RM and LP *Chem. Biol. Technol. Agric.* (2022) 9:70
https://doi.org/10.1186/s40538-022-00332-0

Chemical and Biological
Technologies in Agriculture

RESEARCH **Open Access**

Organic matter in the pest and plant disease control: a meta-analysis

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Abstract

Background: Pesticides have become a central public health problem and a source of environmental contamination. The use of organic matter is an important strategy to reduce synthetic agrochemicals, improve soil conditions, and increase nutrient uptake by plants. Organic matter can also induce plant resistance against biotic stress in some circumstances. However, the results reported for different types of organic matter applications are often very different form each other, thus making difficult their interpretation and hindering and discouraging their use as valuable alternative. Identifying the main factors involved in the efficacy of these sustainable methodologies and the associated research gaps is important to increase the efficiency of organic matter and reduce the use of pesticides.

Materials and methods: We performed a comprehensive meta-analysis of the current recent scientific literature on the use of organic matter as control method for pest and disease, using data reduction techniques, such as principal component analysis. We found 695 articles listing the keywords in the databases between 2010 and 2021 and selected 42 that met inclusion criteria.

Results: In general, all organic matter reported showed a high inhibition of pests and diseases. Control effectiveness was close to 75% for fungal diseases and 67% for the pest control. The source of organic matter most frequently reported was the vermicompost. However, humic substances showed the greatest effectiveness of 74% when compared to both fungal and bacterial disease control. The concentration of humic substances ranged from 1 to 500 mg L^{-1}, with the highest concentrations used in case of soil application.

Conclusions: The study demonstrated the potential role of organic matter as a resistance elicitor in plants, thus allowing a partial/total reduction of pesticides in crops. Despite the efficiency reported in the works, the mechanisms of induction of pest and disease control remains poorly studied.

Keywords: Ecological agriculture, Organic control, Biotic stresses, Resistance induction

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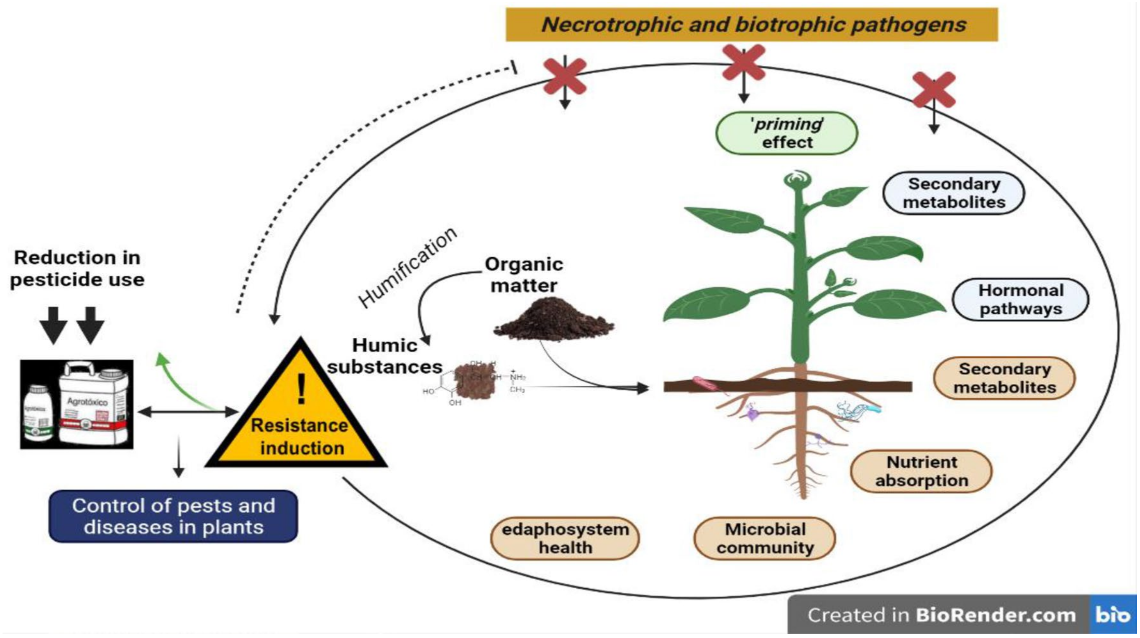
Graphical Abstract



Introduction

Current agricultural practices involve the deliberate maintenance of ecosystems in a heavily simplified, disturbed, and nutrient-rich state [1, 2]. Natural processes are substituted with an excess of chemical fertilization to maximize crop yields, while weeds, insects, and pathogens are actively controlled via chemical pesticides [1]. The consequences of the indiscriminate use of external inputs in agriculture impact economy, environment, and health with devastating effects, especially in the least-developed countries. For example, in the north region of Rio de Janeiro state, Brazil, characterized by family owned tomato farms,, the indiscriminate use of 24 different products (75% insecticides and 25% fungicides) has been found [3]. Farmers and their families including uninvolved children presented several symptoms of acute intoxication, mental disorders, such as depression and anxiety, and respiratory difficulties [4].

Avoiding or drastically decreasing the use of pesticides is a current priority objective of many agricultural safety programs. However, the adoption of integrated pest management which advocates the use of host plant resistance, biological control, and cultural controls along with pesticides was not widely adopted and did not significantly affect the number of pesticides used worldwide [5]. In Europe there is a clear decrease in the use of synthetic agrochemicals due to consumer pressure and restrictive regulations, while in the USA and South America, especially in Brazil, this market keeps increasing [6].

In an application-oriented rationalization scheme the second step to transition processes is the substitution of chemical by biological inputs [7, 8]. At local level, agricultural sustainability is focused on the maintenance of crop productivity combined with improvement of soil fertility and resilience [9]. The best option to achieve these goals is the increase of soil organic matter quantity and quality [9]. Plants grown on soils containing adequate humus content produce more, are healthier and less subject to stress,, thereby showing a larger nutritional quality of harvested foods [10]. The benefits of organic matter amendment to soil properties are extensively studied [11–15]. In the last 40 years, the understanding of the direct effects of humus application on molecular, biochemical and physiological processes in plants also has greatly increased [16–27]. However, despite farmers observation that plants treated with organic matter and its enriched byproducts (compost, vermicompost, teas, humic substances) have a larger tolerance to biotic stress (pests and diseases), scientific studies about the possible structural activity relationships are relatively scarce [28]. The use of different natural organic matters (NOM) has shown valuable and differentiated effects on the control of pests and plant diseases [29–35]. Organic products have been used for biological control of soil-borne diseases and proved effective in reducing the severity of foliar diseases caused by phytopathogens [28, 36–39]. Moreover, their effect against herbivory [33, 40] through the induction of plant resistance to pathogen infestations has been reported [41–43].

NOM can increase plant resistance indirectly through its important role on soil biological properties, as well as on the development of beneficial soil microbial communities, with a resulting increase in richness and diversity [37, 44, 45]. It has been well-documented that various soil microorganisms generically called plant growth promoting rhizobacteria (PGPR) and fungi (PGPF) not only promote plant growth, but also play a crucial role in protecting against pathogens [46–48].

These microorganisms act as the first line of defence [49]. When this barrier is broken, pathogens face plant-induced defence mechanisms [50]. Various organic materials have been tested and proved to induce the plant tolerance and increase the crop resilience against pathogens [51–54]. Humic substances (HS) can trigger the enrichment of microorganisms with the potential to act on both plant growth and plant defence against pathogens [55].

When plant is under the attack of a pathogen, phytohormones such as salicylic acid (SA), jasmonic acid (JA) and ethylene (ET) are synthesized to limit pathogen advancement [56, 57]. These phytohormones stimulate plant immunity and the accumulation of phytoalexin and plant resistance-related proteins, such pathogenesis-related proteins (PRs), including chitinase and β-1,3-glucanase [58]. This inhibition system leads to either induced systemic resistance, (ISR) [59] or systemic acquired resistance (SAR) [60]. SAR is an innate plant defence mechanism requiring SA as signal molecule and characterized by the induction of pathogen-related proteins (PR-proteins) that confer long-lasting protection against a broad spectrum of microorganisms [61–63], by altering plant morphology and anatomy. In contrast to SAR, ISR is a JA-dependent and ET-independent SA mechanism [64], without PR–protein accumulation, and little change in plant morphology [57, 63, 65]. The positive regulation of these pathways leads to increased accumulation of antimicrobial compounds (phytoalexins), and help contrasting pathogens during subsequent attack [66].

In view of the potential benefits of NOM for pest and disease control in plants, a meta-analysis was conducted with the aim to evaluate the available data about the use of organic matter and its fractions as elicitors of resistance in plants, and presenting the following specific objectives: (i) to analyse qualitative and quantitative aspects of the potential effect of different types of organic matter on plants exposed to different pathogens and pests; (ii) to determine the influence of environmental conditions, growing environment, plant type, organic material used and the mode of use; and (iii) to identify gaps in our understanding about the control mechanisms induced by organic materials in plants.

Materials and methods

The meta-analysis study was carried out by collecting scientific data from researches executed in different countries. A preliminary screening was performed using the search engines Web of Science (Clarivate Analytics), Scopus—IBM (International Business Machines Corporation), and Scielo (Scientific Electronic Library Online), using the following keywords and their combinations: vermicompost; compost; vermicompost tea; compost tea; humic substances; humic acids; vs plant disease; pest; plague. The database research returned 695 research articles, published in English, Spanish and Portuguese. Of these articles, only those using an organic source to control diseases and/or pests were further selected. In this first phase of the search, 92 articles were selected from a total of 695.

Criteria for articles inclusion and exclusion

The studies considered for this analysis met the following criteria: (i) research articles published from 2010 to 2021; (ii) the effect of some organic material on crops under attack by pests and diseases was evaluated; (iii) experiments based on trials in a greenhouse, greenhouse/screen house, growth chamber or field tests; (iv) presence of one or more quantitative data regarding the occurrence or not of diseases and/or insect pests in crops. During the data extraction phase, those articles that did not meet the criteria considered for this meta-analysis were excluded, such as: (i) review articles, books and book chapters; (ii) in vitro experiments and (iii) studies, where data were not in extractable forms. The articles selected after the inclusion and exclusion criteria were later considered for meta-analysis, totalling 42 articles that met the inclusion criteria and used in the meta-analysis.

Data sheet

After screening each scientific study, a database was built in an electronic spreadsheet, with information from the article, such as: authors, year of publication, journal and the impact factor. Subsequently, information regarding the specific study were extracted, such as: location of the experiment (city/country), disease/pest and its causal agent, type of culture, growth setting (greenhouse, field and laboratory), growth medium (soil or hydroponics), form of pathogen contamination (inoculated or spontaneous), application form of the organic material (foliar spray, via substrate or via seed), the type of organic material and finally the percentage (%) of inhibition or reduction of disease and/or pest in treated plants in relation to the control. Seven organic sources were found to show measurable reduction or inhibition of pests and diseases development, such as: compost, vermicompost, compost and vermicompost tea, biofertilizer, biochar, humic substances and the combinations thereof. An exploratory data survey was performed to describe the behaviour of the variables in the selected studies. The selected parameters were: type of plant, growth environment, growth medium, type of application, form of contamination, type of causal agent and organic source used.

Data analysis

The exploratory analysis was relying on the number of experiments in relation to the selected sources of variation. In addition to this preliminary investigation, the data were carefully examined considering that the set of studies under analysis were not fully comparable in their methods and/or in the characteristics of the samples included, introducing variability among the effects of the evaluated criteria. If the heterogeneity of the data set was purely random, thus the random effects model was given by: $\theta i = \mu + \mu i$ where $\mu i \sim N(0, \tau 2)$, and the true effects were assumed to be normally distributed with the mean μ and variance $\tau 2$.

To calculate the effect size or outcome measures (and the corresponding sampling variations), the scalc() function was used, whose outcome measure (yi and vi) was designated to determine the risk rate, "RR" (risk ratio): $RR = \log(ai/bi)/(ci/di)$, where ai, bi, ci and di are the means and standard deviation of the treatment and control, respectively.

From the outcome measures, the random model was adjusted by the rma () function, which executes a regression model of random effects by calculating the estimates of the hazard ratio using the maximum likelihood method. In the forest function () used for the graphical representation (Forest Plot) of the objects generated by the adjusted model, the confidence interval of 95% was used. These analyses were carried out using the statistical software R version 4.0.3 (Development Core Team 2020), using the metaphor package (Viechtbauer 2010). To facilitate the comparison between the sources of variation, the pest and disease inhibition efficacy (IPD) was calculated using the pest and disease incidence values observed in the studies and linked to the sources of variation, and subsequently applied to the proposed formula by Sukamto [133]: $Ea = (IPk - IPp)/IPk \times 100\%$ where Ea = Effectiveness; IPk = Disease intensity in controls; IPp = Disease intensity with treatment. Efficacy values were categorized as very good ($Ea > 69\%$), good ($Ea = 50–69\%$), less good ($Ea = 30–49\%$), and not good ($Ea = < 30\%$) as suggested by Sukamto [133].

