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Review

Agricultural waste recycling in horticultural intensive farming systems by on-farm composting and compost-based tea application improves soil quality and plant health: A review under the perspective of a circular economy

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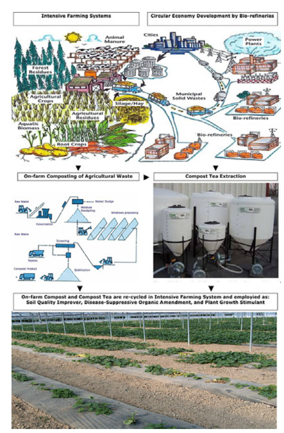
HIGHLIGHTS

- On-farm composting technology by using agricultural waste was described.
- Benefits on soil quality and plant health by use of compost/compost-based tea were given.
- Opportunities and barriers of on-farm composting in cropping systems were considered.
- Sustainability of the on-farm compost/compost tea supply chains was evoked.
- Innovation for on-farm composting and use of economic incentives were required.

GRAPHICAL ABSTRACT



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ABSTRACT

The vegetables supply chain of intensive farming systems has gained huge relevance due to environmental pollution, residual toxicity towards microorganisms and humans, development of plant pathogen resistance, biodiversity loss, and hazard to human health. Studies addressed to clean from misuse of plant fungicides, soil fumigants, and fertilizers have encouraged the search of eco-friendly alternatives. This paper aims to give deeper understand of new insights for on-farm composting and compost-based tea application for soil and plant through the virtuous reuse of agricultural waste. On-farm composting is viable option thanks to benefits on soil quality and plant health which valorize underused biomass. This paper critically discusses and compares the most promising technologies in order to recycle in situ residual biomass into high-value added products for soil amendment (compost) and plant treatment (compost-based tea). Compost contains minerals, heavy metals, humic substances, and endogenous microorganisms to improve soil quality. Compost application had many benefits against plant pathogens and diseases due to innovative tailored formulates. Compost can be employed either alone or in combination with exogenous microbial consortia (protists, fungi, oomycetes, yeast, actinomycetes, and bacteria) acting as biological control agents by fitting the agrochemical market requirements for improving soil quality and plant health. Liquid formulations made of crude compost-based teas and/or tailored mixtures of humic acids, fulvic acids, humin, macro-micronutrients, and endogenous microbiota have many benefits for plant growth

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and crop health. Nonetheless, the complex European regulations and national laws, manure surplus, variability in availability and transporting of compost, variability in compost quality and feedstock composition, greenhouse gas emissions, and energy requirement were very hard barriers for on-farm composting and compost derivatives application. Recommendations, novelties, innovations, sustainability, and directions of future researches that may help to solve a number of these issues under the new perspective of a circular economy system were presented and discussed.

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Contents

1. Introduction

Intensive cropping systems are performed through the consistent use of synthetic chemicals conflicting with the consumer's needs in order to reduce chemical inputs in agriculture and ensure the environmental sustainability of the vegetables supply chains which have gained greater relevance because they are the main agricultural sector where chemical inputs can cause environmental pollution, residual toxicity towards microorganisms and humans, development of plant pathogen resistance, biodiversity loss, and hazard to animal and human health (Ghorbani et al., 2008; Hirooka and Ishii, 2013; Sparks, 2013; Tupe et al., 2014). The growing public concerns for human health due to undesirable effects of the hazardous synthetic chemicals and massive use of mineral fertilizers have encouraged farmers to search safer and eco-friendly alternatives. In addition, frequent and hard soil tillage, short-cycle crop rotations, and continuous monoculture can cause a decrease of the soil organic matter (SOM) content, soil erosion (Sleutel et al., 2003, 2006), and greenhouse gas (GHG) emissions (Kirschenmann, 2010). Improving and maintaining soil quality and fertility over time is challenge for a modern agriculture based on the frequent use of organic inputs to soil (De Corato, 2020b).

Production of high-quality composts and their derivative products represents one possibility for exploiting richer and valuable sources of eco-friendly organic molecules and beneficial microorganisms sourced by agricultural waste and their co/by-products become available in intensive farming systems. Recycling biomass waste by composting process leads either rationalization and reduction of residual biomass or guarantee the supply of humified SOM, minerals, and beneficial microbial consortia associated to soil and plant of which crops needing to increase their nutrition state, vegetative vigour, health, and productivity. Currently, compost is commercially available either as conditioner to improve the physical structure and biological fertility of soil or as organic amendment to enhance the natural suppressiveness of soil against soil-borne plant pathogens (Albiach et al., 2000; Zaccardelli et al., 2011). Compost is a source of macro- micronutrients by reducing the need of mineral fertilizers; thus it can be seen as a profitable source of nutrients by replacing fertilizers, at least partly. Compost can be an excellent substitute of soil in the nursery peat-based potting mixed substrates for seedling growth in greenhouse (Zaccardelli et al., 2006). As a result, the share of industrial composting for municipal waste management has almost doubled from 9% in 2000 to 16% in 2016 (Eurostat, 2018). Nonetheless, composting in situ is still scarcely used in the farming systems as became across the US countries (Fig. 1) characterized by manure surplus, where the yard trimming composting sites represent about 70% if compared to the on-farm composting ones (8%). Compost can also be employed as bioremediation agent for recovering and cleaning marginal soils by heavy metals and organic pollutants contamination (Hickman and Reid, 2008). There are emerging technologies that use formulations made of microbial consortia, minerals, and organic compost-based compounds. Among them, the humic fractions extracted from compost

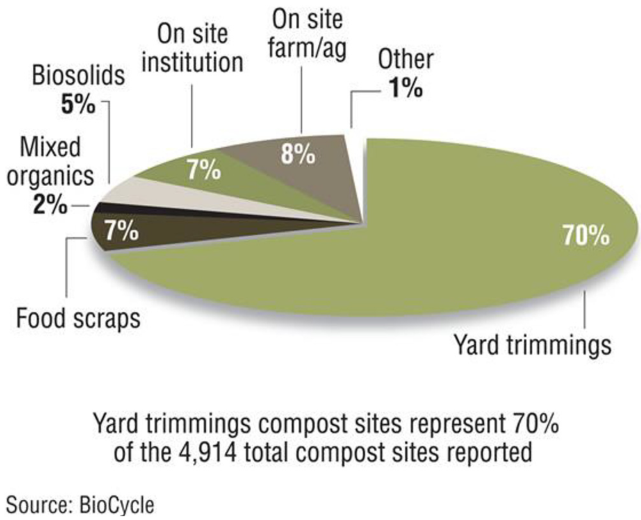

Fig. 1. Distribution of the composting sites in the US countries.
(Source: Reprinted by BioCycle.net).

should be employed either as crude compost teas (CTs) or as tailored mixtures of humic acids and fulvic acids including humus-like fraction (humin). Such soluble organic molecules and mineral nutrients, yet marketable in the phytosanitary market over the last decade, seemed to have direct/indirect effects on many metabolic processes of the plant thanks to their particular molecular structures (Ayuso et al., 1996; Diver and Greer, 2001; Eyheraguibel et al., 2008; Khaled and Fawy, 2011; Morard et al., 2011; Nardi et al., 2002). For example, the use of leachate recovered from piles during composting was proposed for its content in soluble nutrients, however such product needs sanitizing treatment before foliar applications (Diver, 2002).

A very relevant number of review works about the on-farm composting technology and compost-based formulates application have been published through the time overall under the technical point of view. This review work is mainly addressed to give and critically discuss the main benefits, opportunities, novelties, barriers, recommendations, and sustainability of on-farm composting by virtuous reuse in situ of agricultural wastes under the perspective of a circular economy approach. The aim is to provide deeper understanding of the research efforts related to composts and CTs application to soil/plant to improve sustainability (environmental, energetic, and economic) of the vegetables supply chain managed without use (or reduced use) of chemicals. After a brief introduction of the nature, origin, and spread of the agricultural waste produced in the farm (Par. 2.), this review is structured in the following main sections. The first one (Par. 3.) focused on the main characteristics, technologies, uses, and benefits related to on-farm composting in intensive horticultural cropping systems in relation to: (i) circular economy, (ii) soil quality, (iii) plant health, (iv) efficacy and barriers of tailored formulates made of on-farm composts combined with microbial biological control agents (BCAs) in controlling soil-borne pathogens, and (v) microbiome characterization of compost by omics approaches. Afterwards, the main characteristics, technologies, uses, and benefits related to production, formulation, and application of compost-based formulates (crude CTs, humic substances, and compost-derived fractions) in horticultural cropping systems in relation to its benefits on: (i) plant growth and (ii) plant health were provided and critically discussed in the second section (Par. 4.) under the light of the integrated disease management (IDM) frameworks. Feasibility of the on-farm composting and compost-based formulates application in terms of barriers, recommendations, novelties, innovations, and sustainability were given and discussed in the third sections (Par. 5). Concluding remarks and potential directions of future researches were drawn in the last section (Par. 6).

2. Agricultural waste

The agricultural activities generate a significant amount of biomass waste in the forms of animal manure and slurries; residual biomass from cultivated green residues, plant-wastes, non-marketable products and therefore unsold; agro-wastes coming from the crop cultivation fields and minimally-processed fruit and vegetable industries; food-waste and agro-industrial by/co-products from the olives, grapes, and milk processing (De Corato et al., 2018a; Esparza et al., 2020). In absence of alternative productive reuses, the unused or underused biomass must be disposed as a special waste according to the European Waste Code (EWC) with additional fee charges for farmer. Alternatively, in more European countries, green biomass is usually stocked in the farm and left to self-drying and self-decomposing outdoors with consequent environmental problems and disposal costs. Furthermore, the increasing amount of disposable biomass waste should be significantly reduced or even significantly avoided rather than wasted accordingly with a circular economy (bioeconomy) approach, especially those coming from the greenhouse cultivation and warehouse processing.

The oldest works since 2000s lead on how manure and slurries treatment has become a crucial issue for farmers in order to re-address their productive chains for increasing the arable lands requirement. Such recycling waste approach should be more properly considered within the nutrient management framework designed under local conditions and in consideration of the cultivable soils for end-users. In this context, the choice falling on individual or collective plants of different scale sizes for manure and slurries treatment should not be seen as the main objective, since such decision should result from previous studies and designs of the nutrient management planning for recycling manure surplus in plants of different sizes (Flotats et al., 2009).

The most recent researches focus instead on valorisation of fruit and vegetable wastes (FVW) as challenge to solve logistic-related problems, as well as to manage their perishability and heterogeneity in origin and composition (Esparza et al., 2020). FVW constitutes an important potential source for valuable natural products and chemicals that are depending on the intrinsic characteristics and composition of FVW by including, obviously, the existing market demand. The most relevant valorisation options are represented by extraction of a wide range of bioactive compounds (e.g., essential oils, flavours, terpenoids, etc.), production of enzymes (e.g., protease, lipase, invertase, peroxidase, cellulolytic, etc.) and exopolysaccharides, synthesis of bioplastics and biopolymers, and production of biofuels in integrated bio-refineries.

Recently, there are substantial advancements in managing agricultural biomass waste in situ through differentiated sorting of the food-waste and municipal-waste to separate the different organic fractions (green/brown, wet/dry, solid/liquid, etc.). Further reuses of biomass wastes in the local production cycles by landfilling, on-farm composting to produce composts and its own liquid derivatives (as CTs and mixtures of humic acids), and anaerobic digestion to produce biogas, biomethane, and digestate are become a new challenge. On-farm composting have more environmental benefits, from lower greenhouse gas emissions to lower leachate generation, when compared to landfilling and anaerobic digestion (De Corato et al., 2018a). On the other hand, green bio-based refineries (bio-refineries) based on the lignin-cellulosic and oleaginous feedstocks could determine an interesting change of perspective at global level by transforming greater amount of disposable agricultural biomasses into a wide range of high-value added co/by-products for many agriculture purposes (De Corato et al., 2018a). These two approaches, either local by on-farm composting or global by bio-based refineries, should be integrated among them in a given developing country under the perspective of a circular economy system (Graphical abstract).

3. Characteristics, uses, technologies, and benefits of on-farm composting and compost application

3.1. Concepts, definitions, and legislation

Compost can be defined as '*a matured and stabilized organic matter naturally enriched by hydrophobic carbonaceous molecule, called humic substances (HSs), that are traditionally distinguished in three sub-fractions: humic acids, fulvic acids and humin*' (Stevenson, 1994) which make it a recalcitrant biomass to further microbial degradation. Compost production is cogently regulated by guidelines, regalements, and national laws accordingly with the European guidelines (ISO/IEC 17025:2005), European legislation (Regalement UE No. 03/2003), and different laws among countries (Italian Decree Laws No. 217/2006 and 75/2010, and Spanish Decree Law No. 506/2013, for citing the most important legislation only).

