layers of sand and rubble. Indeed this layer called as worm-bed with pierced lid for aeration, is devoted for vermicomposting process. This layer contains the organic solid wastes fed by the epigeic species of earthworms, *Eisenia fetida* (redworm). The worm-bed is covered with a hemp mat to protect the vermicompost against sun and rain. The earthworms are then added at a rate of 25 g earthworm kg^{-1} of the organic solid wastes or 2.5 kg earthworm m^{-2} bed. Vermicompost is prepared by processing the organic solid wastes for around 2 months at 27 ± 2°C. To maintain 80% moisture content in the worm-bed a water reservoir is established with water inlet volume of every 20 drops per minute. After vermicomposting period the stopcock of the upper part of the container is open and water is sprayed for a period of 7 – 8 days. After 10 days, the vermiliquer will be produced in the upper part of the container. The lower part of the container is below the stopcocks to collect the vermiliquer (Fig 1).

3. Application of vermicompost and vermiliquer on plant responses to biotic stresses

Excessively and frequently used chemical pesticides in conventional agriculture causes "biological resistance" to pathogens and pests. Hence, much more logarithmic doses are now needed to efficiently suppress them for the growth of high-yield crops that have become more susceptible to pests and diseases which, albeit, will be accompanied by more negative biological and environmental consequences. In this regards, vermicompost is a great alternative to chemical pesticides, in addition to significantly reducing food production costs (Patriquin et al. 1995; Yasir et al. 2009; Simsek-Ersahin 2011). The results of past researches well prove that that vermicompost can prevent or even kill several fungal pathogens, parasitic nematodes and other pests (Aracon et al. 2007; Edwards et al. 2010) the results of recently conducted research on vermicomposts derived from animal manures, sewage sludge, food waste, vegetable wastes and weed wastes has also led to their new potential application as bio-control agents against pests and diseases (Aghamohammadi et al. 2016; Hussain et al. 2017; Mu et al. 2017; Hussain and Abbasi 2018; Soobhany 2018; Hussain et al. 2020). Foliar applied vermiliquer to prevent late blight disease (*Phytophthora infestans*) on tomato (Zaller 2006), foot rot disease (*Fusarium moniliforme*) of rice (Manandhar et al. 2008) have demonstrated the ability of vermiliquer to control plant diseases. The ability of vermicompost to control plant diseases has been investigated on attacks caused by fungus *Pythium* in cucumbers, *Rhizoctonia* in radishes in the greenhouse, *Verticillium* in strawberries and by *Phomposis* and *Sphaerotheca fulginae* in grapes in the field (Edwards et al. 2004). The ability of vermicompost and vermiliquer to control pests have been demonstrated by George (2006). Aghamohammadi et al. (2016) suggested the combination of leachate derived vermicompost with the acaricide as a promising way to sustainably control spotted spider mite on the bean plant. The positive effects of vermicompost to inhibit Fusarium wilt of strawberry has been reported by Bi et al. (2018), although ability of vermicompost to control the disease also may depend on the earthworm species used, their ecological group, production process, and age of vermicompost (Datta et al. 2016; Singh 2018). Hussain et al. (2016) reported that the presence of some compound such as alcohols, alkanes, alkenes and nitrogenous compounds resulted in a better growth and yield of okra while suppressed the incidence of some plant diseases. Powdery mildew is the most common fungal disease caused by *Podosphaera pannosa* which negatively affects worldwide crops production (Linde and Shishkoff 2017). Interestingly, Kumar and Chandel (2018) have reported the positive effect of vermicompost derivate application on rose powdery mildew under greenhouse conditions. According to Yasir et al. (2009) reports, *actinobacteria* and chitinolytic bacteria being the dominant bacterial communities in the vermicompost were responsible for reducing the sporangium germination of *Fusarium moniliforme*. In a successful report on pest control, the highest rate of egg hatching inhibition was observed with vermiliquer treatment (Rostami et al. 2014). The use of vermicompost and its derivatives has been reported to be of great scientific interest for pest and disease control. However, more new and practical examples of the use of this environmentally friendly compound have led to more beneficial applications in organic farming systems. Tables 1 and 2 show some literature reports based practical examples of the use of vermicompost and vermiliquer in plant pests and diseases suppression, respectively.