For the pest and disease incidence (IPD) and pest and disease prevalence (CT) data sets, principal component analysis (PCA) was performed to explore the relationships between organic sources and the incidence of pests and diseases. The correlation matrix was used in the procedure. The multivariate differences were accessed by testing the random permutations of the data (Monte-Carlo test) (Mielke & Berry, 2001). Multivariate analysis was performed using PC-ORD software, Version 6 [67].

Results

We found 695 articles listing the keywords in the three databases used. Among them, 92 were previously selected and 42 met the inclusion criteria. Most (58%) are from Middle and Far Est Asian countries (China, Egypt, India, Indonesia, Iran, Israel, Pakistan and Thailand), with Iran being the country with the highest number of studies, followed by India and China (Fig. 1). The American continents contributed with nine studies (21%), seven were placed in Europe (16%) and only two studies placed in Africa (5%).

Vermicompost was the most frequently used source of organic matter in pest and disease control studies, followed by the combination of different organic matters with microorganisms and compost tea (Fig. 2).

The number of studies and the use of organic matter is lower against pests (insects + nematodes) than plant diseases (Fig. 3A). Vermicompost was used in the greatest diversity of causal agents (24.5%) (Fig. 3B) and *Fusarium* spp. was the most studied causal agent of plant disease (Fig. 3B).

For cultivated plants the largest range of research works dealt with *Solanaceae* family that also showed the greatest variation in the type of applied organic materials, followed by the *Cucurbitaceae* family (Fig. 3C). Compost (C) and its tea extract (CT) were the preferential organic treatment for pest and disease control in *Solanaceae,* while in the cucurbitaceous crops, the use of V and its tea derivates (VT) was more frequent.

Considering the influence of organic material, on the total of 42 papers it was found a 72.8% of the inhibition on pests and diseases by organic matters in comparison with controls treatments (Fig. 4A). The C, VT and HS revealed higher and similar level of pest and disease control (around 78%), while although the V was the most

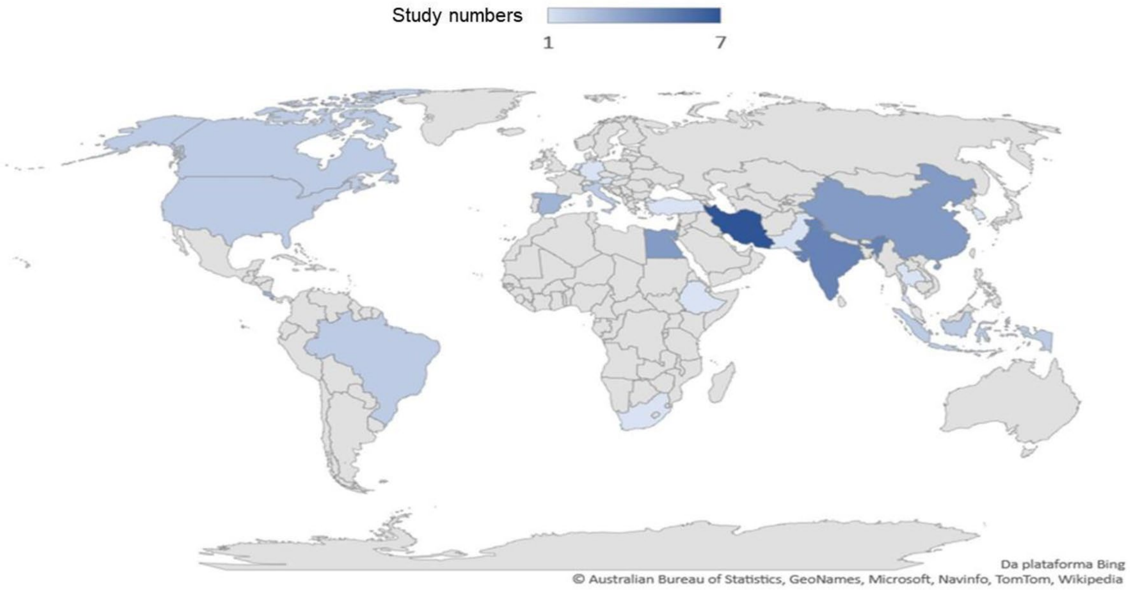


Fig. 1 Geographical distribution of studies that met the inclusion criteria in the meta-analysis

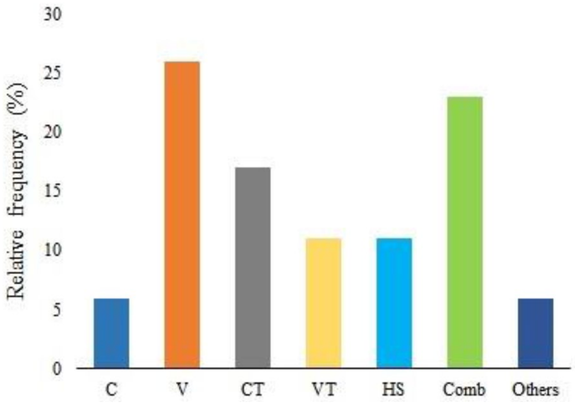


Fig. 2 Relative frequency of organic matter sources used for pests and diseases control in plants. *C* Compost; *V* Vermicompost; *CT* Compost Tea; *VT* Vermicompost Tea; *HS* Humic substances; *Comb* Combinations (Vermicompost + Microorganisms, Compost + Microorganisms, Humic Acid + Microorganisms, Vermicompost + Humic Acid, Vermicompost + Vermicompost Tea, Compost + Charcoal, Humic acid + Chitosan); Others – Biofertilizer and Charcoal

studied organic source it showed a lower effect (65%) in comparison with control treatments (Fig. 4A). This finding was corroborated by the principal component analysis (PCA), which also highlighted a significant effectiveness of HS in respect to control (Fig. 4B). It is worth mentioning that in PCA, the sources of variation considered were only the effectiveness in controlling pests and diseases of the different organic sources used.

For the causal agent the average suppression shown by plant disease (75%) was slightly but significative higher than the output found for pest control (67%) (Fig. 5A). However, the overall decrease of nematodes was more efficient (81%), while the activity against insects was lower (56%) compared to control treatments, thus reducing the general average effectiveness on pest control (nematodes + insects) as compared to the induced tolerance for pathogens. The decrease of fungal and bacterial diseases was around 75% and 72%, respectively (Fig. 5A), indicating a huge potential of organic methodologies in reducing the negative relapses and improving the crop resilience to these biotic stresses. The meta-analysis detected differences between types of plants in response to either pest and disease upon the application of organic matter as control agent following the sequence: Asteraceae 85% > Cucurbitaceae 80% > Solanaceae 70.6% > Fabaceae 53.5%. In the observed data set, there was no difference in the application form of organic matter source (Fig. 5C).Conversely, the data associated with plant growth substrate indicated a significant difference in the potential restrain of both biotic adversities with higher decrease in hydroponics (80%) when compared to plants grown in the soil (72.6%) (Fig. 5D). In addition, we found a better effect of organic bio-control when the diseases were induced in comparison with spontaneous disease incidence (Fig. 5E). Finally, the disease repression was lower in the growth chambers when compared to the effect of organic matter applied under greenhouse conditions (Fig. 5F).

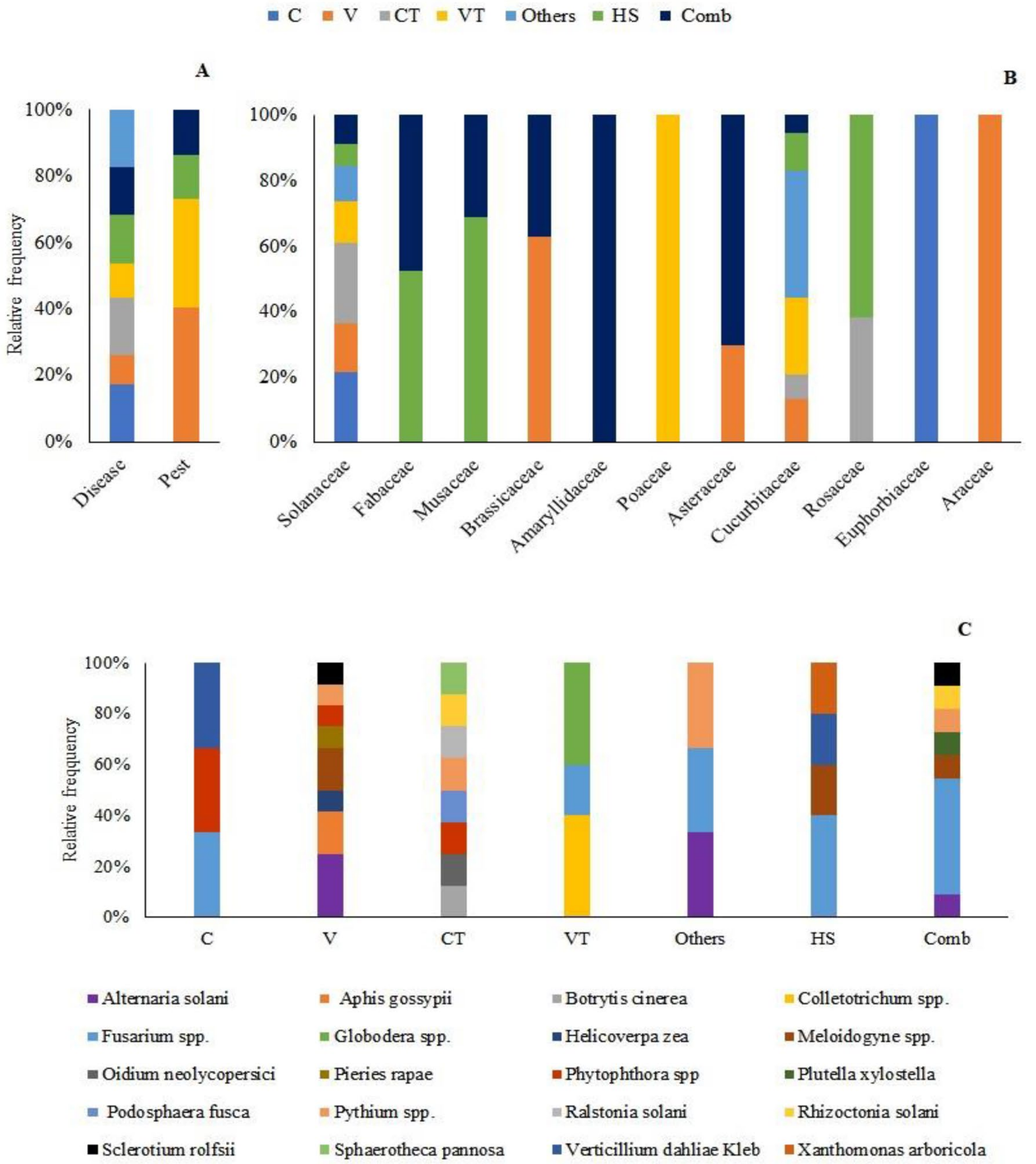


Fig. 3 **A** Relative frequency of the study of pests (insects and nematodes) and diseases (fungal and bacterial) in plants, in relation to the use of organic matter; **B** frequency of cultivated families most studied for each different organic matters to control pests and diseases; **C** frequency of the study of insect pests and pathogens that cause diseases in plants, in relation to the use of organic sources. *C* Compost; *V* Vermicompost; *CT* Compost Tea; *VT* Vermicompost Tea; *HS* Humic substances; *Comb* Combinations (Vermicompost + Microorganisms, Compost + Microorganisms, Humic Acid + Microorganisms, Vermicompost + Humic Acid, Vermicompost + Vermicompost Tea, Compost + Charcoal, Humic acid + Chitosan); Others – Biofertilizer and Charcoal

The majority of the research works involved in this meta-analysis did not directly investigate and discuss the mechanism responsible for the suppression or reduction of disease symptoms. In our study we looked for further indirect evidences able to elucidate the potential structure–activity relationship with applied organic agents.