Composting (or bio-composting) is a natural and ecologically sustainable biological process which thanks to action of endogenous microorganisms that colonize organic feedstocks allows transforming highly biodegradable organic compounds into stabilized organic matter. This bio-oxidative transformation in the solid phase, that is allowed only if the biomass is sufficiently oxygenated by arranging it into piles (or windrows) under forced air, is due to the complexity of the interactions between substrate and microbiota. The development of heat inside the core pile is the key point of the composting process (sanitization by pasteurization) that drives the following phases of them. The first phase, 'thermophilic', is characterized by an increase of temperature even above 60 °C up to 75–78 °C for at least 5–6 consecutive days. It allows sanitizing the whole biomass by eliminating/inactivating seeds and pathogenic microbial species for human, animal, and plant. The second phase, 'mesophilic', is characterized by a progressive slow-down of temperature that takes place when the most part of the carbon molecules are more easily attacked by microorganisms inside the windrow. The pile will be afterward undergo to last phase, 'curing' or 'maturation', by which stabilization and humification of the organic matter will be complete in longer time. Compost usually takes place for at least 90 days from the beginning of the process to have a perfectly marketable organic amendment for agricultural purposes.

3.2. On-farm composting technology and compost application

Composting is typically carried out in industrial or semi-industrial processing plants of small-medium-large size for processing overall organic fractions coming from the separate collection of urban or municipal organic solid waste (MSW) by adopting the most disparate oxygenation systems as turning mechanical in outdoor, forced ventilation in bioreactor, and air insufflation in chamber (Pergola et al., 2020; Zaccardelli et al., 2010). However, regarding the development of compost in organic agriculture, the 'cost factor' of transporting compost among countries and/or different farms of the same country has become a restrictive barrier under the light of the legislation that strongly limit the compost supply chain between different farms (Niladri et al., 2019). This seemingly insurmountable obstacle can be easily bypassed through the management in situ of agro-wastes based on the on-farm technologies, otherwise called 'on-farm composting', that are yet spreading in organic farming systems worldwide. Among safer and sustainable composting systems to produce high-quality compost in addition to the industrial ones, can be included the on-farm technologies that lead the best way for effectively reusing in situ agricultural wastes and related co/by-products (Scotti et al., 2016). Thanks to on-farm composting technology, the increasing amount of raw agricultural wastes (Zaccardelli et al., 2010) and refined co/by products derived from the biofuel chains (De Corato et al., 2015) can be both recycled into the farm, such solving the dual problem of biomass disposal and organic amendment application to improve soil quality and plant health. The desired goals and challenges can be achieved by adopting sustainable technology for recycling in situ agricultural wastes, agro-industrial residues, and related co/by-products allowing the players to self-supply of on-farm compost at lower cost than chemicals and mineral fertilizers (Scotti et al., 2016).

Authors described the on-farm composting technologies yet available by reporting the main results of their environmental, energy, and economic sustainability analysis comparing a set of five on-farm composting plants with different technologies and with different feedstocks (Pergola et al., 2018a). The authors concluded that on-farm technologies resulted to be a strategic toolbox for the sustainability of agricultural activities that may help to solve the disposal of crop residues and livestock wastes. The authors concluded that on-farm composting seemed to be the most sustainable solution under both economic and environmental point of view under different logistics and farming systems when compared to the outside agricultural waste disposal technologies.

3.2.1. Production system

On-farm composting needs of simple technologies than the industrial ones based on equipment already present in the farm or, alternatively, easily accessible to farmer using a very simple flow chart (Graphical abstract). The system that can be adopted depends on the quantity and type of biomass available, frequency of production, and equipment availability (Azim et al., 2017; Epelde et al., 2018). The most simple on-farm composting system is represented by the 'pile static' by which biomass once collected and stored in the farm do not will be marketable until curing phase will be complete. This system is suitable to well-structured biomass, likely lignocellulosic-based matter (i.e. wood, pruning waste, etc.) that, when mixed with cellulose-based material (i.e. herbaceous matter, plant-waste, etc.) and agro-industrial residues (i.e. spent coffee ground, vinery residues, olive mill, etc.) give sufficient porosity and structure to the pile allowing efficient air diffusion. Improvement of the on-farm technology is the 'pile upturning' performed by turning upward piles with an initial carbon/nitrogen (C/N) ratio, usually ranging from 27 to 32 and less than 6 m^3 volume (to avoid anoxic condition that could determine potential phytotoxic effects on the crop) by an impeller (usually at speed of 5 rev min^{-1} for 4 h every 12 h for many days, but depending on the biomass type), and then maintained at room temperature behind roofing. Indeed, the process length essentially depends on availability of company staff, machines, and tools to perform the composting process without wasting time. Finally, the 'static accumulation with forced ventilation' represents the most used technology that can be conveniently adopted for larger size on-farm systems (more than 5 ha) that produce relevant amount of agro-waste per month. In this case, mass periodic ventilation is obtained by a blower, activated by a timer, which diffuses 2–5 L min^{-1} air through perforated pipelines placed at the bottom of the windrow. Temperature was daily measured by a thermo-sensors placed in the core of the pile to check when the heating peak exceeds 60 °C for at least six consecutive days to achieve a better sanitization. A balanced mixture of material woody (as structuring source) and green-grassy material (as nutritional source) is needed to guarantee the most adequate porosity for allowing air diffusion and heat exchange among inside–outside windrow. The biomass decomposition profile measured by a carbon dioxide (CO_2) sensor is based on the fact that, at the ending of the process, the composted biomass loses its natural phytotoxicity, such acquiring higher microbiological, chemical and molecular maturation, and proper stability for ready-to-use high-quality composts. However, the choice of the most appropriate composting technology depends on farmer's evaluation of the feedstock volumes, matrix types and their supply places, and machinery/facilities already present in the farm (Pergola et al., 2018a).

Reviewing the main findings reported in the most recent literature, there are many parameters that must be carefully taken into account for start-up, monitoring, and control quality of the composting process (Azim et al., 2017). When we extrapolate the process from industrial plants into farming systems, optimization of the on-farm composting parameters becomes desirable challenge. For instance, the gas and moisture sensors use should to be used in larger composting consortia (from eight to twelve, at the least) because single farmers and small composters cannot afford the device and analytical cost for monitoring all stages of the process. Furthermore, the start-up parameters can be overviewed by using remote sensing in data logger that giving the C/N rates and moisture calculation in real time for optimization of the whole composting process. Afterwards, other analyses methods as the spectral infrared analysis can be adopted to assess the optimal maturity degree of the compost at the end of curing to avoid phytotoxic effects. Phytotoxicity test on cress still remains the best approach in vivo to calibrate what methods fit a range of composted organic waste. Accordingly with the literature reviewed by Azim et al. (2017), initial C/N ratio (25–30), initial moisture (50–60%) and oxygen (O_2) content in pore space (15%) are needed to begin an effective thermophilic phase. These parameters can be modified by accelerating or slowing the process by reversing the initial conditions as, for example, decreasing initial C/N and increasing initial O_2 content in pore space. Thus, on-farm composting is technically considered a very complex process able to turn wastes into resources that can be continuously adapted taking into account the cumulative costs, the nature of the wastes, and the environmental and energetic impacts (Pergola et al., 2018a).

3.2.2. Composition

Compost contains large amount of soluble organic matter deriving from the biological oxidative process by which biodegradable organic substances (sugars, proteins, lipids, etc.) are slowly transformed into more stable products (HSs) as humic acids, fulvic acids and humin for organic agriculture due to the positive effects on soil quality, plant growth, and plant health (Epelde et al., 2018). Besides HSs, compost also contains macronutrients (nitrogen, phosphorus, potassium), micronutrients (copper, zinc, iron, manganese), heavy metals (lead, cadmium, chromium), and microbial consortia (protists, fungi, oomycetes, yeast, actinomycetes, and bacteria).

Interestingly, regarding humin definition, is due to underline some recent concepts on this apparently underused fraction of the HSs. Traditionally, HSs were considered as the sum of humic acids, fulvic acids and humin, where humin is considered as a part of soil humus and, therefore, should be considered within the concept of HSs. Definitions of HSs comprising the notion of supramolecular associations of relatively small heterogeneous molecules surviving in soil under the abiotic and biotic degradation of vegetal and animal tissues were still taken into account. Within this concept, humic acids, fulvic acids and humin were included within the HSs group. However, nowadays, humin is suggested to be better described as a 'humic-containing material' rather than as a true 'humic substance'. In fact, authors have recently questioned on the concept of humin that should not be included within the HSs since it does not result be conform to the traditional definition of 'humic substance' within the complex soil humeome (Piccolo et al., 2019). The authors claimed that crude humin consists of an aggregate of humic and non-humic materials that does not satisfy the classical definitions because there are not still enough evidences to prove that the major components of humin have been microbiologically and/or chemically transformed, hence, humin does not belong to HSs.

3.2.3. Quality control

Opinion that on-farm green compost is 'low-quality compost' than the commercial one coming from the industrial plant that use MSW as feedstock, is currently perceived among the players and stakeholders (personal communications). Moreover, when using composted organic amendments of animal and/or human origin, the risk of contamination with hazardous organic and/or inorganic compounds, as well as the risk of dissemination of potential food-borne human pathogens and antibiotic resistance genes, must be carefully taken into account before to begin composting, according to the legislation.

Authors characterized in Spain a set of seven composted biomass types (vermicompost, bokashi, municipal solid waste, compost in pellet form, composted cow manure from intensive farms, composted cow manure from organic farms, and composted sheep manure from organic farms in organic farming) in order to evaluate the agro-environmental consequences of their utilization (Epelde et al., 2018). The authors evaluated the: (i) presence of chemicals and hazardous contaminants (metals, aromatics, halogenated hydrocarbons, pesticides, phthalates, and total petroleum hydrocarbons); (ii) food-borne pathogens (*Escherichia coli*, *Salmonella* spp.) and abundance of biological markers (integrase intl1 gene); (iii) physicochemical features (moisture, organic matter, nutrients, C/N ratio); and (iv) microbial characteristics (N-mineralizable, microbial biomass, bacterial and fungal abundance by omics approaches, and community-level physiological profiles (CLPP) by Biolog EcoPlates™). They concluded that: (i) composted organic sheep manure showed the highest content of organic matter, total N, and extractable humic acids; (ii) composted cow manure showed highest values of microbial activity (N-mineralizable) and biomass (microbial biomass, total bacteria), (iii) composting cow manure seemed to be suitable way for agricultural purposes on basis of the lowest content of potentially contaminants to human health and the highest quality, accordingly with the official amendment quality indices.

Others authors instead characterized in Italy a collection of on-farm green composts by using advanced analyses technologies to measure quality factors of the compost-amended soils (Scotti et al., 2016). These factors were determined by using the ^{13}C solid-state CPMAS-NMR spectroscopy to finely characterize the HSs fractions, and Biolog EcoPlates™ to measure the urease, phosphomonoesterase, β-glucosidase, and total hydrolytic activities of the resident microbiota in composts. The authors have demonstrated that amending the soil with such green composts can be displayed enhancements in terms of biological and biochemical activity, and low content of heavy metals and food-borne human pathogens with respect to the soil amended with a commercial MSW-based compost coming from urban industrial processing plants.

3.3. Benefits for the circular economy

Many co/by-products used in organic agriculture can be obtained by recycling agro-bioenergy waste in 'green biorefineries' (De Corato et al., 2015, 2018a). The authors classified the different agricultural tools for improving soil quality, plant health, and crop productivity into: (i) soil amendments (compost, biochar, oil-less seed cake/meal, and digestate), (ii) phytosanitary drugs (biofumigant, fungicide, and herbicide), (iii) plant biostimulant (CTs, seaweed extract, and brassino-steroid), and (iv) soil biofertilizer (oil-less seed cake/meal). Alternative options for on-farm recycling agro-bioenergy wastes (i.e. fermentation of sugary and lignocellulosic feedstocks to produce ethanol, transesterification of cooking oil and used fat to produce biodiesel, and anaerobic co-digestion of wet and green MSW with cow manure+household waste to produce biomethane, other gases, and digestate) seemed to be economically unviable and technically less convincing for farmer. The only exception should regard the largest size farms potentially able to recycle greater amount of residual biomass into compost, biogas, biomethane, and digestate at the same time by energy micro-cogeneration (both thermal and electrical) in small-medium integrated processing plants (Naik et al., 2010). However, the present work addresses its topic only on on-farm composts and CTs application as a better option to easily on-farm recycle agro-waste into sustainable products as valid substitutes, at least partly, of agrochemicals.

Compost can play a key role in the bioeconomy towards the best environmental sustainability of organic cropping systems by transforming agro-wastes into profitable resources. An excellent example is done by the diffusion worldwide of bio-degradable plastics made of starch-based polymeric composite material (Sartore et al., 2018). Although this concern has paid the attention of scientists on eco-friendly disposal methods of bio-polymers by on-farm composting (Spaccini et al., 2016), nonetheless deeper information on the effective transformation of the bio-film derivatives in a real on-farm composting facility are still poorly studied. The authors have investigated the decomposition profile pattern at molecular level of specific starch-based thermoplastic mulching films (bulk biomasses and bio-plastic composite) used for horticultural crops in a real on-farm composting system using ^{13}C-CPMAS-NMR spectroscopy and thermochemolysis-GC–MS spectrometry. This investigation confirmed the complete decomposition of starch components during composting process, such representing a powerful methodology to understand the molecular composition and modification of plastic bio-polymers during the whole composting process. Thus, new insights in order to promote the composting process as viable way to on-farm recycle the biodegradable polymeric films in further agricultural reuses were attempted.