3.1. Mechanisms of plant diseases and pests suppression by vermicompost and vermiliquer

The most important mechanisms that have been reported so far by which vermicompost and **vermiliquer** controls plant pests and diseases are schematically described in Fig 2. The ability of vermicompost and vermiliquer to suppress plant pathogen could be attributed to its antagonistic effects (Simsek-Ersahin 2015). Vermiliquer as a bioremediation unit supplies a pitfall that degrade pathogens while, a high organic matter content in vermiliquer has a high ability to bind and inactivate pathogens (Romero et al. 2010; Fernandez-Bayo et al. 2015). Detoxification capacity of vermiliquer could be attributed to the presence of some extracellular enzymes belonging to oxidoreductase and hydrolase groups, or humic acid and fulvic acid through which can degrade a wide range of pathogens. A very interesting point that has been discovered about vermiliquer is also the presence of carboxyl esterase activity, in which allows to remove organophosphorus pesticides from soil, demonstrating that earthworms play an impressive role in this bioremediation system (Rao et al. 2014 Sanchez-Hernandez et al. 2014, 2015). Different types of microorganisms live in the body of the earthworm, which are also secreted in vermicompost and vermiliquer. Therefore, another possible mechanism in suppressing plant diseases can be attributed to the competition between these antagonistic microorganisms and deleterious pathogens, which in turn significantly limits the growth and development of the pathogen (Sharma et al. 2009; Mu et al. 2017). Accordingly, today the technique of separating antagonistic microorganisms from vermicompost and vermiliquer to control plant diseases and pests has become widespread and practical. Gopalakrishnan et al. (2011), reported that various strains of actinomycetes separated from vermicompost could suppress *Fusarium oxysporum* f. sp. *Cicero* which causes *Fusarium* wilt. The broad –spectrum antagonistic bacterial strains such as *Bacillus* have also been reported to be distributed in the vermicompost with a significant inhibitory effects on some phytopathogenic fungi (Arrebola et al. 2010; Pathma and Sakthivel 2013; Zhao et al. 2014; Mu et al. 2017). Herein, more antagonistic strains is suggested to be identified and isolated to discover clearer mechanisms of biocontrol mediated by vermicompost and vermiliquer in the future. Another mechanism by which vermicompost and vermiliquer are able to suppress plant pathogens incidence, is because a series of antibiotic substances such as lipopeptide antibiotics and volatile compounds, released by the microorganisms in them, while not harmful to plants, are able to inhibit or even kill the pathogens directly (Gopalakrishnan et al. 2011; Sreevidya et al. 2015; Mu et al. 2017). Taking advantage of progresses in this technique, many volatile compounds emitted by bacteria and fungi have been recently recognized which can diffuse through the atmosphere and soils efficiently, resulted in strong inhibitory activity against plant pathogens, which make them quite suitable for biological control (Fernando et al. 2005; Effmert et al. 2012; Morath et al. 2012). For example, Strobel et al. (2011) asserted that some volatile compounds (trans-caryophyllene, some sesquiterpenoids, a number of alcohols and several naphthalene derivatives) shed from a type of fungi (*Poma* sp.) could suppress some plant pathogens. *Paenibacillus polymyxa* has also been reported to generate 1-octen-3-ol, benzothiazole, and citronellol which not only suppresses mycelial growth, but also weakens germination and induces mycelial morphological abnormalities of tested fungal pathogens (Zhao et al. 2011). Another report (Sang and Kim 2012) have demonstrated that 2, 4-di-tert-butylphenol produced by *Flavobacterium johnsoniae* could suppress growth of *Phytophthora capsici*. Yuan et al. (2012) also reported that a mixture of volatile alcohol, aldehyde, ester, ether, and naphthyl released by *Bacillus amyloliquefaciens* completely suppressed the development of *Fusarium oxysporum* f. sp. *Cubense*. Mu et al. (2017) have recently found some new other compounds generated from bacteria in vermicompost, such as 3-methyl-3-hexanol, 1-heptylene-4-alcohol and 1-propoxy-2-propanol that have suppressive properties for the deleterious pathogens. However, researches conducted so far on antifungal properties of volatile compounds of vermicompost and vermiliquer are inadequate and this issue must be more clearly addressed in the future to find efficient, practical and cost-effective protocols in agriculture using microbial isolates and their respective volatile compounds from vermicompost and vermilique to efficiently control plant disease in greenhouse and field trials.