The main resistance mechanism claimed as responsible for the observed results was the induced systemic

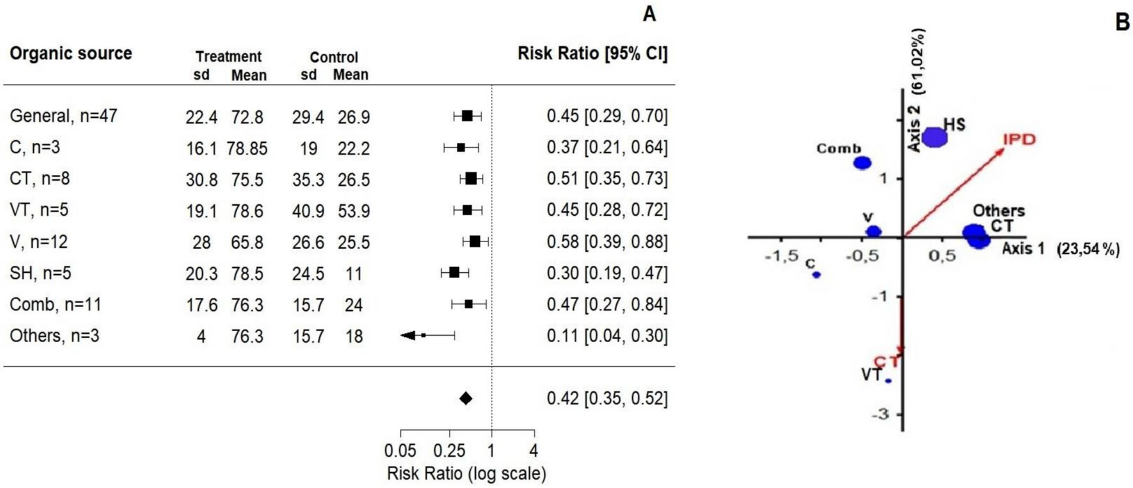


Fig. 4 **A** Influence of organic matter sources on the inhibition of pests and diseases in plants. Where: Squares correspond to the mean effect size and the error bars to the 95% confidence; *CI* Confidence Interval; Lozenge corresponds to the final effect size of the studies included in the meta-analysis. **B** Principal Component Analysis (PCA) of effectiveness in pest and disease control vs. organic matter sources. 84.56% was the percentage of variance explained by PC1 + PC 2, by the Monte Carlo permutation test, $p < 0.0099257$. *C* Compost; *V* Vermicompost; *CT* Compost Tea; *VT* Vermicompost Tea; *HS* Humic substances; *Comb* Combinations (Vermicompost + Microorganisms, Compost + Microorganisms, Humic Acid + Microorganisms, Vermicompost + Humic Acid, Vermicompost + Vermicompost Tea, Compost + Charcoal, Humic acid + Chitosan); Others – Biofertilizer and Charcoal

resistance (ISR) (Table 1). No study, among all those analyzed, pointed to the mechanism of Systemic Acquired Resistance (SAR), as shown in Table 1. Indirect indication refers to studies in which the resistance is based on the percentage of inhibition of the specific disease or pest; the direct evidence derives from the use of resistance markers in plants, such as defense genes and/or defensive enzymes. Some researches (denoted by the acronym NI—No indication, Table 1) did not provide any type of involved process.

The range of C amount used for the biological control of pest/disease varied from 500 to 100 g kg^{-1} with an average of 367 g kg^{-1} and wide standard deviation (SD = 231 g kg^{-1}). The overall V concentration was lower than C (293 ± 204 g kg^{-1}) with a maximum concentration of 200 g kg^{-1} and a minimum of 12.5 g kg^{-1}. The C tea extracts varied in the lower range compared to C and VC with 65 ± 68 g L^{-1} and 28 ± 11 g L^{-1} for CT and VT, respectively. The source of organic matter showing higher efficiency was HS, although the range of applied concentration varied widely, from 500 to 1 mg L^{-1} with an average of 142 mg L^{-1}. The highest concentrations of HS were used in the growth medium, and the lowest concentrations were used directly on the leaf surface. This wide variation in concentrations within each organic source used explains the increase in the standard deviation presented in the table above.

Discussion

Asian continent is responsible for 52.8% of pesticides use in the world, followed by the Americas (30%), Europe (13.7%), Africa (2.2%) and, finally, Oceania (1.3%) [9]. The same ratio was found for the studies considered in our meta-analysis (Fig. 1). Although the climate change draws the attention of researchers mostly on abiotic stress, the effects on crops produced by biotic stresses still preserve the major incidence and magnitude of damage [68]. In conventional agriculture, their control is simply based on the assumption that their efficiency is lost over time, this implying the significant additional negative externalities discussed in the introduction of this work. Integrated pest and disease management is a strategy that does not reduce the use of pesticides for a number of reasons, among the most important being the absence of specialized personnel and the increase in inspection work [5]. Biological control seems to be the most effective strategy, but today it is restricted to a few causal agents and with a cost as high or higher than conventional pesticides. The use of organic matter directly applied on plants (or growth medium) is rarely mentioned in the main strategies to achieve pesticide-free agriculture [69]. However, the everyday experience of family farming, especially in the tropics and the results of this meta-analysis demonstrate an enormous (and overlooked) potential of the

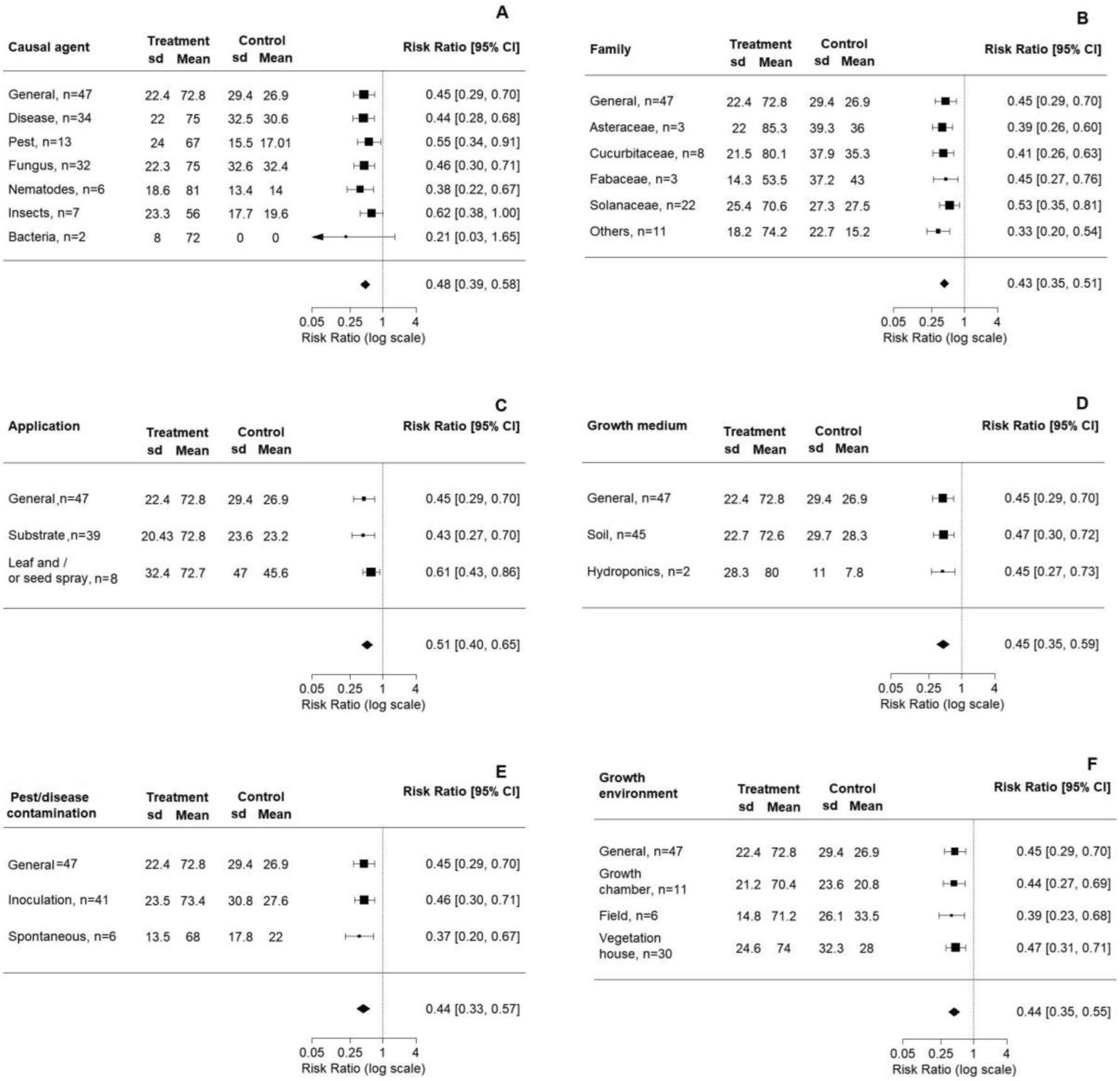


Fig. 5 Influence of the causal agent (**A**); plant family (**B**); application form (**C**); growth environment (**D**); form of contamination (**E**); and growth medium (**F**) under treatment of different organic matter sources in the percentage of inhibition of pests and diseases in plants; where: squares correspond to the mean effect size and the error bars to the 95% confidence; *CI* Confidence Interval; Lozenge corresponds to the final effect size of the studies included in the meta-analysis

tailored application of organic material for the selective restrain of pest and disease in different types of plants. In this context, the study on the use of organic matter and its fractions in the induced tolerance against pests and diseases becomes relevant given the high relative efficiency, low cost, and autonomy of the farmer.

Main organic matter sources used in plant pest and disease control

Vermicompost, teas and HS were the main organic matter sources frequently reported in plant pest and disease control studies (Fig. 3B). Vermicomposting is a non-thermophilic biological oxidation process in which organic material is converted into highly humified and stabilized complex organic matrix called vermicompost [70, 71]. The final product is a peat-like material exhibiting high porosity, water holding capacity and rich microbial activities through the interactions between earthworms and associated microbes [72]. Some important characteristics of V can be related to its effect on pests and diseases control, such as its richness in micro- and macronutrients, the presence of nitrogen fixing bacteria and phosphate solubilizing bacteria [73] as well as the presence of growth regulation substances, such as

Table 1 Resistance mechanisms induced by different types of organic matter

References	Culture	Organic source	Resistence mechanism	Indication	Evidence
Jaya A et al. [138]	Tomato	V	ISR	Indirect	C.E. sclerotium wilt
Sahni et al. [129]	Chickpea	Comb	ISR	Indirect	C.E. fusarium wilt
Rasool et al. [139]	Tomato	Others	ISR	Indirect	C.E. Early blight
Istifadah et al. [140]	Tomato	Comb	ISR	Indirect	C.E. Early blight
Tao et al. [128]	Banana	Comb	ISR	Indirect	C.E. fusarium wilt
Jafary-Jahed et al. [32]	Canola	Comb	ISR	Indirect	C.E. cruciferous moth
Ismail et al., [127]	Garlic	Comb	ISR	Indirect	C.E. basal bulb rot
Khaled et al. [125]	Artichoke	Comb	ISR	Direct	Enzymes defence
Charoenrak et al. [141]	Lettuce	Comb	ISR	Indirect	C.E. root rot
Akinnuoye-Adelabu et al. [142]	Wheat	VT	ISR	Indirect	C.E. root rot
Jaiswal et al. [143]	Cucumber	Others	ISR	Indirect	C.E. root rot
Zhao et al. [144]	Melon	Others	ISR	Indirect	C.E. fusarium wilt
Seddigh & Kiani [145]	Rosa	CT	ISR	Indirect	C.E. pink powdery mildew
Hussain et al. [146]	Female finger	V	ISR	Indirect	C.E. Early blight
Mengesha et al. [106]	Potato	CT	ISR	Indirect	C.E. bacterial wilt
Silva et al. [39]	Cassava	C	ISR	Indirect	C.E. root rot
Seenivasan & Senthilnathan [111]	Banana	HS	NI	No info	not indicated
Mohamadi et al. [147]	Tomato	V	ISR	Indirect	C.E. tomato leafminer
Mardani-Talaee et al. [116]	Pepper	V	ISR	Indirect	C.E. green aphid
El-Mohamedy et al. [148]	Bean	HS	ISR	Indirect	C.E. root rot
El-Mohamedy et al. [148]	Bean	Comb	ISR	Indirect	C.E. root rot
Basco et al. [90]	Tomato	Comb	ISR	Direct	Enzymes defence
Afifi et al. [29]	Cucumber	HS	ISR	indireta	C.E. fusarium wilt
Giovanardi et al. [92]	Peach	HS	ISR	Direct	Genes expression
Blaya et al. [149]	Pepper	C	NI	No info	not indicated
Akhter et al. [126]	Tomato	Comb	NI	No info	not indicated
Xiao et al. [112]	Tomato	V	ISR	Direct	Genes expression
Renco & Kovacik. [150]	Potato	VT	NI	No info	not indicated
Renco & Kovacik. [150]	Potato	VT	NI	No info	not indicated
Demir et al. [137]	Tomato	HS	NI	No info	not indicated
Molina et al. [151]	Potato	C	NI	No info	not indicated
Uribe-Lorío et al. [152]	Pepper	V	NI	No info	not indicated
Rostami et al. [153]	Cucumber	Comb	NI	No info	not indicated
Marín et al. [154]	Pepper	CT	ISR	Indirect	C.E. damping
Marín et al., [155]	Melon	CT	ISR	Indirect	C.E. powdery mildew
Razmjou J et al. [136]	Cucumber	V	NI	No info	not indicated
Castro et al. [130]	Tomato	V	ISR	Indirect	C.E. root-knot nematodes
Sang & Kim. [80]	Pepper	VT	ISR	Direct	Genes expression and enzyme activity
Sang & Kim. [80]	Cucumber	VT	ISR	Direct	Genes expression and enzyme activity
Razmjou et al. [136]	Cucumber	V	NI	No info	not indicated
Little & Cardoza. [156]	Arabidopsis	V	NI	No info	not indicated
Dukare et al. [157]	Tomato	CT	NI	No info	not indicated
Dukare et al. [157]	Tomato	CT	NI	No info	not indicated
Cardoza. [40]	Arabidopsis	V	NI	Indirect	C.E. corn caterpillar
Artavia et al. [36]	Taioba	V	ISR	Indirect	C.E. root rot
Koné et al. [79]	Tomato	CT	ISR	Indirect	C.E. powdery mildew
Koné et al. [79]	Tomato	CT	ISR	Indirect	C.E. gray mold