3.4. Benefits for soil quality

Intensive horticultural cropping systems are characterized by frequent soil tillage, hard soil processing, monoculture systems, short-cycle crop rotation, and SOM loss that determine soil depletion. In greenhouse condition these agronomical practices are amplified due to higher soil temperature compatible with the acceleration of the mineralization process of the SOM. Indeed, SOM loss due to intensive agricultural activities and environmental factors leads inexorably towards soil fertility decline. Therefore, external inputs of organic matter by compost represent an agricultural practice that is not only recommended (Scotti et al., 2015), but strongly needed overall in the arid and semi-arid soils where SOM can be even below 1% (Costantini and Lorenzetti, 2013).

On-farm compost use is considered a better way to improve soil quality by evaluating the benefits and risks balance related to compost use overall under field condition (Alvarenga et al., 2017). Compost can be indeed virtuously used for recovering degraded soils, restoring soil fertility by C-sequestration, and reducing the use of chemical inputs and the negative environmental impacts. Compost can be additionally and successfully used in nurseries and green areas, recovery of waste dumps and gardening for landscape-environmental-hobby activities. Indeed, compost maintains and enhances fertility and productivity of soil by manipulation of soil microbiota in intensive farming systems by long-term effects (Pérez-Piqueres et al., 2006; Santos et al., 2011). Soil supplementation with compost represents one of the best agronomical practices for their benefits to soil plant disease suppressiveness (De Corato, 2020b). Input of composted organic matter plays a key role for maintaining fertility and productivity of agricultural systems to perform nutritional functions, but also to stimulate microbial activity, maintenance of soil structure, oxygenation, gaseous exchange, moisture retention, and buffer capacity (Zaccardelli et al., 2006). Studies demonstrated that compost supplementation provides macro- and micronutrients in soil (Duong et al., 2013; Evanylo et al., 2008; Gil et al., 2008), increases SOM stocks (Hemmat et al., 2010), improves soil structure (Celik et al., 2004) and water-holding capacity (Caravaca et al., 2002), prevents nutrient leaching (Grey and Henry, 1999), enhances crop yield (Zaccardelli et al., 2013), stimulates microbial activity and its biodiversity (Bulluck et al., 2002), and suppresses soil-borne pathogens (Borrero et al., 2013; De Corato, 2020a). Authors observed that soil microorganisms were more sensitive to compost addition in a dose-dependent manner (Araujo et al., 2015; García-Gil et al., 2000), while other studies showed that compost addition may have positive (Bernard et al., 2012; Zhen et al., 2014), neutral (Nair and Ngouajio, 2012), or even negative effects on soil biodiversity and biological activity (Martínez-Blanco et al., 2013).

Advancements on this topic were given by authors that produced in situ and tested a set of four green compost types using composted tomato-based residues in a real on-farm composting system (Table 1). Assessment of tomato-based composts was performed for their chemical, microbiological, and enzymatic properties including their effects on the compost-amended soil and compost-treated plant in a tomato cropping system (Pane et al., 2015). Compost characteristics affected both plant development and productivity through increased nutrient uptake and biological stimulation of metabolic functions. Soil biological activities included the basal respiration, fluorescein diacetate hydrolysis, β-glucosidase, dehydrogenase, alkaline phosphatase, arylsulphatase, and microbial community abundance that were differently affected by application of the composts. Changes in the SOM content and CLPP measured by ^{13}C-CPMAS-NMR spectroscopy and Biolog EcoPlates™, respectively, were related to the polysaccharides and lignin-derived compounds and nutrient content in composts. The potential fertility of the composts was positively correlated to the amount of tomato residues present in the feedstock from which each compost derived.

3.5. Benefits for plant health

Recent issues related to suppression of soil-borne plant diseases by disease suppressive compost (DSC) were interestingly seen by the farmers. Long-term application of DSC (for at least five consecutive years) enhances biodiversity and decreases abundance of plant pathogens by propagules load in soil (De Corato, 2020a; D'Hose et al., 2014). DSC can suppress plant diseases caused by soil-borne pathogens with the widest suppressive responses (Bonilla et al., 2012). Compost capacity to suppress plant diseases has been widely recognized, studied, and critically reviewed for their efficacy, benefits, and risks by many authors (Avilés et al., 2011; Bonanomi et al., 2007; Noble, 2011) where soil amendment by DSC has been proposed to biocontrol of *Pythium ultimum* and *Pythium irregulare* (Pascual et al., 2000; Scheuerell et al., 2005), *Phytophthora nicotianae* (Widmer et al., 1999), *Rhizoctonia solani* (Termorshuizen et al., 2006), *Fusarium oxysporum* (Cotxarrera et al., 2002), and *Verticillium dahliae* (Castãno and Avilés, 2013). Composts sourced from MSW have been tested for controlling *P. ultimum* on cucumber in comparison with on-farm green composts from tomato-waste (Fig. 2), *Fusarium oxysporum* f. sp. *basilici* on basil and *Sclerotinia sclerotiorum* on lettuce by selecting microbial antagonists from various sources of composted biomass (Pugliese et al., 2008). Composts from MSW and cow manure enhanced peat suppressiveness towards damping-off by *P. ultimum*, *R. solani* and *Sclerotinia minor* (Pane et al., 2011, 2013). Authors investigated the effects of a set of four on-farm composts derived from agricultural wastes (Table 1) on soil load of *V. dahliae* in two bell pepper systems (organic and conventional) (Tubeileh and Stephenson, 2020). All composts significantly suppressed pathogen populations two weeks later soil application using plant-based composts with greater effects than composted dairy and horse manure. But, the suppressive effect disappeared within eight weeks (for dairy and horse manure) and fourteen weeks (for green composts) after soil application.

Compost suppression is mainly related to antagonistic microbial community of the organic matter (Hadar and Papadopoulou, 2012; Manici et al., 2004), but also to its phytotoxicity level to cress (Aslam and Van der Gheynst, 2008). For these reasons, DSC belongs to a special compost category in order to improve sustainability of many horticultural organic cropping systems managed under the light of microbiome-assisted strategies in the absence of synthetic chemicals (De Corato, 2020b). The suppressive property of DSC can be explained through different anti-pathogen mechanisms exerted by some molecules or through direct antimicrobial actions triggered by the microbiota (De Corato, 2020a). Mechanisms explaining the variability of the suppressive effects are primarily associated with the biological activity of microbiota which interacts with the soil/plant system (Shi et al.,

Table 1
On-farm composts mostly studied in the last five years for their suppressive effects on soil-borne plant pathogens and diseases in relation to its microbiota structure characterized by next generation sequencing.

Plant disease	Target pathogen	Host plant	Disease-suppressive on-farm compost	Next generation sequencing	Reference
Fusarium wilt	*Fusarium oxysporum* f. sp. *lycopersici*	Tomato	-Green composted differentiated municipal solid organic wastes (green MSW) -Wet composted differentiated municipal solid organic wastes (wet MSW) -Composted cow manure and household waste -C1:17.5% tomato, 15.5% escarole residues, 65% woodchips -C2: 25% tomato residues, 13% escarole residues, 60% woodchips -C3: 37% tomato residues, 11% escarole residues, 50% woodchips -C4: 50% tomato residues,48% woodchips	-Amplicon sequencing of the bacterial 16S rDNA gene and the fungal ITS1 and ITS2 regions of the ITS rDNA gene. *Trichoderma* is identified by sequencing the ITS1-5.8S-ITS2 gene regions of the rDNA (De Corato et al., 2019).	De Corato et al. (2019) Pane et al. (2015)
	Fusarium oxysporum f. sp. *melonis*	Melon	-Composted green MSW and wet MSW -Composted cow manure and household waste	-Amplicon sequencing of the bacterial 16S rDNA gene and the fungal ITS1 and ITS2 regions of the ITS rDNA gene. *Trichoderma* is identified by sequencing the ITS1-5.8S-ITS2 gene regions of the rDNA.	De Corato et al. (2019)
	Fusarium oxysporum f. sp. *basilici*	Basil	-Composted green MSW and wet MSW -Composted cow manure and household waste		
Verticillium wilt	*Verticillium dahliae*	Eggplant	-Composted defatted olive marc and fennel green-waste -Composted un-defatted olive marc and artichoke green-waste -Composted spent coffee ground with green-wastes of celery and carrot -Composted spent tea bags with green-wastes of tomato and lettuce -Composted wood chips with green-wastes of tomato and escarole -Composted aspen chips with green-wastes of artichoke and fennel -Composted vineyard pruning wastes, vinery residues and wheat straw with green-wastes of potato and pepper	-Amplicon sequencing of the bacterial 16S rDNA gene and the fungal ITS1 and ITS2 regions of the ITS rDNA gene. *Trichoderma* is identified by sequencing the ITS1-5.8S-ITS2 gene regions of the rDNA.	De Corato et al. (2019)
			-Composted tomato-waste	-No available	Kanaan et al. (2017)
		Bell pepper	-Dairy and horse manure-based mixed compost -Grape pomace compost -Olive pomace-dairy manure mixed compost -Mixed crop residue compost	-No available	Tubeileh and Stephenson (2020)
		Cotton	-Composted olive mill	-No available	Avilés and Borrero (2017)
Rhizoctonia damping-off	*Rhizoctonia solani*	Bean	-Composted defatted olive marc and fennel green-waste -Composted un-defatted olive marc and artichoke green-waste -Composted spent coffee ground with green-wastes of celery and carrot -Composted spent tea bags with green-wastes of tomato and lettuce	-Amplicon sequencing of the bacterial 16S rDNA gene and the fungal ITS1 and ITS2 regions of the ITS rDNA gene. *Trichoderma* is identified by sequencing the ITS1-5.8S-ITS2 gene regions of the rDNA.	De Corato et al. (2019)
		Cress	-C1: leafy vegetables, fennel and woodchips -C2: maize, livestock waste and woodchips -C3: leafy vegetables, basil, tomato, watermelon and woodchips -C4: leafy vegetables, basil, watermelon and woodchips -C5: leafy vegetables, basil, pumpkin and woodchips -C6: leafy vegetables, basil and woodchips -C7: leafy vegetables, basil, watermelon and woodchips -C8: leafy vegetables, basil and woodchips -C9: leafy vegetables, basil and woodchips -C10: leafy vegetables, basil, pumpkin and woodchips -C11: leafy vegetables, artichoke and woodchips -C12: leafy vegetables, cabbage, walnut husk and woodchips -C13: leafy vegetables, basil, sorghum, tomato, pumpkin and woodchips	-Terminal restriction fragments length polymorphisms targeting the 16S rRNA gene for bacteria.	Pane et al. (2020)
		Lavender	-Green nursery compost from residues of pruning of woody plants and grass clippings from the nursery activities	-Amplicon sequencing the ITS1-5.8S-ITS2 region of the rDNA amplified with the universal primers ITS1 and ITS4.	Chilosi et al. (2017)

(continued on next page)

Table 1 (*continued*)