Another mechanism involved is that some of the microbes in vermicompost and vermiliquer with predatory characteristic to pest or even may act as a parasite by puncturing cell wall and consuming the plant pathogens (Simsek-Ersahin 2011; van Bruggen and Finckh 2016; Rao et al. 2017). Vermicompost enhances soil biodiversity by promoting the beneficial microbes which in turn enhances plant growth directly by production of plant growth-regulating hormones and enzymes and indirectly by controlling plant pathogens, nematodes and other pests, thereby enhancing plant health and minimizing the yield loss (Pathma and Sakthival 2012). Induction of systemic resistance in vermicompost and vermiliquer -treated plants is another hypothesized mechanism that shows a suppressive effect on plant pathogens in vermicompost and vermiliquer (Pharand et al. 2002; Yogev et al. 2006). Vermicompost and vermiliquer improve plant nutrition status, which further strengthens the plant and increase the plant's resistance to pests and diseases (Hussain et al 2020). All these hypothetical mechanisms indicate that the microbial antagonists inhabiting in vermicompost and vermiliquer offer many promising biological control potentials for future sustainable agriculture although it should be noted that different earthworms have different capacities to inactivate pathogens, so the degree of inhibition and control of pathogen depends on the earthworm species used to produce vermicompost (Soobhany et al. 2017). However, our knowledge about those antagonistic microbes as well as our understanding of the mechanism of action of vermicompost and vermiliquer in suppressing the plant diseases and pests is still unclear and will need to be addressed in the future.

4. Application of vermicompost and vermiliquer on plant responses to abiotic stresses

Abiotic stresses such as drought, salinity, temperature, heavy metals and nutritional imbalance negatively affect plant growth, development, and quality of production, because of the adverse effects they have on the rate of nutrient mobilization in soils resulting in poor crop performance Under such environmental conditions, final crop yield can be really jeopardized if stress occurs in plants' most sensitive phonological phases (Khaled and Fawy 2011; Chinsamy et al. 2014; Amiri et al. 2017; Bulgari et al. 2019). Furthermore, using genetic improvements to increase of crop stress tolerance requires long breeding programmes and different cultivation environments for crop performance validation (Bulgari et al. 2019). Therefore, agronomic management conducted in order to enhance plant tolerance towards abiotic stresses evolved over the centuries due to the technologic progress, climate change, scientific knowledge, and farmers' experiences. The choice of the correct cultivar, the best growing period, the sowing density, and the amount of water or fertilizers are some of the most common strategies applied to mitigate the negative effects of abiotic stresses (Mariani and Ferrante 2017). Vermicompost and vermiliquer as biostimulants have been recently considered as an effective agronomic implement in plant growth and development and in mitigating harmful effects of various environmental stresses on plants due to its porous structure, high water storage capacity, having hormone-like substances, plant growth regulators, and high levels of macro and micro nutrients (Hosseinzadeh et al. 2018). Vermicompost and vermiliquer have humic substances (Fig 3), which is produced by earthworm and is believed that the hormone-like activities of humic substances have an important role in enhancing the yield and growth of plants especially grown under abiotic stressed conditions (Bowden et al. 2010; Hosseinzadeh et al. 2018). A few studies are available on the interaction of vermicompost derivate and abiotic stresses such as salinity, temperature, drought and heavy metals toxicity in the world (Chinsamy et al. 2014; Hosseinzadeh et al. 2016; Perez-Gomez et al. 2017; Shirani Bidabadi et al. 2017; Benazzouk et al. 2018; Hosseinzadeh et al. 2018; Benazzouk et al. 2019; Bulgari et al. 2019; Perez-Gomez et al. 2019). Shirani Bidabadi et al. (2017) reported that vermiliquer mitigated the negative effects of salt stress in pomegranate, by limiting the congestion of Na^+ and boosting the activities of antioxidant enzymes by which the efficiency of plant increases. Vermiliquer has also been reported to relieve the negative effects caused by shortage of P and K during the growth tomato seedlings under nutrient stress (Arthur et al. 2012). The use of vermicompost and vermiliquer in detoxification of heavy metals could be also the newest application of these adsorbents (de Godoi Pereira et al. 2014).