CE Control efficiency; *V* Vermicompost; *C* Compound; *CT* Compost tea; *VT* Vermicompost tea; *HS* Humic substances; *Comb* Organic sources in combinations; *Others* (Organic sources with a frequency of less than 5%); *RSI* induced systemic resistance, directly cited by the authors; *NI* No indication of mechanism; The use of molecular markers and enzymatic activities were the parameters used to define a direct or indirect indication, based on whether or not these parameters of systemic resistance were performed; *cDNA–AFLP* cDNA amplified fragment length polymorphism auxins, gibberellins, cytokinins, vitamins, HS and defensive enzymes [74]. Yatoo et al. [28], reported the role of V and its aqueous extract (VT) in sustainable management practices for the treatment of soil and aerial borne plant pests and diseases. Like VT, CT is an aqueous extract [75, 76] that has also been used to correct nutrient deficiency and implement the sustainable management of biotic stress in different crops [77]. It can be applied to the soil, where it delivers nutrients and microorganisms to the plant's rhizosphere [78], or sprayed on leaves surface, promoting either the inoculation of beneficial microorganisms antagonistic of various phytopathogens [53] or the supply of its by-products (nutrients and bioactive organic compounds). Its foliar use has shown high efficiency in the treatment of foliar diseases in previous reports [79, 80] but no differences were found in this meta-analysis when comparing growth medium vs foliar application (Fig. 5C). Its microbial composition is the most reported factor influencing the effectiveness of CT in inhibiting the development of plant pathogens [79]. The microorganisms present in tea can act as antagonists of pathogens through their ability to compete for space and nutrients [81], destroy pathogens by parasitism [82], produce antimicrobial compounds, or induce systemic resistance in plants [43].

Humic substances (HS) consist of up to 80% of organic materials in soil and sediments whose reactivity and dynamics have pivotal importance on microbial activity and plant productivity [16, 17, 71, 83]. Their effects on plant physiology depend on their chemical nature and the availability of biologically active compounds, concentration, type and age of plant species and are correlated with the apparent molecular mass distribution [16, 22, 83–87]. Indirectly, the effect of HS can be associated with the effects of other organic matter sources, such as V, C and teas in the control of pests and diseases in plants, since HS are ubiquitous in all natural organic material. HS can indirectly induce the plant's defense system against harmful microorganisms by inhibition mechanisms or by promoting the growth of microorganisms antagonists of pathogens, thus allowing greater protection for plants [88]. We found in the literature one evidence highlighting the relationship between plant defense mechanism and HS. Schiavon et al. [89] showed that humic acids (HA) were able to promote the activity of PAL (phenylalanine ammonia lyase) and enhance the concentration of total phenolic compounds in leaves extracted from maize. The induction of secondary metabolism and high concentration of phenolics is pivotal for plant defense against biotic and abiotic stress [90–92]. The PAL pathway in the cytoplasm, and the isochorismate pathway in the chloroplast are the two distinct pathways that lead to endogenous salicylic acid (SA) synthesis from chorismate [93]. The increase of SA activates a plant defense response-like PRPs genes induction. However, only isochorismate pathway is responsible for the pathogen-induced SA synthesis in diverse plant species [94], but the effect of HS on this pathway is unknown.

Main pests and diseases controlled by organic matter

The meta-analysis indicated that organic matter was most frequently used for the control of fungal diseases (Fig. 3C). The influence on crop development and productivity resulting from the presence of these pathogens has become an important topic as their resistance against synthetic agrochemicals is slowly increasing [95, 96]. *Fusarium* spp. is the fungal reported with highest frequency in many investigations (Fig. 3C). *Fusarium* species have a wide host range, and most plant diseases are caused by *Fusarium solani* (50%) and *Fusarium oxysporum* (20%) [97]. In addition to *Fusarium* ssp., *Pythium* spp., *Alternaria solani* and *Rizhoctonia solani*, are among the causal agents belonging to the most studied fungi, respectively (Fig. 3C). *Fusarium* spp., *Pythium* spp., and *Rizhoctonia solani* constitute a group of major soil pathogenic fungi [98–100], while *Alternaria*, are among the most common in foliar plant diseases [101]. A fungal infection can cause local or extensive necrosis in plants and inhibit normal growth (hypotrophy) or induce abnormal excessive growth (hypertrophy or hyperplasia) in a part or the entire plant. Symptoms associated with necrosis include leaf spot, rust, scab, rot, deadening, anthracnose, death, and cancer [102]. Among the studies that met the inclusion criteria in the meta-analysis, only two elucidated the effect of organic matter sources on the control of bacterial diseases with a significant average percentage of inhibition (72%). However, as the sample number was very low in relation to the other groups of pathogens, a low weight was obtained in the final mean effect of the analyzed studies (Fig. 5A). *Xanthomonas arbicola* in peach and *Ralstonia solanacearum* in potato were the bacterial adversities faced using HS and CT, respectively (Fig. 3C). In general, bacterial infections are difficult to control and few reports found in this meta-analysis reflect this issue. This is partially attributable to the rapidity with which bacteria penetrate natural openings or wounds in plants [102]. Bacterial wilt is one of the most aggressive soil-borne diseases caused by *Ralstonia solanacearum* and represents a serious threat to the Solanaceae family [103, 104] as it survives for a long time in soil, even in absence of a specific host [105]. Although several methods have been used to wipe out the disease, none of them are yet fully effective [105]. The increment of organic matter in soil offers a management practice that increases microbial antagonism against *Ralstonia solanacearum* [106]. Similar to *Ralstonia solanacearum*, the bacterium of the genus *Xanthomonas* is a highly specialized pathogen that infects species of the Rosaceae family causing bacterial spot disease, and is responsible for important economic incidence in the cultivation systems of this family worldwide. The economic impact results in reduced fruit quality and marketing, decreasing orchard productivity and increased nursery production costs [106]. Giovanardi et al. [92] confirmed through transcriptomic analysis that the application of HS acted as an inducer of resistance to arboreal *Xanthomonas* in peach trees, inducing genes involved in the plant direct response to pathogens. Silva et al. [55] also reported the use of HA combined with *Herbaspirillum seropedicae* as a biotic elicitor in tomato against bacterial disease caused by *Xanthomonas*.

Studies related to the use of organic matter sources in the management of insects had a lower proportion (37.1%), presenting on average a lower percentage of inhibition (67%) than that observed in the studies focused on microorganisms (75%). Organic compounds used to defeat insects showed fewer positive responses (55%) when compared to their effect on nematodes (81%), thereby revealing the V as the most frequently used approach (Figs. 2 and 4A). Root-knot nematodes (Meloidogyne spp.) represented the largest observed group (Fig. 4B). The galls on plant roots are formed because of physiological disturbances in root tissues caused by trophic interactions of female nematodes, and are responsible of considerable economic losses [107]. The use of organic matter against nematodes has been well-reported in the literature [108–110]. Seenivasan and Senthilnathan [111], suggested the use of HA, not only to control nematodes in bananas, but also to stimulate plant growth. The application of VT also has a nematode suppression effect on tomato plants [112]. In addition, several previous results have suggested that the abundance of hormone-like molecules such as auxins, cytokinins and gibberellins in HS of vermicompost can also suppress nematode infestation [113, 115]. VT applied via soil to plants is also capable of reducing aphid damage on pepper plants (Capsicum annuum) [116] and cabbage [114].

Mechanisms of bio-based pest and disease inhibition

As previously pointed out, the large portion of the studies compiled in this meta-analysis did not indicate the mechanisms responsible of the effectiveness of organic matter application on biotic stresses (Table 1). The studies directly highlighting the possible mechanism, through the use of markers of induction of plant resistance against pathogens, make up a total of five. This finding clearly demonstrates the current huge gap in this field of study.

A scientific hindrance is the large number of complementary or alternative biochemical pathways and enzymatic reactions associated with induced resistance in plants [117]. Therefore, different and integrated scientific studies have to be designed to obtain a concrete conclusion on the use of specific organic matter as elicitor of systemic resistance in plants. The main markers of improved tolerance to biotic adversities are defensive enzymes, such as β-1,3-glucanase, kinases, phenylalanine ammonia lyase (PAL), peroxidase (POX), polyphenol oxidase (PPO), superoxide dismutase (SOD) and total polyphenol content (TPC), in addition to the detection of resistance genes. The effect of HS on the induction of catalase activity (CAT) was shown by Cordeiro et al. [118]. Plants treated with HA showed increased activity of SOD, CAT, and APX [119–121].

The enzymes β-1,3-glucans and chitinases are PRPs that degrade the cell walls of pathogens, releasing molecules acting as elicitors in the initial stages of the resistance induction process involving the synthesis of phytoalexins and phenolic compounds [122]. Peroxidases play a key role in plant growth and development and are strongly related to defense mechanisms against pathogens [123, 124]. Polyphenols are abundant in infected tissues and are involved in development of biochemical barriers or senescence. PAL is an enzyme widely studied by physiologists and catalyzes the first committed step in the biosynthesis of phenolics by converting phenylalanine to trans-cinnamic acid and tyrosine to p-coumaric acid. As mentioned above Shiavon et al. [89] were the first to report the relationship of PAL promotion and polyphenol content in plants treated with HS. Khaled et al. [125] investigated whether the combined application of HA + Arbuscular Mycorrhizal Fungi (AMF) was able to induce the response of Jerusalem artichoke plants (*Helianthus tuberosus*) under infestation of *Sclerotium rolfsii*, the fungus that causes the neck rot disease, through the study of the defensive enzymes chitinase, APX and POX. The use of HA + AMF increased the activity of these enzymes between 1.5 and 2.1 fold compared to the control, indicating the induction of systemic resistance against the invasion of S. rolfsii.

Basco et al. [90] also observed an increase in the levels of PAL, POX, PPO, SOD and total TPC when vermicompost was combined with *Trichoderma harzianum* and applied via substrate in tomato plants after infection by *Fusarium oxysporum* f. sp. *Lycopersici*. Other studies analyzed in this meta-analysis tested different sources of organic matter in combinations with microorganisms against diseases caused by *Fusarium* ssp. in plants. The combinations were: Vermicompost + *Pseudomonas* spp.; Compound + *Trichoderma asperellum*; Organic fertilizer + *B. amyloliquefaciens*; Compost + Charcoal, in the respective crops, chickpeas, garlic, bananas and tomatoes [126–129]. Such inhibition possibly occurred by the activation of the ISR, indirectly indicated by the authors.

In cucumber and pepper plants, the observed induction of ISR by foliar application of VT was associated with the increase of β-1,3-glucanase, chitinase and peroxidase enzymes 3 days after inoculation with *Colletotrichum coccodes* and *Colletotrichum orbiculare*, both agents responsible for anthracnose. In addition, Sang and Kim [80] also pointed out an increase in the expression of genes related to pathogenesis PR1-1a, PR-2 (β-1,3-glucanase), PR-3 (chitinase), APOX (Ascorbate peroxidase). Xiao et al. [112] studied the use of VT as a resistance elicitor to root-knot nematodes (*Meloidogyne incognita*) in tomatoes. Real-time quantitative polymerase chain reaction (qRT-PCR) was used as marker tool to detect transcripts of genes involved in secondary metabolism in roots, including polyphenol oxidase D (PPO), flavonol synthase (FLS) and RKN resistance gene (Mi1.2). The PPOD gene involves the metabolism of polyphenols and protects plants against biotic and abiotic stress, while the FLS gene involves the metabolism of flavonoids, and the Mi1.2 gene can confer specific resistance to M. incognita root-knot nematodes. The application via soil of VT in tomato plants susceptible to nematodes promoted an increased expression of these genes in the roots. Castro et al. [130] also indirectly indicates that VT applied via soil in tomato plants can trigger the ISR mechanism against root-knot nematodes (Table 1).