Plant disease	Target pathogen	Host plant	Disease-suppressive on-farm compost	Next generation sequencing	Reference
				For *Trichoderma*: amplification of the chitinase ech42 gene region with the primer pair Chit42-1a and Chit42-2a.	
Pythium damping-off	*Pythium ultimum*	Cucumber	-Composted defatted olive marc and fennel green-waste -Composted un-defatted olive marc and artichoke green-waste -Composted spent coffee ground with green-wastes of celery and carrot -Composted spent tea bags with green-wastes of tomato and lettuce	-Amplicon sequencing of the bacterial 16S rDNA gene and the fungal ITS1 and ITS2 regions of the ITS rDNA gene. *Trichoderma* is identified by sequencing the ITS1-5.8S-ITS2 gene regions of the rDNA.	De Corato et al. (2019)
	Pythium irregulare	Zucchini	-Composted defatted olive marc and fennel green-waste -Composted un-defatted olive marc and artichoke green-waste -Composted spent coffee ground with green-wastes of celery and carrot -Composted spent tea bag with green-wastes of tomato and lettuce		
Phytophthora damping-off/root rot	*Phytophthora nicotianae*	Tomato	-Composted defatted olive marc and fennel green-waste -Composted un-defatted olive marc and artichoke green-waste -Composted spent coffee ground with green-wastes of celery and carrot -Composted spent tea bags with green-wastes of tomato and lettuce		
		Pepper	-Vineyard pruning wastes with pepper sludge and pepper wastes -Vineyard pruning wastes with pepper waste and artichoke wastes -Vineyard pruning wastes with pepper sludge and pepper waste, garlic waste, carrot waste, and almond shells -Vineyard pruning wastes with compost, artichoke sludge and artichoke waste	-Amplicon sequencing of the bacterial 16S rRNA gene and the fungal ITS1 and ITS2 regions of the ITS rRNA gene using Ion Torrent PGM sequencing.	Blaya et al. (2016)
		Lavender	-Green nursery compost from residues of pruning of woody plants and grass clippings during the nursery activities	-Amplicon sequencing the ITS1–5.8S-ITS2 region of the rDNA amplified with the universal primers ITS1 and ITS4. For *Trichoderma*: amplification of the chitinase ech42 gene region with the primer pair Chit42-1a and Chit42-2a.	Chilosi et al. (2017)
	Phytophthora cinnamomi	Azalea	-Composted defatted olive marc and fennel green-waste -Composted un-defatted olive marc and artichoke green-waste -Composted spent coffee ground with green-wastes of celery and carrot -Composted spent tea bags with green-wastes of tomato and lettuce	-Amplicon sequencing of the bacterial 16S rDNA gene and the fungal ITS1 and ITS2 regions of the ITS rDNA gene. *Trichoderma* is identified by sequencing the ITS1-5.8S-ITS2 gene regions of the rDNA.	De Corato et al. (2019)
Sclerotinia root rot	*Sclerotinia sclerotiorum*	Lavender	Green nursery compost from residues of pruning of woody plants and grass clippings from the nursery activities	-Amplicon sequencing of the ITS1-5.8S-ITS2 gene region of the rDNA amplified with the universal primers ITS1 and ITS4. For *Trichoderma*: amplification of the chitinase ech42 gene region with the primer pair Chit42-1a and Chit42-2a.	Chilosi et al. (2017)
		'Iceberg' Lettuce	-Composted agro-industrial residues of spent coffee ground, defatted olive marc and woodchips; -Composted green-wastes of artichoke, fennel and tomato mixed with agro-bioenergy liquid wastes derived from the steam explosion process of lignocellulosic biomass for producing 2nd-generation bioethanol	-Amplicon sequencing of the ITS1 and ITS2 gene regions adjacent to 5.8 S rDNA gene for fungi *Aspergillus*, *Penicillium* and *Trichoderma*.	De Corato et al. (2016)
	Sclerotinia minor	Cress	-C1: leafy vegetables, fennel and woodchips -C2: maize, livestock waste and woodchips -C3: leafy vegetables, basil, tomato, watermelon and woodchips -C4: leafy vegetables, basil, watermelon and woodchips -C5: leafy vegetables, basil, pumpkin and woodchips -C6: leafy vegetables, basil and woodchips -C7: leafy vegetables, basil, watermelon and woodchips -C8: leafy vegetables, basil and woodchips -C9: leafy vegetables, basil and woodchips	-Terminal restriction fragments length polymorphisms targeting the 16S rRNA gene for bacteria.	Pane et al. (2020)

Table 1 (*continued*)

Plant disease	Target pathogen	Host plant	Disease-suppressive on-farm compost	Next generation sequencing	Reference
			-C10: leafy vegetables, basil, pumpkin and woodchips -C11: leafy vegetables, artichoke and woodchips -C12: leafy vegetables, cabbage, walnut husk and woodchips -C13: leafy vegetables, basil, sorghum, tomato, pumpkin and woodchips		

2017). Several models of action have been studied: (i) increased microbial activity and release of mineral nutrients during organic matter decomposition (Melero et al., 2006), (ii) activation of competition for nutrients (Noble and Coventry, 2005), (iii) elicitation of microbiostasis and hyperparasitism (Hoitink et al., 1993), (iv) release of diffusible antibiotic-like compounds (Weller et al., 2002), and (v) activation of systemic disease-resistance mechanisms in the host plant (Bulluck et al., 2002) where the protection exercised by compost-amended soils can be extended to the aerial part through induced resistance mechanisms and improvement of the general condition for plant. Evidence suggests that compost capability to suppress plant pathogens depends on the complex relationships among beneficial microbes, pathogens, and physicochemical properties of the composts (Hadar and Papadopoulou, 2012) that induce diversified suppressive actions. Such mechanisms were traditionally grouped in 'general mechanisms' (Berendsen et al., 2012; Cha et al., 2016) and 'specific mechanisms' (Termorshuizen et al., 2006; Termorshuizen and Jeger, 2008).

Suppression makes DSC one of the most suitable tools for biological control of multiple soil-borne pathogens (De Corato et al., 2018a). In this regard, can be reported recent findings based on compost use in suppressing plant pathogenic fungi, oomycetes, and bacteria. Indeed, application of DSC into conductive soils and potting media in appropriate rates to avoid phytotoxic effects on the crops, is consolidated suitable strategy for effectively controlling many soil-borne pathogens in organic cropping systems (Angelopoulou et al., 2014; Avilés et al., 2011; Chilosi et al., 2017; Kefalogianni et al., 2017). Nonetheless, inability to totally control a wide range of soil-borne diseases by urban/municipal solid waste compost has recently prompted the exploration and evaluation of new green feedstocks made of agro-wastes and agro-industrial co/by-products for making tailored multi-suppressive on-farm composts as an effective mean for controlling a range of soil-borne phytopathogens under greenhouse condition (De Corato et al., 2018c).

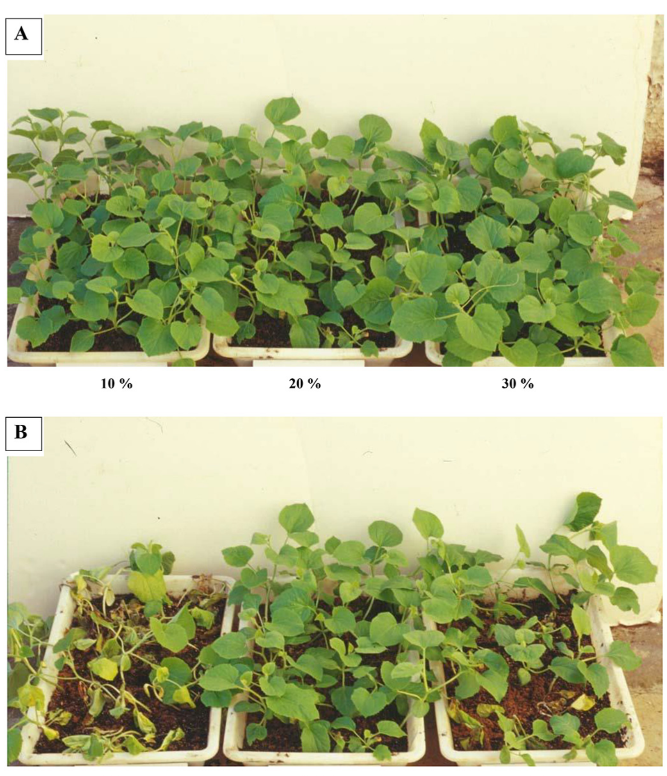

Fig. 2. Suppressive effect on cucumber Pythium damping-off of compost-amended potting soil artificially infested with the oomycete *Pythium ultimum*. (A) soil amended with 10, 20 and 30% (w/w) on-farm compost from tomato-waste, (B) soil amended with 10, 20 and 30% commercial compost from municipal organic solid waste (Picture of the author).

3.6. Combining on-farm compost and soil amendment with biocontrol agents

A special attention should be done on the combined use of on-farm compost with BCAs on the basis of compost capability to serve as carrier for BCAs in controlling soil-borne diseases. Although more findings that use selected fungal and/or bacterial strains (Castãno et al., 2013; Pugliese et al., 2008; Trillas et al., 2006) in combination with on-farm composts and no composted organic amendments were extensively explored by scientists (Ruano-Rosa and Mercado-Blanco, 2015), this strategy has not still been sufficiently applied in the agricultural practice. Several composted biomass types are known as efficient carriers for biocontrol-based microbiota (Table 2). In this regards, authors proposed the better use of BCAs-based microorganisms grown in the same ecological niches where they will be applied (Ruano-Rosa and López-Herrera, 2009) or combining BCAs into microbial consortia showing complementary mechanisms of action against more pathogens (Lugtenberg and Kamilova, 2009; Tailor and Joshi, 2014; Xu et al., 2011). Authors reported that *Trichoderma harzianum*-based formulates applied in seed treatments combined with neem cake soil application were effective against *Fusarium solani* f. sp. *melongenae* in eggplant by reducing the abundance of pathogen propagules (Bhadauria et al., 2012; Blaya et al., 2013). Authors tested different composted and uncomposted green wastes and animal wastes (farmyard manure, leaf compost, poultry manure, press mud, vermicompost, and neem cake) in combination with a *Pseudomonas fluorescens* strain from tomato rhizosphere for controlling tomato damping-off by *Pythium aphanidermatum*. These results can be explained by multiple antimicrobial actions related to competition for nutrients (iron and carbon) and space, production of antibiotics-like compounds, and overall increased microbial biomass that compete with the pathogen growth (Jayaraj et al., 2007). Authors observed a better suppression of the bacterial pathogen *Ralstonia solanacearum* in tobacco during pot experiments when a formulate containing two BCAs was applied in combination with compost (Liu et al., 2013). Compost+BCA application provides additional benefits due to slower release of nutrients more than compost alone with similar dynamics, or even better, if compared to synthetic fertilizers (Ding et al., 2013). The cogent substitution of plant synthetic fungicides and soil fumigants (as methyl bromide) since 2000s with compost/BCA-based formulates in sustainable agroecosystems seemed to be more practicable for cleaning the vegetables supply chain by considering the additional benefits achieved by combining compost with BCAs. Indeed, compost serves as the best organic carrier of BCAs for

Table 2
Combinations among compost/soil amendment and biological control agent for controlling soil-borne plant pathogens and related diseases.

Compost/soil amendment	Biocontrol agent	Target pathogen	Disease/host plant	Reference
-Wheat bran, peat moss	*Trichoderma harzianum*	*Sclerotium cepivorum*	-White rot/Allium	Avila Miranda et al. (2006)
-Vermicompost, neem cake	*T. harzianum*	*Fusarium solani* f. sp. *melongeneae*	-Fusarium wilt/Eggplant	Bhadauria et al. (2012)
-Vineyard pruning waste	*T. harzianum*	*Fusarium oxysporum* f. sp. *melonis*	-Fusarium wilt/Melon	Blaya et al. (2013)
-Cow dung	*T. harzianum*	*F. oxysporum, Sclerotium rolfsii*	-Foot rot/Lentil	Hannan et al. (2012)
-Green compost from pig manure, rice straw, alcohol, vinegar	*T. harzianum* SQR-T037	*Fusarium oxysporum* f. sp. *cucumerinum*	-Fusarium wilt/Cucumber	Yang et al. (2011)
-Fresh chicken manure	*Trichoderma asperellum, Trichoderma atroviride*	*Macrophomina phaseolina*	-Charcoal rot/Strawberry	Domínguez et al. (2014)
-Farm yard manure and poultry manure	*Trichoderma viride*	*Pythium* sp., *Rhizoctonia solani*, *Phytophthora* sp., *Fusarium* sp.	-Damping-off/Tomato	Joshi et al. (2009)
-Green compost from cork, grape, olive marc, and spent mushroom	*T. asperellum*	*R. solani*	-Damping-off/Cucumber	Trillas et al. (2006)
-Espresso spent coffee ground	*T. atroviride, Trichoderma citrinoviride, Aspergillus* sp.	*Sclerotinia sclerotiorum, Phytophthora nicotianae*	-Damping-off/Cress	Chilosi et al. (2020)
-Composted sawdust, potato waste, and rice straw	*T. harzianum, Penicillium oxalicum, Chaetomium globosum*	*F. oxysporum*	-Fusarium wilt/Legumes	Haggag and Saber (2000)
-Compost from pig manure, canola cake	*Bacillus subtilis* SQR 9	*F. oxysporum* f. sp. *cucumerinum*	-Fusarium wilt/Cucumber	Cao et al. (2011)
-Amino acid fertilizer from rapeseed meal fermentation, and compost from pig manure	*B. subtilis*	*Verticillium dahliae*	-Verticillium wilt/Cotton	Lang et al. (2012)
-Amino acid fertilizer from rapeseed meal	*Bacillus pumilus* SQR-N43	*R. solani*	-Damping-off/Cucumber	Huang et al. (2012)
-Compost from pig manure, canola cake	*Bacillus amyloliquefaciens* W19	*Fusarium oxysporum* f. sp. *cubense*	-Fusarium wilt/Banana	Wang et al. (2013)
-Pig manure, rice straw	*B. amyloliquefaciens*	*Ralstonia solanacearum*	-Bacterial wilt/Tomato	Wei et al. (2011)
-Farm yard manure, compost, poultry manure, press mud, vermicompost, and neem cake	*Pseudomonas fluorescens*	*Pythium aphanidermatum*	-Damping off/Tomato	Jayaraj et al. (2007)
-Neem cake, farm yard manure, and micronutrient	*T. viride, P. fluorescens, B. subtilis*	*Lasiodiplodia theobromae*	-Physic nut collar and root rot	Latha et al. (2011)
-Mustard oil cake	*P. fluorescens, Glomus sinuosum, Gigaspora albida,*	*R. solani*	-Root rot/Bean	Neeraj Singh (2011)
-Olive mill waste	*B. amyloliquefaciens, Burkholderia cepacia*	*V. dahliae*	-Verticillium wilt/Olive	Vitullo et al. (2013)
-Compost from pig manure, canola cake	*T. harzianum, Paenibacillus polymyxa*	*Fusarium oxysporum* f. sp. *niveum*	-Fusarium wilt/Watermelon	Wu et al. (2009)
-Commercial organic fertilizer made of compost from pig manure, canola cake	*P. polymyxa, B. subtilis, Penicillium* spp., *Aspergillus* spp.	*F. oxysporum* f. sp. *melonis*	-Fusarium wilt/Melon	Zhao et al. (2011)

bio-fortified formulates (De Ceuster and Hoitink, 1999). Interestingly, on-farm composted espresso spent coffee ground from the Autogrill coffee shop along the highway is a high-value organic waste used as soil amendment in horticultural potting mixes with a 10% (w/w) peat substitution rate in suppressing damping-off of cress by *S. sclerotiorum* and *P. nicotianae* in greenhouse. These results can be explained by multiple antagonistic effects related to bioactivity of antimicrobial compounds, toxic volatiles, and non-volatile metabolites produced by fungal BCAs belonging to *Trichoderma atroviride*, *Trichoderma citrinoviride*, and *Aspergillus* sp. (Chilosi et al., 2020).