4.1. Mechanisms of abiotic stress alleviation mediated by vermicompost and vermiliquer

As shown in Fig 3, the presence of humates, humic substances and fulvic acid in vermicompost and vermiliquer reduce the oxidative stress and electrolyte leakage, improve chlorophyll and photosynthetic efficiency, activate the physiology and antioxidant defense system and accelerate the absorption of nutrients in stressed plants, thereby alleviate the abiotic stresses (Reyes-Perez et al. 2014; Shirani Bidabadi et al. 2017). Prevention of chlorophyll depletion and decreased photosynthetic efficiency due to abiotic stresses following the application of vermiliquer to plants under salinity, temperature, water, and nutrient stresses have been previously reported (Chinsamy et al. 2013; Aremu et al. 2014; Chinsamy et al. 2014, Shirani Bidabadi et al. 2017). Vermicompost and vermiliquer may have an important role in alleviating the abiotic stresses-induced damage to the chloroplasts by reducing chlorophyllase activity (Chinsamy et al. 2013). Canellas et al. (2002) reported that humic substances in vermicompost increased root elongation, lateral root emergence and the activity of H^+-ATPase in maize plants. The humates and humic substances existed in the vermicompost and vermiliquer activate the physiology, absorption of nutrients and mitigate the stress (Reyes-Perez et al. 2014). Oliver et al. (2007) attributed the induction of salt stress resistance in tomato plants to humic presence in vermicompost. One of the possible mechanisms of induction of stress resistance by vermicompost and vermiliquer might be attributed to an increased sucrose content in plants due to increased activity of sucrose phosphate synthase (Chinsamy et al. 2013; Perez-Gomez et al. 2017). Detoxification of toxic Na^+ ions, limitation of Na^+ translocation from the root to the shoot, improvement of osmotic adjustment mainly through proline synthesis and keeping the rate of net photosynthesis high in salt effected plants by vermiliquer is a recently discovered mechanism by which the tolerance of vermiliquer -treated plants against salinity stress is increased (Benazzouk et al. 2018). Studies on the effect of vermiliquer on the reduction of Na^+ in the leaves and its increase in the roots can be hypothesized that vermiliquer may reduce the negative effect of salinity on the plant by controlling the retrieval of Na^+ from the xylem which as an important component of salinity tolerance in plants (Zhu et al. 2017). Abscisic acid (ABA) stimulates H^+ discharge into xylem and leading to an enhanced rate of Na^+/H^+ in salt effected plants (Plett and Moller 2010). Another task of ABA is to induce the ABSCISIC ACID INSENSITIVE (ABI) 4 gene coding for a transcription factor which down-regulate HKT1; 1 gene expression and increase Na^+ xylem content (Shkolnik-Inbar et al. 2013). Recent research has shown that vermiliquer reduces the amount of ABA and instead increases its catabolic products including dihydrophaseic and phasic acid, which in turn increases the amount of soluble sugars accumulation in roots of salt-affected plants and ultimately induces plant resistance to salinity (Benazzouk et al. 2018; Zheng et al. 2019). Anthocyanin have an important roles in salt-stressed plants, not only as antioxidants but also as modulators of nitrogen metabolism (Truong et al. 2018). Benazzouk et al. (2019) have reported that vermiliquer enhances anthocyanin in salt effected plants thereby increase their resistance to stressed conditions. Proline accumulation and decreased MDA accumulation have been reported by various researchers (Shirani Bidabadi et al. 2017; Benazzouk et al. 2019) in the leaves of vermiliquer -treated plants. The review of these recent researches well prove that vermiliquer -induced proline accumulation may render protection against NaCl-induced oxidative stress. Abiotic stress conditions such as drought, heavy metal, salinity, high/low temperature, and ultraviolet radiations, result in accumulation of various phenolic compounds which, among other roles, have the potential to scavenge harmful reactive oxygen species in stressed plants (Sharma et al. 2019). These phenolic compounds such as protocatechic, *p*-hydroxybenzoic, *p*-coumaric and ferulic acid has been also reported to be increased in VCL treated plants (Aremu et al. 2015). The results of the recently conducted research by Benazzouk et al. (2019) also showed that vermiliquer delays senescence in young leaves by alleviating salt-induced decrease in stomatal conductance, reducing ethylene synthesis, as well as increase in proline and anthocyanin contents. They suggested that vermiliquer - induced proline accumulation might acquire protection against NaCl-induced oxidative stress in plants. Vermiliquer does not increase abscisic acid content in salt-stressed plants and does not lead to ACC accumulation while it increases jasmonate accumulation and modifies the pattern of cytokinin profile with an increase in dihydrozeatin-types in old leaves and N^6-(Δ^2-isopentenyl) adenine-types in young ones leading to mitigate negative effects of salt stress (Benazzouk et al. 2018). Although, auxin-like and CK-like activity of humic acid has been reported previously by Trevisan et al. (2010) and Pizzeghello et al. (2013), respectively, the involvement of phytohormones on the recorded improvement by vermiliquer still remains an open question. Vermiliquer contains various nutrients