Giovanardi et al. [92] tested the transcriptomics approach to study the complex transcriptional changes promoted by HS in plant–pathogen interaction, especially in Xanthomonas arboricola pv. pruni (Xap)-peach tree. A cDNA–AFLP analysis of differential gene expression was performed in plant tissue treated with HA + AF. This cDNA–AFLP–dHPLC analysis allowed the collection of fourteen fragments derived from upregulated transcripts belonging to peach genes and supposedly involved in the defense response. The genes were activated 24 h after treatment, triggering the induced systemic resistance involved in maintaining a state of protection in plants against biotic stresses. Mengesha et al. [106] used CT to inhibit bacterial disease in potato caused by *Ralstonia solanacearum* and observed the induction of systemic resistance with an inhibition percentage of 67% with respect to control.

The induction of SAR in cultivated plants under organic matter application is very little reported. We did not find any study in the total set of data analyzed in this meta-analysis citing organic matter as an elicitor of SAR (Table 1). De Hita et al. [131] reported the increase of SA and JA in cucumber plants, 24 and 72 h after HA foliar application, respectively, indicating a possible effect on the activation of SA and JA signaling pathways as plant defense response. Based on the evidence found in literature, humified organic matter may be involved with RAS [17, 88, 119, 120, 131], but further studies are needed to prove it.

The role of humic substances

HS was the organic matter source that showed the greatest effectiveness (74.9%) in plants pest and disease control according to model proposed by Sukamto [133], and suggesting their potential role as biotic elicitors in stimulating defense pathways. Humic substances comprise humic and fulvic acids and consist of natural molecules of amphiphilic nature able to generate supramolecular assemblies in solution [134, 135]. HS are also widely recognized as biostimulants as they promote plant growth-related processes, enhance plant nutrient uptake and use efficiency, induce resistance and tolerance to abiotic stress, and improve the quality of crop-derived products when applied in small amounts. Specific research works relating their effects and their use as resistance elicitors in plants against biotic stress are scarce. HS can modify the plant metabolic profile, thus promoting greater resistance against pests and diseases [89, 136]. The studies of Afifi et al. [29] and Giovanardi et al. [92], evaluating defensive enzymes and resistance genes, concluded that HS can induce ISR in cucumber and peach plants (Table 1). The meta-analysis revealed that the highest efficacy (100%) among the studies analyzed using HS was reported for the application of HA in control root-knot infestation control in bananas. However, specific mechanisms by which HA may be involved has not been elucidated [111]. The effectiveness of HS may be related to a combination of their chemical composition, and the applied concentration. The use of HS in low concentrations in plants can promote changes in physiology, morphology, biochemistry and the expression of plant genes [16]. The greatest efficacies of HS (100%, 84% and 78%) were observed using lower concentrations (40; 150 and 1 mg L-1) in plants of banana, peach and cucumber, for the treatment of *Meloidogyne* spp., *Xanthomonas arbicola* and *Fusarium spp.*, respectively (Table 2). The concentration of HS is an important point to discuss, since the effectiveness in disease suppression should be addressed without interfering with the growth of the plants. At high concentration the HS can have phytotoxic effects, as reported by Bonanomi et al. [30]. However, Demir et al. [137], investigated the use of HA applied a concentration of 500 mg L-1 of HA to control root rot in tomato plants and obtained an efficacy of 67.2%.

The most reported forms of application in the analyzed studies were via substrate and via foliar application. De Hita et al. [131] observed that HS applied to both soil and

Table 2 Concentration and efficacy (%) of organic matter used for disease and pest control in different plants

Organic source	Concentration	Mean	SD	Efficiency (%)	SD
Vermicompost	20–500 g/kg	292.5	204.01	56.04	31.14
Compost	100–500 g/kg	366.7	230.94	69.94	22.89
Vermicompost tea	20–40 g/L	28.0	10.95	39.89	26.32
Compost tea	12.5–200 g/L	65.3	83.22	69.67	31.64
Humic substances	1–500 mg/L	141.7	208.57	74.89	20.39
Combinations	–	–	–	62.29	29.70
Others	30–80 g/kg	56.7	25.17	70.43	7.17

Efficacy is given by the formula proposed by Sumkato, 2003 = (Incidence of disease or pest in control—incidence in treatment/incidence in control) × 100

SD standard deviation

leaves promoted an increase in hormone levels in cucumber plants, such as cytokinins, IAA, JA and JA-Ile, the last being involved in ISR pathway.

Main factors that interfere with the suppressive role of organic matter

It is evident that there exist some factors strongly interfering with the potential role of organic matter in plant pests and diseases control. The origin of the organic material, the decomposition process and the pathogen under study are some important factors to be considered, in addition to the concentration used (139). The decomposition process continually modifies the chemistry of organic matter and the microbiome, thus affecting the disease-suppressing capacity of plants [37].

Bonanomi et al. [30] in their meta-analysis, reported that the decomposition of organic material had a significant effect in 73% of the studies analyzed. Further investigating the suppressive capacity of different organic materials at different stages of decomposition, they found that decomposition affected the suppression of Rhizoctonia solani in 92% out of 14 different types of organic materials used in the study, with consistent suppression of the pathogen reported only for humus [37].

Humus has a unique chemical composition, which in addition to being rich in organic nitrogen with a low C/N ratio, is also rich in aromatic compounds alongside with low content of di-O-alkyl C and O-alkyl C fractions related to easily accessible polysaccharides by microbials. Pathogens such as R. solani showed poor growth on lignin-rich materials and aromatic fractions, such as humus (140). However, an important aspect to be considered is the concentration to be used. Although humus was able to inhibit the growth of *R. Solani*, when applied at the same concentration to plants not inoculated with the pathogen, it caused phytotoxicity in the plants, indicating the importance of optimizing the application rate to combine plant growth promotion and disease suppression [37].

Termorshuizen et al. [132] investigated the suppression of 18 organic compounds of different origins in response to a variety of pathogens. From the tests performed in their study, 54% showed significant disease suppression and only 3.3% showed significant stimulation. It should be noted that no compound showed significant disease suppression against all pathogens, as well as those pathogens were not similarly affected by all compounds, thus evidencing the relationship of organic material and a specific pathogen.

Based on the results discussed so far, it is important to highlight the need for more investigations to refine the main interferences in the biotic control process and allow both disease suppression and plant growth stimulation.

Conclusions

Considering the works that met the inclusion criteria in this meta-analysis, the average effect of organic matter on control of plant diseases was higher (75%), while the effect on pest control was smaller (67%). The most used organic matter source was V but mainly in pest control. However, the most effective organic matter source was HS, which presented an efficiency of 74%, mainly in the control of nematode, fungal and bacterial diseases. The concentrations of HS used ranged from 1 mg L^{-1} to 500 mg L^{-1}. Soil application of HS reduced root-knot nematode infestation and foliar application decreased damage caused by bacterial diseases. A great variation in the effectiveness of different organic matter sources in controlling pests and diseases was observed, suggesting that it may be related to factors ranging from their origin, the molecular composition, the target causal agent and the crop. The meta-analysis identified two basic questions that need to be addressed: despite the high effectiveness found in the papers, rigorous studies on the mechanisms involved in the control are scarce. Another issue concerns the combined use of organic matter from different sources, applied simultaneously to the growing medium and leaves and in combination with pesticides (compatibility studies, that is, whether the continued use of pesticides can interfere with the effectiveness of organic material in the pest and disease control in plants). Pesticide-free agriculture is a noble goal and the use of organic matter can significantly contribute to achieving it.

Abbreviations

APX: Ascorbate peroxidase; CAT: Catalase; CC: Compost; cDNA–AFLP–dHPLC: CDNA–Amplified fragment length polymorphism–dHPLC; CT: Compost tea; ET: Ethylene; FA: Fulvic acids; FLS: Flavonol synthase; HA: Humic acids; HS: Humic substances; ISR: Induced systemic resistance; JA: Jasmonic acid; Mi1.2: RKN resistance gene; PAL: Phenylalanine ammonia lyase; POX: Peroxidase; PPO: Polyphenol oxidase; PRPs: Proteins related to pathogenesis; AMF: Arbuscular mycorrhizal fungi; qRT-PCR: Real-time quantitative polymerase chain reaction; SA: Salicylic acid; SAR: Systemic acquired resistance; SOD: Superoxide dismutase; TPC: Total polyphenol content; VC: Vermicompost; VCT: Vermicompost tea.

Acknowledgements
We would like to thank Prof. Ricardo Spaccini and Dr Hiarhi Monda for their very valuable comments and suggestions.

Author contributions

Luciano Pasqualoto Canellas was responsible by experimental idea and wrote the first version of manuscript. Rakiely Martins da Silva carried out the meta-analysis; All authors read and approved the final manuscript. All authors read and approved the final manuscript.

Funding
This work was supported by Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ) Cientista do Nosso Estado, Conselho Nacional de Desenvolvimento de Pesquisa e Tecnologia (CNPq). RMS has received a fellowship from CAPES.

Availability of data and materials

Not applicable.

Declarations

Ethics approval and consent to participate

This manuscript is an original paper and has not been published in other journals. The authors agreed to keep the copyright rule.

Consent for publication

The authors agreed to the publication of the manuscript in this journal.

Competing interests

The authors declare that they have no competing interests.

Received: 3 May 2022 Accepted: 4 September 2022

References

1. Power AG. Ecosystem services and agriculture: tradeoffs and synergies. Phil Trans R Soc Lond B Biol Sci. 2010;365(1554):2959–71. https://doi.org/10.1098/rstb.2010.0143.
2. Tilman D. Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices Proc. Natl Acad Sci. 1999;96:5995–6000. https://doi.org/10.1073/pnas.96.11.5995.
3. da Silva JN, Araujo TC, Ponciano NJ, Souza CLM. Diagnóstico do uso de agrotóxicos por tomaticultores do município de São José De Ubá. RJ Rev Bras Agrop Sus. 2020;10:45–50. https://doi.org/10.21206/rbas.v10i1.8579.
4. Buralli RJ. Health effects of environmental and occupational exposure to agricultural pesticides. Thesis, Faculdade de Saúde Pública da Universidade de São Paulo. 2020 doi:10.11606/T. 6. 2020. tde- 20022020- 082631.
5. Rusinamhodzi L. Challenges in maximizing benefits from ecosystem services and transforming food systems. In: Rusinamhodzi L, editor. The role of ecosystem services in sustainable food systems. Cambridge: Academic Press; 2020. p. 263–74. https://doi.org/10.1016/B978-0-12-816436-5.00013-5 (**ISBN 9780128164365**).
6. Sharma A, Kumar V, Shahzad B, et al. Worldwide pesticide usage and its impacts on ecosystem. SN Appl Sci. 2019;1:1446. https://doi.org/10.1007/s42452-019-1485-1.
7. Canellas LP, Olivares FL, Aguiar NO, Jones DL, Nebbioso A, Mazzei P, et al. Humic and fulvic acids as biostimulants in horticulture. Sci Hortic. 2015;196:15–27. https://doi.org/10.1016/j.scienta.2015.09.013.
8. Lamine C. Transition pathways towards a robust ecologization of agriculture and the need for system redesign. Cases from organic farming and IPM. J Rural Stud. 2011;27(2):209–19. https://doi.org/10.1016/j.jrurstud.2011.02.001.
9. FAO-GSOC. GlobalSymposium on Soil Organic Carbon Unlocking the Potential of Soil Organic Carbon 21–23 March FAO HD Rome Italy 2017; http://www.fao.org/documents/card/en/c/25eaf720-94e4-4f53-8f50-cdfc2487e1f8/. Acessado em 21 de novembro de 2021.
10. Nardi S, Pizzeghello D, Schiavon M, Ertani A. Plant biostimulants: physiological responses induced by protein hydro- lyzed-based products and humic substances in plant metabolism. Sci Agric. 2016;73:18–23. https://doi.org/10.1590/0103-9016-2015-0006.
11. Baldock JA, Nelson PN. Soil organic matter. In: Sumner ME, editor. Handbook of soil science. Boca Raton: CRC Press; 2000.
12. Diacono M, Montemurro F. Long-term effects of organic amendments on soil fertility. A Rev Agron Sustain Dev. 2010;30:401–22. https://doi.org/10.1051/agro/2009040.
13. Lal R. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. Land Degrad Dev. 2006;17:197–209. https://doi.org/10.1002/ldr.696.
14. Scotti R, Pane C, Spaccini R, Palese AM, Piccolo A, Celano G, Zaccardelli M. On-farm compost: a useful tool to improve soil quality under intensive farming systems. Appl Soil Ecol. 2016;107:13–23. https://doi.org/10.1016/j.apsoil.2016.05.004.
15. Wood SA. Soil microbial diversity and ecosystem functioning in smallholder African agroecosystems. C Univ Acad Commons. 2015. https://doi.org/10.7916/D8902335.
16. Canellas LP, Olivares FL. Physiological responses to humic substances as plant growth promoter. Chem Biol Technol Agric. 2014;1:1–11. https://doi.org/10.1186/2196-5641-1-3.
17. Canellas LP, Canellas NOA, Souza LE, Olivares FL, Piccolo A. Plant chemical priming by humic acids. Chemical and Biol Technol Agric. 2020;7(1):1–17. https://doi.org/10.1186/s40538-020-00178-4.
18. García AC, Tavares OCH, Balmori DM, dos Santos AV, Canellas LP, García-Mina JM, Louro Berbara RL. Structure-function relationship of vermicompost humic fractions for use in agriculture. J Soils Sediments. 2018;18:1365–75. https://doi.org/10.1007/s11368-016-1521-3.
19. Jannin L, Arkoun M, Ourry A, Laîné P, Goux D, Garnica M, Fuentes M, São Francisco S, Baigorri R, Cruz F. Microarray analysis of the effects of humic acid on the growth of *Brassica napus*: Envolvement of N, C and S metabolisms. To plant Solo. 2012;359:297–319. https://doi.org/10.1007/s11104-012-1191-x.
20. Nardi S, Pizzeghello D, Muscolo A, Vianello A. Physiological effects of humic substances in higher plants. Soil Biol Biochem. 2002;34:1527–37. https://doi.org/10.1016/s0045-6535(01)00160-6.
21. Nardi S, Carletti P, Pizzeghello D, Muscolo A. Biological activities of humic substances. In: Biophysico-Chemical Processes Involving Natural Nonliving Organic Matter in Environmental, 2009; chap 8, p 301–337.
22. Nardi S, Schiavon M, Francioso O. Chemical structure and biological activity of humic substances define their role as plant growth promoters. Molecules. 2021;26:2256. https://doi.org/10.3390/molecules26082256.
23. Olaetxea M, de Hita D, Garcia AC, Fuentesa M, Baigorri R, Mora V, Garnica M, Urrutia O, Erro J, Zamarreño AM, et al. Hypothetical framework integrating the main mechanisms involved in the promoting action of rhizospheric humic substances on plant root-and shoot growth. Appl Soil Ecol. 2018;123:521–37. https://doi.org/10.1016/j.apsoil.2017.06.007.
24. Rose MT, Patti AF, Little KR, Brown AL, Jackson WR, Cavagnaro TR. A meta-analysis and review of plant-growth response to humic substances: practical implications for agriculture. Adv Agron. 2014;124:37–89. https://doi.org/10.1016/B978-0-12-800138-7.00002-4.
25. Rouphael Y, Colla G. Synergistic biostimulatory action: designing the next generation of plant biostimulants for sustainable agriculture. Front Plant Sci. 2018;9:1655. https://doi.org/10.3389/fpls.2018.01655.