The choice of the most suitable compost+BCA combinations is important when developing BCA-based formulations. Nonetheless, more studies on the addition of BCAs in order to produce fortified composts for seed/root treatment showed that microorganisms do not last long in the rhizosphere, but only lasting for some weeks, at least. Indeed, seems a general statement among scientists and farmers that the effective control of disease by BCAs is very difficult to achieve by short-time application strategies. The two main open questions that should be carefully taken into account are: (i) Do can any strategies be used to preserve relevant BCAs groups in the rhizosphere for longer time when artificially added in multiple times? (ii) Do can the protective effect against soil diseases to persist for months or even years without further amendments? These two questions have risen promising results that can be expected within the IDM frameworks.

3.7. Microbiome characterization by next generation sequencing

Next generation sequencing carried out on a set of seven on-farm composts from agro-wastes and agro-industrial co/byproducts (Table 1) by amplicon high-throughput sequencing (HTS) targeting the 16S rRNA gene (for bacteria and other prokarya) and the internal transcriber space 1 (ITS1) gene region (for fungi) or, alternatively, the 18S rRNA gene (for eukarya), showed the most varied microbiomes identified at specie level (De Corato et al., 2019). The authors found that the microbiome patterns were highly diversified in relation to the composted feedstock and strictly related to suppression of Rhizoctonia damping-off of bean by *R. solani*, Verticillium wilt of eggplant by *V. dahliae*, Pythium damping-off of cucumber by *P. ultimum*, and Phytophthora root rot of tomato by *P. nicotianae*. On the other hand, a set of three on-farm composted MSW and co-composted cow manure with household waste (Table 1) given instead the most specific microbiome pattern related to suppression of a restrict group of pathogens as Fusarium wilt of melon, tomato and basil by *Fusarium oxysporum* f. spp. *melonis*, *tomato* and *basilici*, respectively (De Corato et al., 2019). Others authors evaluated the microbial structure of a set of four disease-suppressive on-farm composts by recycling vineyard pruning–pepper-based wastes (Table 1). Composts showed different suppressiveness degrees to Phytophthora root rot of pepper by *P. nicotianae* using HTS by the Ion Torrent sequencing PGM platform Blaya et al.

(2016, 2016). Although microbiota of these disease- suppressive green composts was identified at genus level, at the most, the findings of Blaya et al. (2016, 2016) showed however higher positive correlations with the suppression attributes than MSW-based composts according to the findings of De Corato et al. (2019). Others authors studied the microbiomes abundance and taxonomic composition, alpha- beta-diversity, and variability of a set of thirteen on-farm green composts (Table 1). These microbiome variables were chosen as suitable biological indicators related to control of *R. solani* and *S. minor* against damping-off of cress and determined by terminal-restriction fragments length polymorphisms (T-RFLPs) targeting the 16S rRNA gene for bacterial community characterization (Pane et al., 2020). These authors have confirmed the findings of Blaya et al. (2016, 2016) and De Corato et al. (2019) concluding that the beta-diversity of the bacterial community allowed to separate a lot of composts in distinct functionally meaningful clusters by concluding that disease suppression could be driven by restricted microbiota groups in determining the most important mechanism.

Other recent study combined instead different techniques, both molecular and biochemical, to characterize two on-farm agricultural green waste-based suppressive composts using both omics (amplicon HTS by Illumina MiSeq platform) and classic approaches (Biolog EcoPlates™) for giving a unique overview on the microbial communities, in terms of both taxonomic structure and physiological roles, in explaining the disease suppressiveness and plant biostimulation on basis of the wide complexity of the microbiota (Scotti et al., 2020). The authors suggested a potential role for *Nocardiopsis* and *Pseudomonas* genera in suppressing damping-off of cress against *R. solani* and *S. minor*, while *Flavobacterium* and *Streptomyces* genera seemed to be potentially involved in plant biostimulation.

Two recent revision works carried out by De Corato (2020b) and Vida et al. (2020) have lead on how compost microbiota plays a key role in suppressing soil-borne plant pathogens by manipulating the natural soil suppressiveness. Soil microbiome disturbance by DSC application triggers specific perturbation to change and shape the soil microbial communities network for increasing suppression against phytopathogens and related diseases. Besides composting, very important goals have been reached in manipulation of the soil microbiota through agronomical practices based on soil pre-fumigation with ecofriendly compounds, amendment with un-composted organic matter, crop rotation and intercropping either used alone or in combination with compost application. Nevertheless, to limit inconsistencies, drawbacks, and failures related to use of composts and organic amendments inducing soil-borne pathogen suppression, a detailed understanding of the microbiome shifts during manipulation under the light of microbiome-assisted strategies is needed. In this regards, next-generation sequencing by Illumina and Ion Torrent often offers a better overview of the soil microbial communities during the microbiome manipulation by compost application, but sometime they does not provide detailed information on the highest taxonomic resolution of the microbial communities. In general, HTS performed by Illumina MiSeq and HiSeq platforms seemed to be better option than Ion Torrent PGM platform and T-RFLPs sequencing for characterizing the fungal and bacterial microbiomes in composts of various composition, origin, and geographical provenience (De Corato, 2020b). These authors demonstrated significant differences among the microbiome profiles in terms of abundance, richness, awareness, and alpha- beta-diversity strictly correlated to the different feedstocks from which each compost (or organic amendment) was derived.

4. Characteristics, uses, technologies, and benefits of compost-derived tea application

4.1. Concepts and definitions

Emerging technologies and concrete possibilities when using formulations made of mixtures of microorganisms, HSs, and mineral elements derived from compost are available in the agrochemicals market as plant stimulant for improving growth, productivity, and phytopathogens control. The two most important compost-based derivatives to improve sustainability of the horticultural cropping systems managed under organic cultivation are the aqueous extracts (WEs) and CTs. These two products essentially differ for the production process. WEs are obtained from compost by simple water extraction of soluble components (Joshi et al., 2009). Composition of WEs formulation depends on compost from which it is derived. In recent years, more research is addressed to WEs coming from next-generation green composts for enhancing the suppressive properties of composted MSW-based biomass by recruiting the WEs from suppressive green compost into the MSW-based ones during composting process (De Corato et al., 2018c). CTs are instead obtained by a fermentation/oxidation process that determines new condition in the main physicochemical and microbiological characteristics of the end-products. The content of HSs and mineral nutrients increases into CTs during the fermentation/oxidation process with respect to the compost from which it is derived (Ingham, 1999). Humic acids, fulvic acids and humin can be used for their effects on plant growth promotion and plant disease suppression (Colpas-Castillo et al., 2018; Gholami et al., 2018). Effectiveness of the compost-derived products is highly appreciated by farmers to yield both quality and disease resistance for the crops (Zaccardelli et al., 2012). Such soluble organic molecules seemed to have beneficial effects on the plant metabolic processes thanks to their particular molecular structure (Zandonadi et al., 2019). Likely organic compounds, also bacteria, fungi, and yeasts have a decisive impact in the CTs ability to suppress diseases and/or promote plant growth (Ayuso et al., 1996; Diver and Greer, 2001; Eyheraguibel et al., 2008; Khaled and Fawy, 2011; Morard et al., 2011; Nardi et al., 2002).

According to the Compost Tea Task Force Report (NOSB, 2004, 2006) and technical definitions given by Scheuerell and Mahaffee (2002) and St. Martin and Brathwaite (2012), CTs are usually defined as compost-water extracts (CWEs) that can be technically divided in two main groups, the aerated-CTs and non-aerated-CTs, depending on the aeration degree given by the air production systems (Zaccardelli et al., 2011). CTs are liquid organic-filtered formulates produced by immersion-extraction-oxygenation of a compost in a liquid, generally water, for a period of time ranging from few hours to two weeks, with or without additives, and in absence of any solvent. Organic molecules, soluble inorganics, and microorganisms carried out in suspension increase in their content during extraction where bacteria, like-bacteria (as actinomycetes), filamentous fungi, oomycetes, and yeasts have a decisive impact in promoting plant growth and suppressing diseases. The plant stimulant capacity of CTs is exercised through direct and/or indirect effects on the plant nutrition and hormone-like activities. Plant growth promotion and disease suppression are also stimulated by the microbiota that induces maintenance of the normal phytosanitary condition of the plant. Moreover, likely to compost, CTs can also improve soil quality by altering the physicochemical properties, water-holding capacity, biodiversity, and the micro- macronutrients content (Scheuerell and Mahaffee, 2004; Siddiqui et al., 2009).

4.2. Compost-derived tea technology and compost tea application

4.2.1. Production system

CTs are produced inside bioreactors in the liquid phase by fermentation or oxidation beginning from high-quality compost. Fermentation takes place without oxygenation of the liquid phase for producing non-aerated-CTs, while aerated-CTs are produced using ventilation systems. Bioreactors can vary from the most complex layouts to simpler bench bioreactors (Pane et al., 2010). Therefore, it is possible to see a range of apparatus, from the artisanal fermenters (Graphical abstract) used in farming systems to more sophisticated industrial plants used in green biorefineries. Since advanced technology must ensure complete oxygenation of the composted biomass for the uniform distribution and efficient extraction in aerated-CTs, the process should be carried out in air permeable bag inside the bioreactor. Optimal oxygenation can be achieved by continuous recirculation of liquid or direct ventilation by forced insufflation of air. An efficient process for producing CTs regards the additives use by partial or total replacement of water during the extraction phase. The use of whey, buttermilk, 'borlanda', molasses, casein, and fish flour has been proposed as additives (Al-Mughrabi, 2006). The purpose of the replacement water/additive lies in improving quality of the biotic and abiotic components of the end-products (Pane et al., 2012b).

4.2.2. Composition

Salinity and pH of CTs usually does not reach the toxicity levels for the crops. CTs contain large quantity of inorganics dissolved in solution which represent a real tool for ready-to-use nutrients for the crops. Macronutrients as nitrogen (N), as well as phosphorus (P) and potassium (K) are well present in CTs. But, if the starting composts are not of good quality due to their high content of heavy metals beyond the legal limits, such contaminants as lead, cadmium, copper, and iron could be released into the CTs under bioavailable forms for the crop. Moreover, repeated treatments with contaminated CTs could increase concentration of heavy metals in the sprayed soil, so determining negative impact on the environmental sustainability and human health after long-term application of heavy metals-contaminated CTs. On the other hand, if the starting compost is of good quality (Zaccardelli et al., 2012), concentration of such contaminants will be lower in the soil (Baldantoni et al., 2010). The organic molecules are overall represented by humic acids, fulvic acids, and humin where humic acids may be present in CTs with tips of 0.66 g L^{-1} using an acidifying additive (Ciancio, 2010). Such process, due to high variability of the composts composition and numerous co-products of reaction, lead formation of complex and heterogeneous organic molecules characterized by higher molecular weight and C-humified structures resulting more stable than the starting composts.