(N, P, K^+, Ca^{2+}, Mg^{2+}), humic acids and antioxidant compounds which may contribute to salt resistance of plants (Benazzouk et al. 2018; Benazzouk et al. 2019). Aremu et al. (2015) detected major phenolic compounds such as protocatechic, p-hydroxybenzoic, p-coumaric and ferulic acid in vermiliquer. These phenolic compounds are also involved in the management of oxidative stress. Anthocyanins not only as antioxidants but also as modulators of nitrogen metabolism have been detected in vermiliquer which play an important role in abiotic stressed plants (Benazzouk et al. 2019; Truong et al. 2018). Vermicompost increases photosynthetic pigments under conditions of environmental stress and thus prevents the decline in yield due to stress (Shirani Bidabadi et al. 2017; Hosseinzadeh et al. 2018). It appears that vermiliquer retains water availability and nutrients in abiotic stressed plants, which are involved in regulation of osmotic pressure (Hosseinzadeh et al. 2016). Vermicompost increases the amount of water entering roots due to its good water-holding capacity (Atik 2013). Chinsamy et al. (2014) attributed the increase in plant resistance to drought and temperature stress to the positive effect that vermiliquer has on improving stem thickness, leaf area and shoot to root biomass production. One of the possible mechanisms in reducing the stress of heavy metals in plants by vermicompost and vermiliquer might be the formation of metal-humic substance complexes (Fig 4) which could mitigate the toxicity of heavy metals to plant (Singh and Kalamdhad 2012; de Godoi Pereira et al. 2014). Vermicompost has a high surface area and vast porous and high fragments of humic acid (Fig 4), through which it is remarkably able to trap heavy metals or inactivate them by forming metal-humic substance complexes, thereby reducing heavy metal stress (de Godoi Pereira et al. 2014). The inhibitory effect of nutrient stress on phytochemical attributes of plant crops is well documented (Gremigni et al. 2003; Juszczuk et al. 2004). Humic substances in vermicompost and vermiliquer appears to be responsible for the proliferation of root mass of plants (Bhalerao et al. 2002; Ervin et al. 2008). Hence, the increased lateral roots in vermicompost and vermiliquer treated plants might be ascribed to the presence of auxin in the humic substances, which has an important role in lateral root development. This increase in roots makes the plant better able to withstand the stress conditions of nutrients in the soil (Alvarez and Grigera 2005). However, many studies are needed to elucidate the role of vermicompost and vermiliquer as well as to discover the mechanisms by which they alleviate nutrient stress in plants. Most of the vermicompost and vermiliquer-existed compounds responsible for induction of tolerance against abiotic stresses are unknown and their characterization in term of composition is almost impossible. Therefore, the need for more research to gain better insight on bioactive molecules in vermicompost and vermiliquer on the basis of their role in plants must be frequently emphasized in the future to more clearly understand the underlying mechanisms by which tolerance is induced against abiotic stressed plants.

Conclusions and Future Prospects

This review reports the progress on the recent development of the vermicompost and vermiliquer-existed compounds with special emphasis on their effects, improving tolerance to abiotic stresses in plant crops. During their life cycle, crops are often exposed to biotic and abiotic stresses, which could dramatically reduce the yield and quality of products. The vermicompost and vermiliquer could represent an effective and sustainable tool to enhance plant growth and productiveness, improving tolerance against biotic and abiotic stresses. In fact, vermicompost and vermiliquer have been successfully applied for improving nutrients and water use efficiency of crops, enhancing tolerance against salinity, water stress, cold, high temperature, etc., increasing yield and quality of agricultural crops. In any case, it could not be ignored that the complex and variable nature of raw materials used for vermicomposting and the heterogeneous mixture of components of the final product may cause it difficult to attribute a specific mode of action to each vermicompost. Furthermore, the vermicompost and vermiliquer activity of a product may also depend on the nature and severity of the biotic or abiotic stress. Anyway, our understanding of the mode of action also depends on the amount of information provided by scientific papers, on the numbers of analyses performed, and on their investigation level. The availability of innovative research tools will surely improve the knowledge of vermicompost and vermiliquer composition, but this information will not be exhaustive. Therefore, the vermicompost and vermiliquer mode of action can be understood through plant responses at the physiological, biochemical, and molecular levels.