26. Trevisan S, Botton A, Vaccaro S, Vezzaro A, Quaggiotti S, Nardi S. Humic substances affect Arabidopsis physiology by altering the expression of genes involved in primary metabolism, growth and development. Environ Exp Bot. 2011;74:45–55. https://doi.org/10.1016/j.envexpbot.2011.04.017.
27. Yakhin OI, Lubyanov AA, Yakhin IA, Brown PH. Biostimulants in plant science: a global perspective. Front Plant Sci. 2017;7:2049. https://doi.org/10.3389/fpls.2016.02049.
28. Yatoo AM, Ali MN, Baba ZA, et al. Sustainable management of diseases and pests in crops by vermicompost and vermicompost tea. A Rev Agron Sustain Dev. 2021;41:7. https://doi.org/10.1007/s13593-020-00657-w.
29. Afifi MMI, Ismail AM, Kamel SM, Essa TA. Humic Substances: a powerful tool for controlling fusarium wilt disease and improving the growth of cucumber plants. J Plant Pathol. 2017;99:61–7. https://doi.org/10.4454/jpp.v99i1.3810.
30. Bonanomi G, Antignani V, Pane C, Scala F. Suppression of soil-borne fungal diseases with organic amendments. J Plant Pathol. 2007;89(3):311–24.
31. Loffredo E, Berloco M, Senesi N. The role of humic fractions from soil and compost in controlling the growth in vitro of phytopathogenic and antagonistic soil-borne fungi. Ecotoxicol Environ Saf. 2008;69:350–7. https://doi.org/10.1016/j.ecoenv.2007.11.005.
32. Jafary-Jahed M, Razmjou J, Nouri-Ganbalani G, Naseri B, Hassanpour M. Bottom-up effects of organic fertilizers on *plutella xylostella* with selected cruciferous crop plants. J Lepid Soc. 2020;74(1):7–17. https://doi.org/10.18473/lepi.74i1.a2.
33. Mottaghinia L, Hassanpour M, Razmjou J, Hosseini M, Chamani E. Functional Response of *Aphidoletes aphidimyza Rondani* (Diptera: *Cecidomyiidae*) to *Aphis gossypii Glover* (Hemiptera: *Aphididae*): effects of vermicompost and host plant cultivar. Neotrop Entomol. 2015. https://doi.org/10.1007/s13744-015-0343-0.
34. Simsek-Ersahin Y. The use of vermicompost products to control plant diseases and pests. In: Karaca A, editor. Biology of earthworms, soil biology. Berlin: Springer; 2011. p. 191–123. https://doi.org/10.1007/978-3-642-14636-7_12.
35. Zhang S, Raza W, Yang X, et al. Control of Fusarium wilt disease of cucumber plants with the application of a bioorganic fertilizer. Biol Fertil Soils. 2008;44:1073–80. https://doi.org/10.1007/s00374-008-0296-0.
36. Artavia S, Uribe L, Saborio F, Arauz LF, Castro L. Efecto de la aplicacion de abonos organicos em la supresion de Pythium myriotylum em plantas de tiquisque (*Xanthosana sagittifolium*). Agronomia Costarricense. 2010;34(1):17–29.
37. Bonanomi G, Zotti M, Idbella M, Di Silverio N, Carrino L, Cesarano G, et al. Decomposition and organic amendments chemistry explain contrasting effects on plant growth promotion and suppression of *Rhizoctonia solani* damping off. PLoS ONE. 2020;15(4):e0230925. https://doi.org/10.1371/journal.pone.0230925.
38. Postma J, Nijhuis EH. Pseudomonas chlororaphis and organic amendments controlling Pythium infection in tomato. Eur J Plant Pathol. 2019;154:91–107. https://doi.org/10.1007/s10658-019-01743-w.
39. Silva JM, Medeiros EV, Duda GP, Barros JÁ, Santos UJ. Fames and microbial activities involved in the suppression of cassava root by organic matter. Rev Caatinga. 2017;30(3):708–17. https://doi.org/10.1590/1983-21252017v30n319rc.
40. Cardoza YJ. Arabidopsis thaliana resistance to insects, mediated by an earthworm-produced organic soil amendment. Pest Manag Sci. 2010;67:233–8. https://doi.org/10.1002/ps.2059.
41. Han Y, Wang Y, Bi JL, et al. Constitutive and induced activities of defense-related enzymes in aphid-resistant and aphid-susceptible cultivars of wheat. J Chem Ecol. 2009;35(2):176–82. https://doi.org/10.1007/s10886-009-9589-5.
42. Zhang W, Hoitink HAJ, Dick WA. Compost-induce systemic acquired resistance in cucumber to pythium root rot and anthracnose. Phytopathology. 1996;86:1066–70. https://doi.org/10.1094/Phyto-86-1066.
43. Zhang W, Han DY, Dick WA, Davis KR, Hoitink HAJ. Compost and compost water extract-induced systemic acquired resistance in cucumber and arabidopsis. Phytopathology. 1998;88:450–5. https://doi.org/10.1094/PHYTO.1998.88.5.450.
44. Hartmann H, Adams HD, Anderegg WRL, Jansen S, Zeppel MJB. Research frontiers in drought-induced tree mortality: crossing scales and disciplines. New Phytol. 2015;205:965–9. https://doi.org/10.1111/nph.13246.
45. Hiddink GA, van Bruggen AHC, Termorshuizen AJ, Raaijmakers JM, Semonov AV. Effect of organic management of soils on suppressiveness to *Gaeumannomyces graminis* var tritici and its antagonist *Pseudomonas fluorescens*. Eur J Plant Pathol. 2005;113:417–35. https://doi.org/10.1007/s10658-005-5402-7.
46. Hossain MM, Sultana F, Islam S. Plant growth-promoting fungi (PGPF): phytostimulation and induced systemic resistance. In: Singh D, Singh H, Prabha R, editors. Plant-microbe interactions in agro-ecological perspectives, microbial interactions and agro-ecological impacts, vol. 2. Singapore: Springer; 2017. p. 135–91. https://doi.org/10.1007/978-981-10-6593-4.
47. Hossain MM, Sultana F. Application and mechanisms of plant growth promoting fungi (PGPF) for phytostimulation. In: Das SK, editor. Organic agriculture. London: IntechOpen; 2020. https://doi.org/10.5772/intechopen.92338.
48. Pankievicz VCS, do Amaral FP, Ané J-M, Stacey G. Diazotrophic bacteria and their mechanisms to interact and benefit cereals. MPMI. 2021;34:491–8. https://doi.org/10.1094/MPMI-11-20-0316-FI.
49. Mendes R, Kruijt M, de Bruijn I, Dekkers E, van der Voort M, Schneider JHM, Piceno YM, DeSantis TZ, Andersen GL, Bakker PAHM, Raaijmakers JM. Deciphering the rhizosphere microbiome for disease-suppressive bactéria. Science. 2011;332:1097–100. https://doi.org/10.1126/science.1203980.
50. Jones JDG, Dangl JL. The plant immune system. Nature. 2006;444:323–9. https://doi.org/10.1038/nature05286.
51. González-Hernández AI, Suárez-Fernández MB, Pérez-Sánchez R, Gómez-Sánchez MÁ, Morales-Corts MR. Compost tea induces growth and resistance against *Rhizoctonia solani* and *Phytophthora capsici* in Pepper. Agronomy 2021;11(4),781. https://doi.org/10.3390/AGRONOMY11040781
52. Palese AM, Pane C, Villecco D, Altieri G, Celano G. Effects of organic additives on chemical, microbiological and plant pathogen suppressive properties of aerated municipal waste compost teas. Appl Sci. 2021. https://doi.org/10.3390/app11167402.
53. Pane C, Spaccini R, Piccolo A, Scala F, Bonanomi G. Compost amendments enhance peat suppressiveness to *Pythium ultimum, Rhizoctonia solani* and *Sclerotinia minor* Biol. Control. 2011;56:115–24. https://doi.org/10.1016/j.biocontrol.2010.10.002.
54. Pane C, Spaccini R, Piccolo A, Celano G, Zaccardelli M. Disease suppressiveness of agricultural greenwaste composts as related to chemical and bio-based properties shaped by different on-farm composting methods Biol. Control. 2019. https://doi.org/10.1016/j.biocontrol.2019.104026.
55. da Silva APS, Olivares FL, Sudré CP, et al. Attenuations of bacterial spot disease *Xanthomonas euvesicatoria* on tomato plants treated with biostimulants. Chem Biol Technol Agric. 2021;8:42. https://doi.org/10.1186/s40538-021-00240-9.
56. Ratchaseema MTN, Kladsuwan L, Soulard L, et al. The role of salicylic acid and benzothiadiazole in decreasing phytoplasma titer of sugarcane white leaf disease. Sci Rep. 2021;11:1–9. https://doi.org/10.1038/s41598-021-94746-9.
57. Van Loon LC, Van Strien EA. The families of pathogenesis-related proteins, their activities, and comparative analysis of PR-1 type proteins. Physiol Mol Plant Pathol. 1999;55(2):85–97. https://doi.org/10.1006/pmpp.1999.0213.
58. Abdul Malik NA, Kumar IS, Nadarajah K. Elicitor and receptor molecules: orchestrators of plant defense and immunity. Int J Mol Sci. 2020;21(3):963. https://doi.org/10.3390/ijms21030963.
59. Mishra AK, Sharma K, Misra RS. Elicitor recognition, signal transduction and induced resistance in plants. J Plant Interact. 2012;7(2):95–120. https://doi.org/10.1080/17429145.2011.597517.
60. Robert-Seilaniantz A, Grant M, Jones JD. Hormone crosstalk in plant disease and defence: more than just jasmonate-salicylate antagonism. Annu Rev Phytopathol. 2011;49(1):317–43. https://doi.org/10.1146/annurev-phyto-073009-114447.
61. Durrant WE, Dong X. Systemic acquired resistance. Annu Rev Phytopathol. 2004;42:185–209. https://doi.org/10.1146/annurev.phyto.42.040803.140421.