Microbiological composition of CTs influences the propensity of the farmer to adopt them. CTs contain a wide biodiversity of bacteria, actinomycetes, yeasts, saprophytic microbes, and mycorrhizal fungi. Authors clarified that microbiota diversity, rather than its abundance, should be considered as key factor to microbiological quality of CTs (Palmer et al., 2010). Such microbiota confers specific properties for biological control of foliar and fruit plant diseases or plant growth promotion. The biotic component being affected from the different variables of the fermentation/oxidation processes result be highly variable, as well as the starting compost. Authors reported that improved efficiency of the nutrients extraction and increased abundance of microbial population are both related to the specific production conditions (Shrestha et al., 2011). Optimal compost/water ratio (1,10, v/v) ensures continuous exchange between the two liquid/solid phases maintaining the oxygenation rate more than 6 ppm as concentration limit. Furthermore, particular emphasis is given in order to use of additives during fermentation/oxidation for increasing microbial biomass (Scheuerell, 2006). However, this aspect is still debated because, tough additives can effectively affect the microbial community by increasing its abundance and biodiversity, development of human pathogens as *E. coli* could be stimulated (Scheuerell, 2003).

4.2.3. Quality and application of compost tea and compost-derivatives

Improvements in CTs quality have been reported for a range of CTs. A key feature of CTs is the increased microbial diversity when applied on the foliar system (Gaius and Micah, 2019). Quality of the starting composts and additives affects effectiveness of the marketable formulates more than other factors. Composts with disease-suppressive property have greater potential to generate higher quality CTs more effective against plant pathogens than other compost-based teas (Joshi et al., 2009). In addition to the intrinsic features, the maturity degree of the starting composts can even influence the quality of the CTs. A research showed that aerated-CTs produced by immature composts resulted to be more suppressive on bean/gray grey mold by *Botrytis cinerea* than the stabilized ones (Palmer et al., 2010). Additives also stimulated microbial growth for promoting microbial biomass (Siddiqui et al., 2008) and producing antifungal substances (Ingham, 2005). Bioactive formulates enhance the suppressive potential of CTs by increasing efficiency and spectrum of action. Additives, even if added at lower dose, can give very relevant effects on disease suppression. For instance, significant reduction of the incidence and severity indices of mildew symptoms on potato by *Phytophthora infestans* were occurred by adding 1% of additive (Al-Mughrabi, 2007). Instead, oxygenation does not be decisive for disease effectiveness of CTs. Indeed, direct comparisons among aerated-CTs and non-aerated-CTs did not show significant differences of suppression to *P. ultimum* on cucumber (Scheuerell and Mahaffee, 2004) and *Xanthomonas vesicatoria* on tomato (Al-Dahamani et al., 2003).

Application of CTs-based formulates is generally performed through root/soil drenching or foliar wetness by sprayer and mini-sprinkler. However, foliar/fruit spraying seemed to be a better option for optimization of the plant nutrition and pathogen control (Gaius and Micah, 2019). When spraying the foliar system in horticultural crops as cucumber, it is necessary to pay attention to working pressure which does not exceed certain limits for preserving integrity of the living microbiota on foliar surface (Shafeek et al., 2016). CTs can be applied both in preventive and curative treatments. Authors indicated that preventive applications are generally more effective than the curative ones as a result of the possibility of the epiphytic microbiota to develop its own biomass in relation to the interactions among microbes and pathogens (Koné et al., 2010). CTs are usually applied as undiluted liquid formulates or, alternatively, as diluted solutions with water (from 1:5 to 1:10, v/v). The dose, being calibrated in relation to targeted pathogen/crop, usually ranges from 50 to 140 L ha^{-1} in the case of *P. infestans* on potato up to 900 L ha^{-1} for controlling *Septoria lycopersici* on tomato (Al-Mughrabi, 2007). Unlikely crude CTs, the purified/semi-purified HSs fractions are already marketable in the phytosanitary market as 'ready-to-use' formulates and mixtures that make the application dose less arbitrary than CTs following the recommended doses and application modes clearly specified on the manufacturer's labels.

4.3. Benefits for plant growth

The beneficial effects of HSs as biostimulants of plant growth have been well-known since the 1980s, and they can be supportive to a circular economy if they are extracted from different renewable resources of organic matter including harvest residues, wastewater, sewage sludge, and manure. Plant stimulation is exercised through overall direct and/or indirect mechanisms on plant nutrition and hormone-like activity by stimulating the photosynthetic capacity. Among all abiotic factors, HSs seem play the main role in plant growth stimulation. Indeed, it has been reported that crude HSs can induce yield increase thanks to its own stimulating action on plant physiology and nutrition (Hartz and Bottoms, 2010; Selim et al., 2009; Varanini and Pinton, 2001; Virgine Tenshia and Singaram, 2005).

Crude HSs, when directly applied to the plant, show different mechanisms of action. A number of findings about the plant stimulant effects by CTs and their derivatives application were reported in literature (Table 3). In particular, authors described many effects on nutrient uptake (Aguirre et al., 2009; Virgine Tenshia and Singaram, 2005) and N-assimilation (Palumbo et al., 2018), hormone-like activity (Bernal-Vicente et al., 2008; Mora et al., 2010), photosynthetic efficiency (Siddiqui et al., 2008), root-associated microorganisms for plant nutrition and nutrient uptake (Jasson, 2017; Lanthier, 2007), growth parameters (Almeida Gomes Júnior et al., 2019), and phytosanitary condition (Scheuerell and Mahaffee, 2002). This is the case, for example, of *Centella asiatica* where CTs application increased vegetative growth, dry biomass, and the antioxidants content (Siddiqui et al., 2011). Likely,

Table 3
Plant growth promotion due to foliar and soil application of crude compost teas and their purified/semi-purified derivatives (humic substances) on horticultural crops.

Compost tea and compost-derivative formulate	Crop	Stimulant effect	Reference
-Humic acids	Tomato	-Increasing in plant height, leaf area and dry weight of shoot and root. -Increasing in uptake of macro- micronutrients and increasing in the efficient uses.	Atiyeh et al. (2002)
-Humic acids from vermicompost	Pepper and strawberry	-Increasing in root growth. -Increasing of production per square meter (on average 23% for pepper).	Arancon et al. (2003)
-Humic acids from vermicompost	Cucumber	-Increasing in plant height, leaf area and dry weight of shoots and roots.	Atiyeh et al. (2002)
-Compost + Humic acids + amino-acid	Bean	-Productivity increasing.	Shehata and El-Helaly (2010)
-Humic acids	Chicory	-Stimulation of total fresh biomass.	Valdrighi et al. (1996)
-Humic acids + vermicompost	Chicory (for inulin accumulation in root)	-Improvement of the yield and the total contents of phenolics and flavonoids	Gholami et al. (2018)
-Purified humic acids	Cucumber	-Increase in shoot growth associated with an enhancement in root H+-ATPase activity, increase in nitrate shoot concentration, and decrease in roots. -Effects associated with increases in the shoot concentration of cytokinins and polyamines (principally putrescine) and concomitant decreases in roots.	Mora et al. (2010)
-Humic acids	Chili pepper and eggplant	-Plant growth promoter by inducing changes in root, architecture, and dynamics of growth resulting in larger root size	Colpas-Castillo et al. (2018)
-Purified humic acids from composted olive mill wastewaters (OMW) and pre-treated municipal solid waste (MSW)	*Zea mays*	-Increased plant growth by enhanced nitrogen assimilation and glycolysis due to increased activity of nitrate reductase, phosphoglucose isomerase, and pyruvate kinase (more for OMW than MSW).	Palumbo et al. (2018)
-Compost-tea + NPK mineral fertilizer at half dosage	*Centella asiatica*	-Increasing of plant vegetative growth, productivity and antioxidant substances content in the tissue.	Siddiqui et al. (2011)
-Compost-tea from green compost	*Abelmoschus esculentus*	-Increasing of plant vegetative growth, photosynthesis efficiency and productivity.	Siddiqui et al. (2008)
-Compost-tea from green compost	Oilseed rape and cabbage-turnip	-Increasing of plant vegetative growth. Increasing of production per square meter (on average 35% for cabbage-turnip).	Keeling et al. (2003)
-Compost-tea from composted oranges and lemons co-products	Melon	-Increasing of total fresh biomass.	Bernal-Vicente et al. (2008)
-Compost-tea from plant green-waste and agro-industrial co-product	Tomatoes	-Increasing of production per square meter (on average 46%).	Pane et al. (2012a)

foliar application of CTs showed beneficial effects on *Abelmoschus esculentus* improving the morphological characters (aerial part height, root length, number of leaves, and leaf area index), physiological parameters (chlorophyll content and the photosynthesis/photorespiration ratio) and the productive performance (Siddiqui et al., 2008). Authors obtained interesting results on tomatoes sprayed every 7–10 days with CTs from green composts where such treatment determined high berries production (on average 46%) in the absence of fungicide treatment (Pane et al., 2012b). These results pointed on how CTs can perform the dual action of plant growth promotion and crop protection by only one treatment. CTs application on melon root combined with composted citrus fruit residues showed slight increasing of total biomass in a melon cropping system cultivated under greenhouse nurseries, due to bioactive action of auxin-like and cytokine-like molecules (Bernal-Vicente et al., 2008).

More researches have provided instead interesting insights if HSs were applied in their different purified forms rather than as crude HSs in root and foliar application for plant growth. Amino-acids and humic acids stimulate vegetative and root growth in pepper (Arancon et al., 2003); increase fresh and dry biomass in cucumber and tomato (Atiyeh et al., 2002); promote growth, yield, productivity, storage ability, and chemical parameters of strawberries (Shehata et al., 2011) and sweet pepper (Shehata and Abdel-Wahab, 2018); and induce changes in root architecture and biomass growth in pepper and eggplant by producing larger root size (Colpas-Castillo et al., 2018). The effects of humic acids and vermicompost on the yield and phenolic components of the chicory aerial parts for inulin production were investigated by Gholami et al. (2018). The authors concluded that humic acids and vermicompost improved chicory yield and the total phenolics and flavonoids content. The highest yield of dry aerial parts (20.29 g per plant) was achieved by applying 0.9 kg per hectare humic acids in combination with 10 t per hectare vermicompost, while the highest total contents of phenolics and flavonoids were reached if humic acid was applied at 0.9 kg per hectare in combination to 7.5 t per hectare vermicompost. A recent study aimed at differentiating among the mechanisms of action of a short-term foliar application vs a root ones using a sedimentary humic acid (SHA) for promoting plant development (De Hita et al., 2020). Although both application strategies improved the shoot and root growth, nevertheless foliar applied- and root applied-SHA shared the capacity to increase the concentration of indole-3-acetic acid in roots and cytokinins in shoots. In addition, both strategies increased the root concentrations of jasmonic acid and jasmonoyl-isoleucine. These hormonal framework changes caused by foliar application could be a stress-related symptom and connected to the loss of leaves trichomes and the diminution of chloroplasts size. The contact of seed with humic acid triggers reactions which lead increased plant development and vegetative vigour, and drives physiological processes under gene control (Aguirre et al., 2009). Ability of such substances to enhance root growth by changing the root architecture is often linked to their phyto-hormonal activities as auxin-like effects and nitric oxide production. Numerous studies reported the capability of HSs to increase shoot growth in plant under diverse conditions. However, the mechanism responsible for the HSs effect is still poorly understood. The mechanism of action of humic acids on cucumber in root and shoot growth-promoting was studied on the basis of hypothesis by which root/shoot promotion could involve primary mechanisms based on the abscisic acid (ABA) content in root, H+-ATPase activity, and nitrate root–shoot distribution in the plant tissues (Mora et al., 2010; Olaetxea et al., 2019). Such mechanisms affecting shoot growth could cause substantial changes in the root–shoot distribution of cytokinins, polyamines, and ABA. The authors confirmed that the beneficial effects of HSs on shoot development in cucumber could be directly associated with nitrate-related effects on the active cytokinins and polyamines concentration in shoot. Other study instead leaded more importance to the soil humeome that serve as a molecular constituents pool based on HSs by revealing the importance of the alkyl compounds.

Interestingly, alkamides present in the humic acid fraction, due to their particular molecular conformation and chemical activity, seemed to be particularly active in plant stimulation (Zandonadi et al., 2019). Nonetheless, plant growth promotion is also exercised by the microbiota that can induce maintenance of the normal phytosanitary condition in order to promote optimal plant growth. These combined effects were seen on the different morphological, physiological, and productive characteristics of compost tea-treated crops such contributing to improve their agronomic performances (Zaccardelli et al., 2012).

In conclusion, a recent overview focus the key factors, such as the chemical structure of HSs, application method, optimal rate, and field circumstances, that play together a crucial role in improving plant growth by HS treatment (Jindo et al., 2020).

4.4. Benefits for plant health

CTs have concrete applications to partly replace fungicides in the foliar and fruit diseases control strategies (Scheuerell and Mahaffee, 2002). CTs can induce antimicrobial effects when directly applied to the plant showing disease-suppressive property against pathogens by stimulating physiologic responses that make it an efficient improver of the yield for the qualitative and quantitative characters (Reeve et al., 2010). In most of the cases, biotic and abiotic components can perform complementary and synergic actions that reflect on the suppressive properties of CTs determining the nutritional role that the abiotic components play in favor of the biotic ones.