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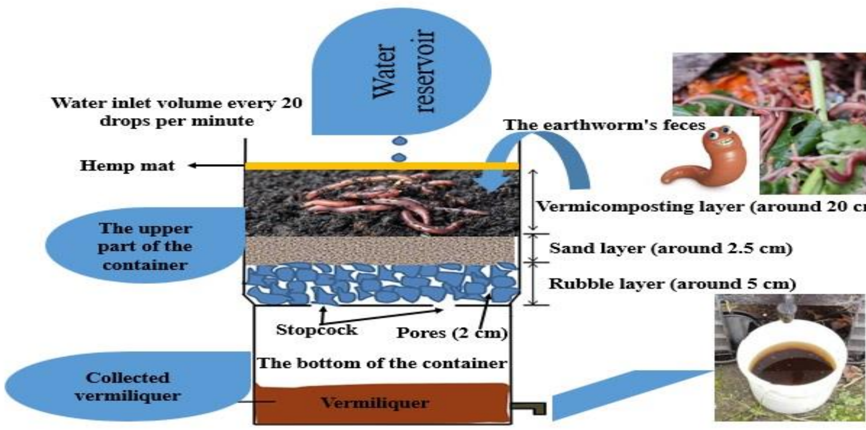

Fig 1. Schematic diagrams showing organization of a vermiliquer collection unit.

Table 1. Some successful examples of the use of vermicompost and vermiliquer to control plant diseases

Source	Pathogen	Plant	Disease control	Reference
Vermiliquer	*Xanthomonas campestris* *Alternaria solani*	Tomato	Bacterial leaf spot Early leaf blight	Pattnaik et al. (2015)
	Fusarium solani *F. oxysporum*	Eggplant	Fusarium wilt	
	Rhizoctonia solani	Mustard	Damping off root	
	F. oxysporum	Eggplant	Fusarium wilt	
	Pectobacterium carotovorum	Carrot	Soft rot disease	Rao et al. 2017
	Sarocladium oryzae	Rice	Sheath rot disease	Jayakumar and Natarajan (2013)
	F. oxysporum	Banana	Fusarium wilt	
	Pestalotia theae	Tea	Leaf spot disease	
	Curvularia lunata	maize		
	Colletotrichum gloeosporioides	Mango	Anthracnose disease	
	Bipolaris oryzae	Groundnut	Charcoal rot	
	Rhizoctonia bataticola	chickpea	Dry root rot	Gopalakrishnan et al. (2011)

	Macrophomina phaseolina	Sorghum	Charcoal root rot	
	Fusarium moniliforme	Rice	Foot rot disease	Manandhar and Yami (2008)
	F. oxysporum *F. capsici* *R. solani* *Phytophthora capsici* *Phytophtora. ultimum* *Plectosporium tabacinum* *Scleretonia rolfsii*	Tomato Cucumber	Root rot disease Foliar phytopathogens	Edwards ET AL. (2011)
	R. solani	Cucumber	Damping –off disease	Simsek-Ersahin et al. (2009)
	X. campestris	Tomato	Bacterial spot siaeas	Reddy et al. (2012)
Vermicompost	*Fusarium chlamydosporum* *Ralstonia solanaceaeum* *Meloidogyne incognita*	*Coleus forskohlii*	Root rot disease	Singh et al. (2018)
	Liriomyza spp. *Alternaria altemate*	Okra	Leaf miner damage Leaf spot disease	Hussain et al. (2020)

Table 2. Some successful examples of the use of vermicompost and vermiliquer to control pests