62. Obanor FO, Walter M, Jones EE, et al. Eficácia de indutores de resistência adquirida sistêmica no manejo da mancha foliar da oliveira. Australas Plant Pathol. 2013;42:163–8. https://doi.org/10.1007/s13313-012-0186-7.
63. Van Loon LC, Bakker PAHM, Pieterse CMJ. Systemic resistance induced by rhizosphere bacteria. Annu Rev Phytopathol. 1998;36:453–83. https://doi.org/10.1146/annurev.phyto.36.1.453.
64. Verhagen BWM, Glazebrook J, Zhu T, Chang HS, van Loon LC, Pieterse CMJ. The Transcriptome of Rhizobacteria-induced systemic resistance in arabidopsis. Molr Plant-Microbe Interact. 2004;17:895–908. https://doi.org/10.1094/MPMI.2004.17.8.895.
65. Pieterse CMJ, Van Loon LC. Salicylic acid-independent plant defense pathways. Trends Plant Sci. 1999;4:52–8. https://doi.org/10.1016/S1360-1385(98)01364-8.
66. Chakraborty BN, Chakraborty U. Molecular detection of fungal pathogens and induction of phytoimmunity using bioinoculants. Indian Phytopathol. 2021;74:307–22. https://doi.org/10.1007/s42360-021-00351-1.
67. McCune BE, Mefford MJ. PC-ORD: Multivariate analysis of ecological data, versão 6.0 para windows. MjM software, Gleneden Beach, Oregon, EUA 2011.
68. Ewel JJ. Natural systems as models for the design of sustainable systems of land use. Agrofor Syst. 1999;45:1–21. https://doi.org/10.1023/A:1006219721151.
69. Jacquet F, Jeuffroy M-H, Jouan J, Le Cadre E, Litrico I, Malausa T, Reboud X, Huyghe C. Pesticide free agriculture as a new paradigm for research. Agron Sustain Dev. 2022;42:8. https://doi.org/10.1007/s13593-021-00742-8.
70. de Aquino AM, Canellas LP, da Silva APS, Canellas NO, da Lima SL, Olivares FL, Piccolo A, Spaccini R. Evaluation of molecular properties of humic acids from vermicompost by 13 C-CPMAS-NMR spectroscopy and thermochemolysis–GC–MS. J Anal Appl Pyrolysis. 2019;141:104634. https://doi.org/10.1016/j.jaap.2019.104634.
71. Martinez-Balmori D, Olivares FL, Spaccini R, Aguiar KP, Araújo MF, Aguiar NO, Guridi F, Canellas LP. Molecular characteristics of vermicompost and their relationship to preservation of inoculated nitrogen-fixing bacteria. J Anal Appl Pyrolysis. 2013;104:540–50. https://doi.org/10.1016/j.jaap.2013.05.015.
72. Pathma J, Sakthive N. Microbial diversity of vermicompost bacteria that exhibit useful agricultural traits and waste management potential. Springer plus. 2012;1:26. https://doi.org/10.1186/2193-1801-1-26.
73. Yatoo AM, et al. Vermicomposting: a green approach to recycling/organic waste management. In: Hakeem K, Bhat R, Qadri H, editors., et al., Bioremediation and biotechnology. Cham: Springer; 2020. https://doi.org/10.1007/978-3-030-35691-0_8.
74. Ravindran B, Wong JW, Selvam A, Sekaran G. Influence of microbial diversity and plant growth hormones in compost and vermicompost from fermented tannery waste. Bioresour Technol. 2018;217:200–4. https://doi.org/10.1016/j.biortech.2016.03.032.
75. Ksheem AM, Bennett JMCL, Antille DL, Raine SR. Towards a method for optimized extraction of soluble nutrients from fresh and composted chicken manures. Waste Manage. 2015;45:76–90. https://doi.org/10.1016/j.wasman.2015.02.011.
76. Riggle D. Compost teas in agriculture. Biocycle. 1996;37:65–7.
77. Islam MK, Yaseen T, Traversa A, Ben Kheder M, Brunetti G, Cocozza C. Effects of the main extraction parameters on chemical and microbial characteristics of compost tea. Waste Manage. 2016;52:62–8. https://doi.org/10.1016/j.wasman.2016.03.042.
78. Bess VH. Understanding compost tea. Biocycle. 2000;41(10):71–2.
79. Koné SB, Dionne A, Tweddell RJ, Antoun H, Avis TJ. Suppressive effect of non-aerated compost teas on foliar fungal pathogens of tomato. Biol Control. 2010;52(2):167–73. https://doi.org/10.1016/j.biocontrol.2009.10.018.
80. Sang MK, Kim KD. Biocontrol activity and primed systemic resistance by compost water extracts against anthracnoses of pepper and cucumber. Phytopathology. 2011;101:732–40. https://doi.org/10.1094/PHYTO-10-10-0287.
81. Al-Mughrabi KI, Bertheleme C, Livingston T, Burgoyne A, Poirier R, Vikram A. Aerobic compost tea, compost and a combination of both reduce the severity of common scab (*Streptomyces scabiei*) on potato tubers. J Plant Sci. 2008;3:168–75. https://doi.org/10.3923/jps.2008.168.175.
82. El-Masry MH, Khalil AI, Hassouna MS, Ibrahim HAH. In situ and in vitro suppressive effect of agricultural composts and their water extracts on some phytopathogenic fungi. World J Microbiol Biotechnol. 2002;18:551–8. https://doi.org/10.1023/A:1016302729218.
83. Canellas LP, Piccolo A, Dobbss LB, Spaccini R, Olivares FL, Zandonadi DB, et al. Chemical composition and bioactivity properties of size-fractions separated from a vermicompost humic acid. Chemosphere. 2010;78:457–66. https://doi.org/10.1016/j.chemosphere.2009.10.018.
84. Canellas LP, Dobbss LB, Oliveira AL, Chagas JG, Aguiar NO, Rumjanek NO, Novotny EH, Olivares FL, Spaccini R, Piccolo A. Chemical properties of humic matter as related to induction of plant lateral roots. Eur J Soil Sci. 2012;63:315–24.
85. García AC, Castro TAVT, Berbara RLL, Tavares OCH, Elias SS, Amaral Sobrinho NMB, Pereira MG, Zonta E. Revisão sobre a relação estrutura-função das substâncias húmicas e a sua regulação do metabolismo oxidativo em plantas. Rev Virtual Quim. 2019;11(3):754–70. https://doi.org/10.21577/1984-6835.20190055.
86. Lamar RT, Monda H, Sleighter R. Use of ore-derived humic acids with diverse chemistries to elucidate structure-activity relationships (SAR) of humic acids in plant phenotypic expression front. Plant Sci. 2021. https://doi.org/10.3389/fpls.2021.758424.
87. Savarese C, di Meo V, Cangemi S, et al. Bioactivity of two different humic materials and their combination on plants growth as a function of their molecular properties. Plant Soil. 2022. https://doi.org/10.1007/s11104-021-05267-3.
88. Pereira RV, Filgueiras CC, Dória J, Peñaflor MFGV, Willett DS. The effects of biostimulants on induced plant defense. Front Agron. 2021;3:630596. https://doi.org/10.3389/fagro.2021.630596.
89. Schiavon M, Pizzeghello D, Muscolo A, Vaccaro S, Francioso O, Nardi S. High molecular size humic substances enhance phenylpropanoid metabolism in maze (*Zea mays* L.). J Chem Ecol. 2010;36:662–9. https://doi.org/10.1007/s10886-010-9790-6.
90. Basco MJ, Bisen K, Keswani C, Singh HB. Biological management of Fusarium wilt of tomato using biofortified vermicompost. Mycosphere. 2017;8(3):467–83. https://doi.org/10.5943/mycosphere/8/3/8.
91. Canellas LP, da Silva S, Olk D, Olivares FE. Foliar application of plant growth-promoting bacteria and humic acid increases corn yield. J Agric Foods Environ. 2015;13:131–8.
92. Giovanardi D, Dallai D, Dondini L, Mantovani V, Stefani E. Elicitation of resistance to bacterial canker of stone fruits by humic and fulvic acids (glucohumates): a cDNA-AFLP-dHPLC approach. Sci Hortic. 2016;212:183–92. https://doi.org/10.1016/j.scienta.2016.09.048.
93. Dempsey DMA, Vlot AC, Wildermuth CM, Klessig FD. Salicylic acid biosynthesis and metabolism. The Arabidopsis Book. 2011;9:e0156. https://doi.org/10.1073/pnas.92.10.4076.
94. Vlot AC, Dempsey DMA, Klessig DF. Salicylic acid, a multifaceted hormone to combat disease. Annu Rev Phytopathol. 2009;47:177–206. https://doi.org/10.1146/annurev.phyto.050908.135202.
95. Li J, Sang H, Guo H, Popko JT, He L, White JC, Dhankher OP, Jung G, Xing B. Antifungal mechanisms of ZnO and Ag nanoparticles to Sclerotinia homoeocarpa. Nanotechnology. 2017;28(15):155101. https://doi.org/10.1088/1361-6528/aa61f3.
96. Marin-Menguiano M, Morenosanchez I, Barrales RR, Fernandezalvarez A, Ibeas JI. N-glycosylation of the protein disulfide isomerase Pdi1 ensures full Ustilago maydis virulence. PLoS Pathog. 2019;15:e1007687. https://doi.org/10.1371/journal.ppat.1007687.
97. Kosmidis C, Denning DW. Opportunistic and systemic fungi. In: Infectious diseases. Amsterdam: Elsevier; 2014. p. 1681–709. https://doi.org/10.1016/B978-0-7020-6285-8.00189-1.
98. Gonzalez M, Pujol M, Metraux JP, Gonzalez-Garcia V, Bolton MD, Borrás-Hidalgo O. Tobacco leaf spot and root rot caused by *Rhizoctonia solani* Kuhn. Mol Plant Pathol. 2011;12:209–16. https://doi.org/10.1111/j.1364-3703.2010.00664.x.
99. Michielse CB, Rep M. Pathogen profile update*: Fusarium oxysporum*. Mol Plant Pathol. 2009;10:311–24. https://doi.org/10.1111/j.1364-3703.2009.00538.x.
100. van West P, Appiah AA, Gow NAR. Advances in research on oomycete root pathogens. Physiol Mol Plant Pathol. 2003;62:99–113. https://doi.org/10.1016/S0885-5765(03)00044-4.