CTs formulations have greater abundance and wider diversity of bacteria, fungi, protists, and nematodes potentially useful for the disease-suppressive properties more than compost. A number of studies agrees on the fact that the suppressive contribute comes by the biotic component, especially microbial, that act as pathogen-antagonist (El-Masry et al., 2002). Likely compost, beneficial microbiota and related pathogen-suppressive metabolites are the main factors influencing the CTs efficacy in inhibiting plant pathogens (Koné et al., 2010). The dominant taxonomic groups isolated from microbial-enriched CTs belonged to the genera *Bacillus*, *Pseudomonas*, *Micrococcus*, *Staphylococcus*, *Burkholderia*, *Clavibacter*, *Lactobacillus* and other bacterial species (Naidu et al., 2010), actinomycetes, yeasts, *Trichoderma*, *Aspergillus*, *Penicillium*, and other minor filamentous fungi (Naidu et al., 2012). Authors demonstrated the key role of the microbiota in suppressing diseases by microbial-enriched CTs that inhibited in vitro radial growth of *Sclerotium bataticola*, *F. oxysporum* f. sp. *lycopersici*, *Fusarium solani*, *Fusarium graminearum*, *S. sclerotiorum*, *R. solani*, *Rhizoctonia bataticola*, *Pythium* spp., and *V. dahliae* (Kerkeni et al., 2007). Moreover, the literature documents a number of cases study by which CTs suppressed diseases on different hosts as: powdery mildew by *Oidium neolycopersici*, *Leveillula taurica*, and *Erysiphe polygoni* of tomato and artichoke; downy mildew by *P. infestans* of tomato and potato; grey mold by *B. cinerea* and alternariosis by *Alternaria* spp. of tomato; and septoriosis by *S. lycopersici* of celery (Pane et al., 2007; Segarra et al., 2009; Koné et al., 2010). Moreover, CTs application has been reported for suppression of bacterial foliar diseases by *Pseudomonas syringae* pv. *tomato* (Pane et al., 2007) and mottling bacterial tomato by *X. vesicatoria* (Al-Dahamani et al., 2003). Full-field CTs application for controlling pathogens of potato as *Helminthosporium solani*, *Alternaria solani*, *Fusarium* spp., *R. solani* (Al-Mughrabi, 2006), and *P. infestans* (Al-Mughrabi, 2007; Al-Mughrabi et al., 2008) were occurred. In addition, CTs were studied on many horticultural cropping systems where the different formulation types seemed active against soil-borne diseases as corky root of tomato by *Pyrenochaeta lycopersici* and damping-off of cucumber and bean by *P. ultimum* and *R. solani*, respectively (Pane et al., 2012a). CTs suppressed stem canker by *R. solani* (Islam et al., 2013) and dollar spot by *Sclerotinia homoeocarpa* (Hsiang and Tian, 2007). Recently, authors reported that root treatment with CTs from on-farm green composts effectively controlled rot root of 'Iceberg' lettuce by *S. sclerotiorum* and *S. minor* (Zaccardelli et al., 2012). Table 4 summarizes the suppressive effect of crude compost teas on soil-borne pathogens and plant diseases in relation to the microbiota bioactivity.

Microorganisms can develop their own antagonistic action through mycoparasitism (Bernal-Vicente et al., 2008; El-Masry et al., 2002) and competition with the pathogen for space, nutrients, and infection sites (Segarra et al., 2009). Authors demonstrated that heat-sterilization of CTs from composted rice straw and empty fruit bunch determined the suppressiveness loss against *Choanephora cucurbitarum*, the causal agent of wet rot in okra (Siddiqui et al., 2009). Microbial competition can be thus considered the main mechanism of action associated to mycoparasitism. Indeed, removing microbiota from CWEs by Millipore filter-sterilization may have a negative impact on suppressiveness since such treatment induces the disease suppression loss. In contrast, other authors concluded that antibiosis could be the main mechanism for suppressing diseases since filter-sterilized CWEs retained their suppressive activity more than un-sterile teas and, most of them, even after autoclaving treatment (Cronin et al., 1996; Yohalem et al., 1994).

Authors have found that effectiveness of the CTs formulates does not depend by microbiota (Al-Dahamani et al., 2003). In this issue has been hypothesized that macro- micronutrients, HSs, and phenolic substances may have a significant contribution to disease suppression by toxic effects on the pathogen. Mixtures of humic acids and fulvic acids applied to root by soil/root drenching may have determined, for example on tomato, a significant increase of root system resulting from reduction of rot disease severity by *Fusarium* spp. (Yigit and Dikilitas, 2008). Humic fractions can influence directly and/or indirectly the plant/pathogen system by inducing disease suppression. Studies showed the possibility to use of humic acid-based substances derived from compost for controlling pathogens. Indeed, HSs were reported to be consistently suppressive against *P. ultimum* (Pane et al., 2011; Pascual et al., 2002). Recent studies showed significant relationships among the chemical and functional properties of such humic fractions in their ability to

Table 4
Some examples of soil-borne plant disease suppression due to action of crude compost teas on horticultural crops.

Plant disease	Target pathogen	Host plant	Compost tea	Application	Reference
Pythium damping-off	*Pythium ultimum*	Cucumber	-Compost teas from composted yard trimming and vermicompost.	Soil drenching	Scheuerell and Mahaffee (2004)
			-Compost teas from composted bovine, sheep and chicken manure; shrimp and seaweed.	Soil drenching	Dionne et al. (2012)
	Pythium aphanidermatum		-Compost teas from composted solid olive mill wastes, seaweed (*Posidonia oceanica*), and chicken manure.	Soil drenching	Jenana et al. (2009)
Phytophthora blight	*Phytophthora capsici*	Pepper	-Compost teas from composted pig, cow and poultry manure; sawdust; livestock wastes; dregs of oil and lees.	Root drenching	Sang et al. (2010)
Choanephora wet rot	*Choanephora cucurbitarum*	Okra	-Compost teas from composted empty fruit bunches of oil palm and rice straw.	Root drenching	Siddiqui et al. (2009)
Sclerotinia root rot	*Sclerotinia sclerotiorum* *Sclerotinia minor*	'Iceberg' lettuce	-Compost teas from on-farm green composts.	Root drenching	Zaccardelli et al. (2012)

inhibit phytopathogens (Loffredo and Senesi, 2009; Loffredo et al., 2008). The effect of such molecules can determine improvement of the nutritional status of the whole plant which can exhibit less susceptibility to disease. Besides mycoparasitism, competition, and antibiosis, authors reported that *Trichoderma* spp. carried by CTs into bio-based formulate can trigger defence mechanisms against *Phytophthora* spp. by induced systemic resistance (ISR) (Hoitink et al., 2006). Authors investigated ISR against *C. cucurbitarum* by treating okra plants with both un-sterile and filter-sterilized CTs basing on the increased concentration in plant tissues of inducible resistance-related enzymes (peroxidase, polyphenol oxidase, and phenylalanine ammonia lyase) (Siddiqui et al., 2008, 2009). Biotic and abiotic factors can induce systemic acquired resistance (SAR) in the host, revealing this mechanism for bio-based formulation (Hoitink et al., 2006). Similar mechanisms were also described in tomato and onion treated with non-aerated CTs against *A. solani* and *Alternaria porri*, respectively (Haggag and Saber, 2007). Finally, compost-based teas inhibited the mycelial growth and conidial germination of *V. dahliae* by 90.6% and 78.24%, respectively, by compost-mediated induction of resistance in controlling Verticillium wilt of strawberry (Li et al., 2020).

However, it is very difficult to fully understand these complex mechanisms since does not clear whether pathogen inhibition is due to mycoparasitism, or competition for nutrients and colonization sites, or production of antibiotics, or ISR and SAR mechanisms because the selective pressure coming from the abiotic component towards foliar microbiota contributes to define and continuously modify its own structure and biodiversity. Finally, the key role in suppression of the microbial secondary metabolites having antibiotic-like activity produced during the fermentation/oxidation process should not be overlooked in future research directions.

5. Feasibility of the on-farm composting chain and compost tea application

5.1. Barriers

The paper has analyzed the on-farm composting process and further processing steps to produce liquid compost-based derivatives. Although composts and CTs have more extra-benefits than chemicals and mineral fertilizers, their application on the soil-plant system can be nevertheless associated to many drawbacks and failures (here named as 'barriers'). But, benefits and barriers might be balanced among them in relation to compost dose, feedstock, soil type, crop management, etc. In general, the most critical issues regarding the composting process variables considered as 'critic' are pH, C/N ratio, moisture content, aeration rate, particle size, and porosity (degree of compaction of the organic matter). In addition to that, odour emissions can represent a significant environmental impact and, at the same time, a very important issue to produce low-quality compost under unsuitable processing conditions (Cerda et al., 2018).

In particular, in order to implement on-farm composting and compost application, this section of the paper discusses the main barriers basing on the excellent study carried out in Belgium (Viaene et al., 2016). Using questionnaires, the authors concluded that maintaining and improving soil quality and its fertility by on-farm compost, very important challenges were reached for a modern organic agriculture. But, the same authors also investigated on what barriers can derive from on-farm compost application since information of this topic are still scarce and fragmented worldwide. The authors identified a relatively large number of potential barriers including technical, financial, economic, informational, and legislative. Among them, the most significant barriers were analyzed and categorized into the following four groups: (i) technological and scientific, (ii) economic and market, (iii) institutional and policy, and (iv) behavioral and informational. A more stringent regulation framework, considerable financial and time investment required, lack of experience and knowledge of the farmers were the main limiting factors for on-farm composting and compost application worldwide. The reduced availability of woody biomass for composting (North Europe), manure surplus and policy implications in Flanders (Belgium) and Catalonia (Spain) characterized by intensive livestock farming, discontinued feedstock availability for processing plants (Italy and Portugal), difficulty of compost transporting around all countries of the European Union (EU), wide variability of compost quality, and different composition and origin of the feedstocks, represent barriers against application of on-farm compost from agricultural waste and compost-based liquid formulates in organic agriculture. These barriers, together with the long-term beneficial effects on soil quality, make compost application as a serious obstacle for on-farm composting.

As regards to compost-based formulates and to avoid any misunderstanding for readers about the use of compost tea technology in the farm, I must underline that adding compost-based solutions enriched with microorganisms, HSs, minerals, and other compost-derivative active compounds is not alone enough to improve soil quality including soil suppressiveness. The partial interpretation of the potential beneficial effects of compost tea on soil quality affirming that '*soil suppression and soil quality might be induced by adding compost-based solutions rather than organic matter*', as often is reported in certain undervalue literature or in scientific meeting and symposia (personal communications), has unfortunately become a true marketing toolbox for agrochemical companies in promoting their commercial formulations. Whilst, I must recall again that the main factor of soil quality is represented by the SOM content, humification degree, and microbiota diversity which play the key roles in supporting soil microbiota and microbial diversity under both qualitative and quantitative points of views (De Corato, 2020a, 2020b).

Table 5 summarizes the main recognized barriers against on-farm composting and compost/compost tea application on basis of the recent literature consulted.

5.2. Recommendations, novelties, and innovation

The study carried out in Belgium (Viaene et al., 2016) leads on a number of empirical recommendations and good practices that should potentially solve, at least partly, the detrimental effects of the barriers. A total of five recommendations were suggested to mitigate these effects for increasing attractiveness of farmers towards compost use. Specifically, the authors recommended the following measures to reduce or even eliminate a consistent number of barriers as: (i) exploiting alternative technologies for on-farm compost production, (ii) searching some forms of financial incentives to compensate the high production costs associated with the compost production and application, (iii) searching alternatives to certain types of biomass which can be competitive with other sectors (i.e. cleaner energy), (iv) adopting flexibility degrees in current policies and institutional frameworks, and (iv) implementing a better dissemination of information/formation/results for farmers in order to re-cycle agricultural biomass waste by a modern composting strategy. In particular, the most feasible measures that should be taken into account are addressed on few, but significant, key points. First, alternative means of production can use service providers and data logger to setup and monitor all stages of the on-farm composting on larger scale. Farmers would invest less time to produce compost and utilize more time to purchase needed equipment instead. Second, another alternative mean of compost production might be make 'jointing services' between farmers and stakeholders falling in the same areas by re-organizing their cycle production. For instance, residual biomasses that are unsuitable to be continuously processed in an industrial composting plant due to higher seasonality, smaller amounts, and difficulty to be transported for longer distances, could be instead individually collected by farmers and being processed in few centralized 'big local bulks' rather than in more smaller farms. The biomass provided by different users could be shared and composted in bigger

Table 5
Summarization of the main recognized barriers against on-farm composting and compost/compost tea application.