Source	Pathogen	Plant	**Pest** control	Reference
Vermiliquer	*Meloidogyne incognita*	Tomato	Root knot nematode	Rao et al. (2015)
	Globodera rostochiensis *G. palida*	Potato	Potato – cyst nematodes	Renco and Kovacik (2015)
	Acalymma vittatum *Manduca sexta*	Cucumber Tomato	Cucumber beetle hornworm populations	Edwards et al. (2009)
	Meloidogyne javanica	Cucumber	Root-knot nematode	Rostami et al. (2014)
	Meloidogyne hapla *Myzus persicae* (aphids) *Tetranychus sp.* (spider mites)	Tomato	Root-knot nematode Arthropod pests	Edwards et al. (2007)
Vermicompost	*Acalymma vittatum* (striped cucumber beetle) *Diabrotica undecimpunctata* hovardii (spotted cucumber beetle) *Manduca quinquemaculata*	Cucumber Tomato	Cucumber beetle Hornworm populations	Yardim et al. (2006)
	Myzus persicae Sulz (Aphids), *Pseudococcus* sp. (mealy bugs) *Pieris brassicae L.* (cabbage white Caterpillars)	Pepper Tomato Cabbage	Insect pest populations and plants damage	Arancon et al. (2005)
	Tetranychus urticae (spotted spider mite) *Pseudococcus* sp. (mealy bug) *M. persicae* (Aphid)	Bush bean Eggplant Cucumber Tomato Cabbage	Insect pest populations	Arancon et al. (2205)
	Pratylenchus sp.	Tomato	Soil nematode	Nath and Singh (2011)
	Earias vittella (fruit borer)	Okra	Fruit borer	Hussain et al. (2020)

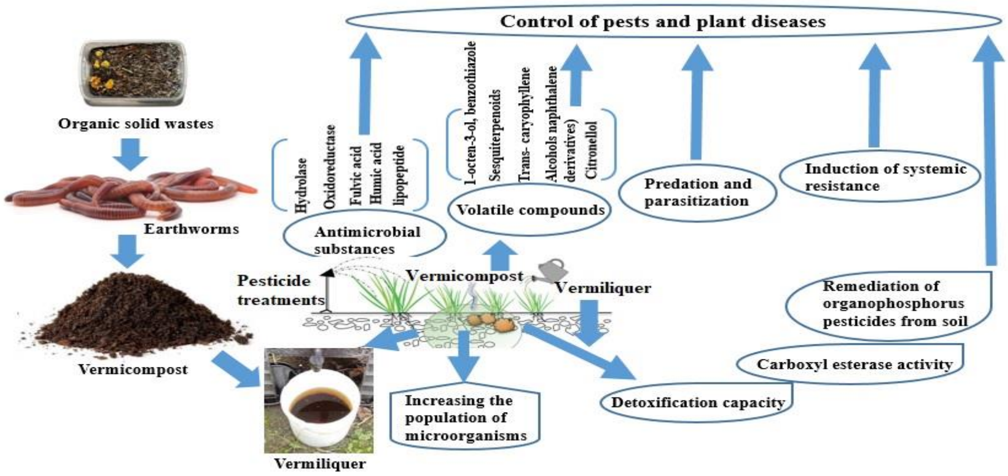

Fig 2. The beneficial of vermicompost and vermiliquer in the control of pests and plant diseases, as well as the remediation of chemical toxin residues along with possible mechanisms.