101. Töfoli JG, Domingues RJ. Alternarioses em hortaliças: sintomas, etiologia e manejo integrado. 2006; http://www.infobibos.com/Artigos/2006_3/alternarioses/Index.htm Acesso em: 12/12/2021Pel
102. Pelczar MJ, Kelman A, Shurtleff MC and Pelczar RM. Plant disease. Encyclopedia Britannica. 2021; https://www.britannica.com/science/plant-disease. Acessado em: 21 de dezembro de 2021.
103. Ding C, Shen Q, Zhang R, Chen W. Evaluation of rhizosphere bacteria and derived bio-organic fertilizers as potential biocontrol agents against bacterial wilt (*Ralstonia solanacearum*) of potato. Plant Soil. 2013;366:453–66. https://doi.org/10.1007/s11104-012-1425-y.
104. Jiang G, Wei Z, Xu J, Chen H, Zhang Y, She X, Macho AP, Ding W, Liao B. Bacterial wilt in China: history, current status, and future perspectives. Front Plant Sci. 2017;8:1549. https://doi.org/10.3389/fpls.2017.01549.
105. Choudhary DK, Nabi SU, Dar MS, Khan KA. *Ralstonia solanacearum*: a wide spread and global bacterial plant wilt pathogen. J Pharmacogn Phytother. 2018;7:85–90. https://doi.org/10.1111/mpp.12038.
106. Mengesha WK, Powell SM, Evans KJ, et al. Diverse microbial communities in non-aerated compost teas suppress bacterial wilt. World J Microbiol Biotechnol. 2017;33:49. https://doi.org/10.1007/s11274-017-2212-y.
107. Collange B, Navarrete M, Peyre G, Mateille T, Tchamitchian M. Root-knot nematode (*Meloidogyne*) management in vegetable crop production: The challenge of an agronomic system analysis. Crop Prot. 2011;30(10):1251–62. https://doi.org/10.1016/j.cropro.2011.04.016.
108. Abd-Elgawad MMM. Optimizing safe approaches to manage plant-parasitic nematodes. Plants. 2021;10(9):1911. https://doi.org/10.3390/plants10091911.
109. Akhtar M, Alam MM. Utilization of waste materials in nematode control: a review. Biores Technol. 1993;45:1–7. https://doi.org/10.1016/0960-8524(93)90134-W.
110. Widmer TL, Mitkowski NA, Abawi GS. Soil organic matter and management of plant parasitic nematodes. J Nematol. 2002;34(4):289–329.
111. Seenivasan, Senthilnathan. Effect of humic acid on Meloidogyne incognita (Kofoid & White) Chitwood infecting banana (Musa spp). Int J Pest Manag. 2017. https://doi.org/10.1080/09670874.2017.1344743.
112. Xiao Z, Liu M, Jiang L, Chen X, Griffiths BS, Li H, Hu F. Vermicompost increases defense against root-knot nematode (*Meloidogyne incognita*) in tomato plants. Appl Soil Ecol. 2016;105:177–86. https://doi.org/10.1016/j.apsoil.2016.04.003.
113. Arancon NQ, Edwards CA, Lee S, Byrne R. Effects of humic acids from vermicomposts on plant growth. Eur J Soil Biol. 2006;42:65–9. https://doi.org/10.1016/j.ejsobi.2006.06.004.
114. Arancon NQ, Edwards CA, Yardim EM, Oliver TJ, Byrne RJ, Keeney G. Suppression of two-spotted spider mite (*Tetranychus urticae*), mealy bug (*Pseudococcus* sp) and aphid (*Myzus persicae*) populations and damage by vermicompost. Crop Prot. 2007;26(1):29–39. https://doi.org/10.1016/j.cropro.2006.03.013.
115. Oka Y. Mechanisms of nematode suppression by organic soil amendments—a review. Appl Soil Ecol. 2010;44:101–15. https://doi.org/10.1016/j.apsoil.2009.11.003.
116. Mardani-Talaee M, Razmjou J, Nouri-Ganbalani G, et al. Impact of chemical, organic and bio-fertilizers application on bell pepper, capsicum annuum L. and biological parameters of *Myzus persicae* (Sulzer) (Hem.: Aphididae). Neotrop Entomol. 2017;46:578–86. https://doi.org/10.1007/s13744-017-0494-2.
117. Ojaghian MR, Wang L, Cui ZQ, Yang C, Zhongyun T, Xie GL. Antifungal and SAR potential of crude extracts derived from neem and ginger against storage carrot rot caused by *Sclerotinia sclerotiorum*. Ind Crops Prod. 2014;55(2):130–9. https://doi.org/10.1016/j.indcrop.2014.02.012.
118. Cordeiro FC, Santa-Catarina C, Silveira V, De Souza SR. Humic acid effecton catalase activity and the generation of reactive oxygen species in corn (Zea mays L.). Biosci Biotechnol Biochem. 2011;75:70–4. https://doi.org/10.1271/bbb.100553.
119. Aguiar NO, Medici LO, Olivares FL, Dobbss LB, Torres-Netto A, Silva SF, Novotny EH, Canellas LP. Metabolic profile and antioxidant responses during drought stress recovery in sugarcane treated with humic acids and endophytic diazotrophic bacteria. Ann Appl Biol. 2016;168:203–13. https://doi.org/10.1111/aab.12256.
120. García AC, Santos LA, de Souza ALG, Tavares OCH, Zonta E, Gomes ETM, García-Mina JM, Berbara RL. Vermicompost humic acids modulate the accumulation and metabolism of ROS in rice plants. J Plant Physiol. 2016;192:56–63. https://doi.org/10.1016/j.jplph.2016.01.008.
121. Yildiztekin M, Atum AL, Kaya C. Physiological effects of brown algae (*Ascophyllum nodosum*) and humic substances on plant growth, enzymatic activities of certain pepper plants grown under salt stress. Future Biology. 2018;69:325–35. https://doi.org/10.1556/018.68.2018.3.8.
122. Silva HAS, Romeiro RS, Macagnan D, Halfeld-Vieira BA, Pereira MCB, Mounteer A. Rhizobacterial induction of systemic resistance in tomato plants: non specific protection and increase enzyme activities. Biol Control. 2004;29(2):288–95. https://doi.org/10.1016/S1049-9644(03)00163-4.
123. Boava LP, Kuhn OJ, Pascholati SF, Di Piero RM, Furtado EL. Effect of biotic and abiotic inducers on the activities of chitinase and peroxidase and rust control caused by Puccinia psidii on Eucalyptus. Summa Phytopathol. 2010;36(2):168–72. https://doi.org/10.1590/S0100-54052010000200012.
124. Kurabachew H, Wydra K. Induction of systemic resistance and defense-related enzymes after elicitacion of resistance by rhizobacteria and silicone application against *Ralstonia solanacearum* in tomato (*Solanum lycopersicum*). Crop Prot. 2014;57:1–7. https://doi.org/10.1016/j.cropro.2013.10.021.
125. Khaled EE, Mohamed HHA, Enas MM, Mahran ME, Ahmed AA, Basma HA, Ibrahim M, Maha MA. Arbuscular mycorrhiza and environmentally biochemicals enhance the nutritional status of *Helianthus tuberosus* and induce its resistance against *Sclerotium rolfsii*. Ecotoxicol Environ Saf. 2019;196:1–12. https://doi.org/10.1016/j.ecoenv.2019.109783.
126. Akhter A, Hage-Ahmed K, Soja G, Steinkellner S. Potential of Fusarium wilt-inducing chlamydospores, in vitro behaviour in root exudates and physiology of tomato in biochar and compost amended soil. Plant Soil. 2016;406:425–40. https://doi.org/10.1007/s11104-016-2948-4.
127. Ismail N, Rosmana A, Sjam S, Ratnawati R. Shallot basal bulb rot management through integration of trichoderma asperellum, composted plant residues and natural mulch. J Pure Appl Microbiol. 2020;14(3):1779–88. https://doi.org/10.22207/JPAM.14.3.16.
128. Tao C, Li R, Xiong W, Shen Z, Liu S, Wang B, Ruan Y. Bio-organic fertilizers stimulate indigenous soil Pseudomonas populations to enhance plant disease suppression. Microbiome. 2020;8:137. https://doi.org/10.1186/s40168-020-00892-z.
129. Sahni S, Kumar S, Prasad BD. Integration of salicylic acid, vermicompost and bioagent for effective management of chickpea wilt disease. J Environ Biol. 2021;42:1274–80. https://doi.org/10.22438/jeb/42/5/MRN-1745.
130. Castro L, Flores L, Uribe L. Efecto del vermicompost y Quitina sobre el control de meloidogyne incognita en tomate a nivel de invernadero. Agron Costarric. 2011;35(2):21–32.
131. De Hita D, Fuentes M, Fernández V, Zamarreño AM, Olaetxea M, García-Mina JM. Discriminating the short-term action of root and foliar application of humic acids on plant growth: emerging role of jasmonic acid. Front Plant Sci. 2020;11:493. https://doi.org/10.3389/fpls.2020.00493.
132. Termorshuizen AJ, van Rijn E, van der Gaag DJ, Alabouvette C, Chen Y, Lagerlöf J, Malandrakis AA, Paplomatas EJ, Rämert B, Ryckeboer J, Steinberg C, Zmora-Nahum S. Suppressiveness of 18 composts against 7 pathosystems: Variability in pathogen response. Soil Biol Biochem. 2006;38(8):2461–2477. https://doi.org/10.1016/j.soilbio.2006.03.002.
133. Sukamto S. Pengendalian Secara Hayati Penyakit Busuk Buah Kakao com Jamur Antagonis *Trichoderma harzianum*. Prosiding Kongres Nasional XVII dan Semin Ilmiah PFI Bandung. 2003;6(9):134–7.
134. Gerzabek MH, Aquino AJA, Balboa YIE, Petrov D, Tunega DA. Contribution of molecular modeling to supramolecular structures in soil organic matter. J Plant Nutr Soil Sci. 2022;185:44–59. https://doi.org/10.1002/jpln.202100360.
135. Klučáková M. The effect of supramolecular humic acids on the diffusivity of metal ions in agarose hydrogel. Molecules. 2022;27(3):1019. https://doi.org/10.3390/molecules27031019.
136. Razmjou J, Mohammadi M, Hassanpour M. Effect of vermicompost and cucumber cultivar on population growth attributes of the melon aphid (hemiptera: *Aphididae*). J Econ Entomol. 2011;104:1379–83. https://doi.org/10.1603/EC10120.
137. Demir S, Şensoy S, Ocak E, Tüfenkçi S, Durak ED, Erdinç C, Ünsal H. Effects of arbuscular mycorrhizal fungus, humic acid, and whey on wilt disease caused by Verticillium dahliae Kleb. in three solanaceous crops. Turk J Agric For. 2015;39:300–9. https://doi.org/10.3906/TAR-1403-39.
138. Jaya A, Lautt BS, Antang EU, Supriati L, Dohong S. Effect of individual and combined application of Trichoderma sp. and vermicompost on the management of Sclerotium rolfsii and growth of chilli under peatlands agro-climatic conditions. J Exp Biol Agric Sci 2021;9(4):445–56.

139. Rasool M, Akhter A, Soja G, Haider MS. Role of biochar, compost and plant growth promoting rhizobacteria in the management of tomato early blight disease. Sci Rep. 2021;11(1):1–16.
140. Istifadah N, Firman AR, Desiana MF. Effectiveness of compost and microbial-enriched compost to supress powdery mildew and early blight diseases in tomato. J Anim Plan Sci. 2020;30(2):377–83.
141. Charoenrak P, Chamswarng C, Intanoo W, Keawprasert N. The effects of vermicompost mixed with tricorderma asperellum on the growth and pythium root the of lettuces. Int J GEOMATE. 2019;17(61):215–21.
142. Akinnuoye-Adelabu DB, Hatting J, de Villiers C, Terefe T, Bredenhand E. Effect of Redworm Extracts against Fusarium Root Rot during Wheat Seedling Emergence. Agronomy 2019;11(5):2610–18.
143. Jaiswal AK, Elad Y, Cytryn E, Graber ER, Frenkel O. Activating biochar by manipulating the bacterial and fungal microbiome through pre-conditioning. New Phytol 2018;219(1):363–77.
144. Zhao J, Liu J, Liang H, Huang J, Chen Z, Nie Y, Wang C, Wang Y. Manipulation of the rhizosphere microbial community through application of a new bioorganic fertilizer improves watermelon quality and health. PLosONE. 2018;2740:1–14.
145. Seddigh S, Kiani L. Evaluation of different types of compost tea to control rose powdery mildew (Sphaerotheca pannosa var. rosae). Int J Pest Manag. 2017;(64(2):178–84.
146. Hussain N, Abbasi T, Abbasi SA. Enhancement in the productivity of ladies finger (Abelmoschus esculentus) with concomitant pest control by the vermicompost of the weed salvinia (Salvinia molesta, Mitchell). Int J Recycl Organ Waste Agric. 2017;6(4):335–43.
147. Mohamadi P, Razmjou J, Naseri B, Hassanpour M. Population growth parameters of Tuta absoluta (Lepidoptera: Gelechiidae) on tomato plant using organic substrate and biofertilizers. J Insect Sci. 2017;17(2):1–7.
148. El-Mohamedy RSR, Shafeek MR, El-Samad EHA, Salama DM, Rizk FA. Field application of plant resistance inducers (PRIs) to control important root rot diseases and improvement growth and yield of green bean (Phaseolus vulgaris L.). Aust J Crop Sci. 2017;11(5): 496–505.
149. Blaya J, Marhuenda FC, Pascual JA, Ros M. Microbiota characterization of compost using omics approaches opens new perspectives for phytophthora root rot control. PLOS ONE. 2016;11:8.
150. Renco M, Kovacik P. Assessment of the nematicidal potential of vermicompost, vermicompost tea, and urea application on the potato-cyst nematodes Globodera rostochiensis and Globodera pallida. J Plant Prot Res. 2015;55(2):187–92.
151. Molina OI,Tenuta M, El Hadrami A, Buckley K, Cavers C, Daayf F. Potato early dying and yield responses to compost, green manures, seed meal and chemical treatments. Am J Potato Res. 2018;91(4):414–28.
152. Uribe-Loría L, Barquero LC, Cavallini FA, Henríquez CH, Meneses MB Effect of vermicompost on pepper plants inoculated with Phytophthora capsici. Soamericana. 2014;25(2)243–53.
153. Rostami M, Olia M, Arabi M. Evaluation of the effects of earthworm Eisenia fetida-based products on the pathogenicity of root-knot nematode (Meloidogyne javanica) infecting cucumber. Int J Recycl Organ Waste Agric. 2014;3(2):1–8.
154. Marín F, Diánez F, Santos M, Carretero F, Gea FJG, Castañeda C, Navarro MJ, Yau JA, Control of Phytophthora capsici and Phytophthora parasitica on pepper (Capsicum annuum L.) with compost teas from different sources, and their effects on plant growth promotion. Phytopathologia Mediterranea. 2014;53(2):216–28.
155. Marín F, Santos M, Diánez F, Carretero F, Gea FJ, Yau JA, Navarro MJ. Characters of compost teas from different sources and their suppressive effect on fungal phytopathogens. World J Microbiol Biotechnol 2013;29:1371–82.
156. Little AG, Cardoza YJ. Host plant effects on generalist and specialist lepidopterous cabbage pests modulated by organic soil amendment. Pedobiologia. 2011;54:353–59.
157. Dukare AS, Prasanna R, Dubey SC, Nain L, Chaudhary V, Singh R, Saxena AK. Evaluating novel microbe amended composts as biocontrol agents in tomato. Crop Protect. 2011;30(4):436–42.

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