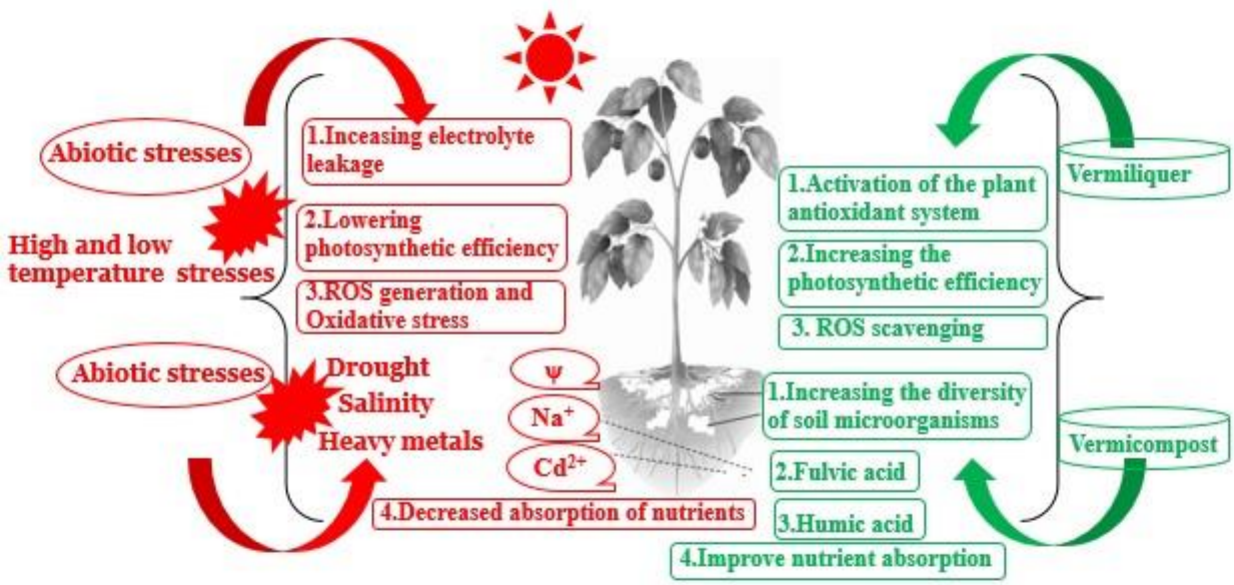

Fig 3. The ameliorative effects of vermicompost and vermiliquer in plant and abiotic stresses interaction

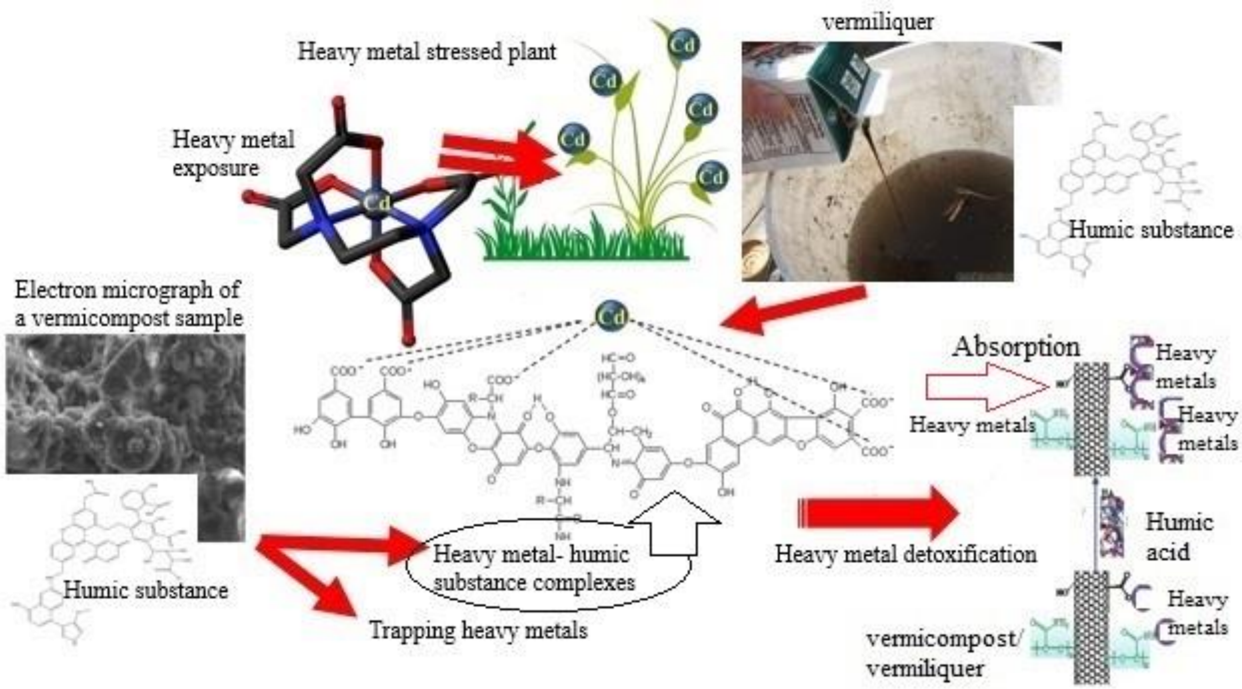

Fig 4. The ameliorative effects of vermicompost and vermiliquer on heavy metal stress