Barrier	Critical issue	Reference
On-farm composting technology	-Shortage of woody biomass. European incentives for green energy production by incineration and anaerobic digestion has raised a distortion of the biomass (especially woody biomass) use towards the cleaner energy sector by micro-cogeneration in situ. This makes on-farm composting more expensive for farmers that do not already possess sufficient woody biomass for their on-farm plants. -License for composting. Since on-farm composting needs the proper combination of brown (e.g., wood chips and straw) and green (more nitrogen-rich, e.g., crop residues) feedstock to make high-quality composts with an optimal carbon/nitrogen (C/N) ratio, an external biomass must be purchased with additional costs investment (e.g., installing a concrete pad for composting, a system to capture and store run-off waste water, measurements to reduce odour, emissions and dust, and mandatory compost quality control) for farmer that must require environmental license to use it. -Financial investment. A good quality compost relies heavily on the right balance of oxygen, CO_2, water, and temperature throughout the whole composting process. Monitoring and managing the balance of oxygen and CO_2, water requirement, aeration levels, and temperature require a number of expensive and specific compost turning machines and other tools (temperature probes and CO_2 sensors) that yield the best results. This equipment should be purchased externally to the farm with additional cost for the farmer. -Time investment. The time is needed for monitoring the whole process and turning the compost. Time is required to monitor seasonality and fast decay of grass clippings and crop residues feedstock. -Lack of experience and knowledge. Farmers usually underline a lack of knowledge about the regulations for on-farm composting. -Profitability. Frequent farmers' perception is that the on-farm composting costs and related compost application is higher than the costs of applying chemical fertilizers, fungicides, and fumigants.	Viaene et al. (2016)
Compost application	-Complex regulations. An overlooked issue is given by the complex and often contradictory and confusing regulations across the EU guidelines (ISO/IEC 17025:2005), EU legislation (Regalement UE No. 03/2003, EU Nitrates Directive 91/676/EEC, and EU Water Framework Directive 2000/60/EU), and legislation among the different countries (Italian Decree Laws No. 217/2006 and 75/2010, Spanish Decree Law No. 506/2013). -Availability and transport. Due to frequent compost un-availability in horticultural intensive farming systems, the purchased compost cannot be freely transported from the compost production site (on-farm or commercial compost) into the receiving farm unless either a certified transporter or certified sender. This determines an additional cost for farmer. -Farmer's experience. Farmer often have a lack of experience when using compost and overall lack of knowledge of the scientific bases of the on-farm composting technology and compost application. -Manure surplus. The intensive livestock farming in some countries as Flanders (Belgium) and Catalonia (Spain) creates a ready supply of slurry, which is mostly provided and spread on the field at no charge. This creates an important barrier to compost application.	Viaene et al. (2016); Flotats et al. (2009)
Compost quality	-Cost for farmer to monitor physicochemical features: moisture, organic matter, nutrients, C/N ratio, temperature, oxygenation, CO_2. -Cost for farmer to monitor chemical contaminants: heavy metals, aromatics, halogenated hydrocarbons, pesticides, phthalates, and total petroleum hydrocarbons. -Cost costs for farmer to monitor microbial characteristics: mineralizable nitrogen, microbial biomass carbon, bacterial and fungal abundance and community-level physiological profiles. -Cost for farmer to monitor absence of food-borne pathogens loads: *Escherichia coli*, *Salmonella* spp. -Cost for farmer to monitor useful genes: Integrase intl1 gene abundance. -Cost for farmer to monitor biological and enzymatic activities of the microbial communities: urease, phosphomonoesterase, β-glucosidase, and total hydrolytic activities. -Cost for farmer to characterize the humic fractions: humic acids, fulvic acids, and humin.	Epelde et al. (2018); Scotti et al. (2016); Piccolo et al. (2019)
Compost formulation	-Microbiota survival. Endogenous microorganisms sourced by composts and exogenous biocontrol agents combined with them do not last long in the rhizosphere, but only lasting for some weeks, at least.	De Corato (2020b)
Greenhouse gas (GHG) emissions	-Climate-altering gas evaluation. Gaseous compounds as CH_4, N_2O, CO_2 and NH_3 were directly released into the atmosphere from the green compost production chain from agricultural waste.	Pergola et al. (2020)
Compost tea and humic acid application in soil	-Use of compost tea for improving soil suppressiveness. Compost-based solutions are not alone enough to improve soil suppression.	De Corato (2020a)

processing plants rather than in smaller on-farm composting plants. But, when bulk biomass is being processed, the feedstock must be homogeneous for its composition and origin accordingly with the EWC (green/brown, wet/dry, liquid/solid, woody/herbaceous, etc.) standards. So, might be reduced the investment time; the production and transport costs for each farmer; and, additionally, the cost of purchasing the needed composting equipment, the mandatory investments, and the tasks that could be shared among farmers. Third, some financial incentives could contribute to compensate the highest production costs associated with on-farm composting by using 'carbon certificates'. Such incentives, yet used for cooling–heating the sustainable greenhouses placed in south of Italy (Sicily and Apulia) by purchasing 'green/white certificates', are based on the use of sun and biomass by the solar cooling and biomass heater technologies, respectively (De Corato and Cancellara, 2019). Fourth, it has been recommended the search of alternative biomass to woody biomass being increasingly used for energy production by combustion. Indeed, biomass less suitable to generate thermal energy could be more conveniently composted rather than combusted. In this regard, De Corato et al. (2015) have reviewed a wide range of co/by-products derived from the biofuel (bio-ethanol, biodiesel, and biogas) chains that should be more easily composted in green biorefineries rather than wasted for safety reasons, as becomes for anaerobic digestate slurries from the wastewater treatment plants. As last point, but not less important, more and better dissemination of information, formation, results obtained, and education for farmers focused on the different technical and economic aspects of composting should reduce or even eliminate a number of barriers. Farmers are nowadays more attracted and sensitive to new information than past years; however, institutions should periodically organize activities and programs to increase understanding, attractiveness, familiarity, competence, and sensitivity to on-farm composting and compost application by implementing the education and dissemination services among countries.

Table 6 summarizes the main recognized recommendations, novelties, and innovations towards on-farm composting and compost tea application on basis of the more recent literature consulted.

Table 6
Summarization of the main recognized recommendations, novelties, and innovations towards on-farm composting and compost tea application.

Recommendation	Novelty and innovation	Reference
-Searching alternative feedstocks to woody biomass for compost production.	-Use of agro-waste, green plant-waste, and agro-industrial residues and co/by-products produced in situ. -Use of bio-energy co-products from the biofuel (bioethanol and biomethane) chains.	De Corato et al. (2015, 2016, 2018b, 2019); Pane et al. (2013)
-Searching financial incentives.	-Easy access to the 'white/green certified' system.	De Corato and Cancellara (2019)
-Using a certain degree of flexibility in current policies and institutional arrangements.	-Stimulation of local policies and national laws.	Viaene et al. (2016)
-Adopting more and better dissemination of information.	-Development of meetings and congresses.	
-Monitoring all compost quality parameters along the whole processing chain.	-Use of advanced technology for characterizing the 'humeoma' (^{13}C-CPMAS-NMR spectroscopy), heavy metals and other organic contaminants (thermochemolysis-GC–MS spectrometry), microbial community-level physiological profiles (Biolog EcoPlates™), and microbiome profile (next generation sequencing by high-throughput sequencing).	Epelde et al. (2018); Pane et al. (2015); Piccolo et al. (2019); Scotti et al. (2016)
-Increasing microbiota survival for longer time in the soil and foliar system.	-Use of more stable formulates by use of alginates and stabilizers, and drying treatment by lyophilisation and dehydration of the microbiota.	Zaccardelli et al. (2013)
-Implementing the risk assessment of the whole on-farm green compost production chain from agricultural waste.	-Evaluation of the environmental impacts of the GHG emissions, energy consumptions, and cumulative production costs of all composting stages by the Life Cycle Assessment (LCA) methodology.	Pergola et al. (2020)
-Do not using compost-derived liquid formulates for improving soil suppressiveness, but using them for foliar application only.	-Supplementation of exogenous organic matter by soil amendment combined with tailored suppressive compost and selected microbial consortia.	De Corato (2020a, 2020b)
-Investigating the mechanisms of actions of compost teas and their derivatives in suppressing plant diseases.	-Investigation of the key role of the microbial secondary metabolites having antibiotic-like activity produced during the fermentation/oxidation process	Loffredo and Senesi (2009)

5.3. Sustainability

Besides the possibility to reduce or even avoid potential risks for human health due to environmental and hazardous contaminants (Epelde et al., 2018), other authors have instead questioned that another fundamental criterion should be routinely adopted to sustain the on-farm green compost production chains from agricultural waste (Pergola et al., 2020). Indeed, the risk assessment due to GHG emissions (i.e. CO_2, methane, nitrous oxide, ammonia, etc.) directly released into the atmosphere during composting process should be next frontier, accordingly with the environmental EU policies (Hao et al., 2001). In fact, the EU has strongly promoted composting over landfilling and anaerobic digestion by implementing own environmental legislation. Nonetheless, recommendations, novelties, and innovations related to the compost production chains should not be overlooked in relation to the risks–benefits balance that are strictly linked to life cycle assessment (LCA) of all composting steps.

In order to evaluate sustainability of the environmental impact of GHG emissions, energy consumption for mixing and aeration, and production cost of the green compost production chains, a number of LCA models were applied in many papers reviewed by Pergola et al. (2018b). These models taken into account overall the manure processing technologies along the entire life cycle of manure and related end-products, industrial composting and waste management systems, bio-waste treatments, and food-waste home composting systems. On the other hand, very few papers were found by taking into account the environmental impact, energy consumption, and cumulative production cost that affect during the on-farm composting chain of green waste. Only combining the economic, environmental, and energy output-input of an entire production process by LCA approach may be achieved the desired goals to the best management strategies. Thus, authors have found interesting finding about the environmental impacts, energy consumptions, and cumulative production costs of a windrow composting system (equipped with five automatic blowing systems for aeration by air pipelines, automatic system for the recovery of processing waters by submersible pump, and electric control panel with probe-systems for monitoring temperature, O_2 content, humidity, and data logger) placed in south of Italy (Campania) under greenhouse condition by using the LCA methodology according to ISO 14040 and ISO 14044 standards (Pergola et al., 2020). These authors have tried to evaluate all stages of the composting process using pruning residues, wood chips, straw, and tomato-wastes as feedstock by including bulking agent acquisition and transporting; agricultural waste processing; compost production, transport, and distribution on field. Results show that compost production meanly emitted from 199 to 250 kg CO_2eq in the atmosphere, required energy consumption from 1500 to 2000 MJ, and reached cumulative production costs between 98 and 162 euros per ton of compost for about 9 tons of green compost produced in a week. These findings underline the need to promote the rational agronomic use of compost by spreading this low-cost technology to recycle agricultural waste in organic farming systems.

6. Concluding remarks and potential directions of future researches

The increasing need of circular economy drives on-farm composting of agricultural biomass waste as a viable option to enhance on soil quality, plant health, and crop protection due to its own multiple beneficial effects. Additionally, on-farm composting meets the bioeconomy requirement because it valorizes agro-waste or biomass unsuitable for energy production. Agricultural utilization of compost meets the targeted 20-20-20 objectives of the EU countries to decrease the quantity of organic waste going to landfill sites up to 20% by 2010 and 50% by 2050. On-farm compost application enhances productivity and quality of the vegetables supply chain and reduces the amount of agro-wastes, mineral fertilizers, plant fungicides, and soil fumigants. Combination of compost+BCA in tailored formulates likely constitutes a viable challenge towards the success within the IDM frameworks. Some questions on how compost may influence soil microbiota by compost in combination with BCAs to develop more stable and effective formulations are still left open for further researches. Use of crude compost-based substances and their derivative purified formulates is considered suitable frontier for cleaning the vegetables supply chain thanks to their easy application by foliar spraying and soil/root drenching. CTs as well as tailored mixtures of humic acids, fulvic acids and humin have greater benefits on plant growth and plant health by combined application to plant root and aerial parts. This double application in a single intervention represents an ambitious challenge for organic agriculture. Farmers even will move towards better and more efficient enriched(fortified)-formulates containing biotic and abiotic components responsible of the agronomical and phytopathological advantages. Liquid compost-based formulates to low dosage represent new frontiers for producing low-impact vegetables with benefits for human health and environmental safety.

The benefits described here are susceptible to potential directions of future researches for exploiting the most promising properties of compost-based formulations in agreement with the market requirements and governmental policies. First, regulatory standards on the quality control of organic amendments must be certainly improved. Despite the increased microbiome characterization of compost in relation to key roles in nutrient cycles and mineralization, the microbial composition is often not routinely monitored when analyzing compost and CTs quality. Moreover, measurement of the heavy metals content is usually required without pay attention to many others organic contaminants, overall due to high cost restrictions for farmer. There is a strong demand for reliable and simpler diagnostic markers that can integrate the information regarding the risks–benefits balance associated with the use of compost and CTs. For instance, abundance of integrase intl1 gene appeared to be suitable diagnostic marker. Second, the complex European regulation frameworks, manure surplus, variability in availability and transporting compost, variability in compost quality and composition, are hard barriers against the cleaner vegetables supply chain, but recommendations, novelties, and innovations that could reduce over time a number of barriers are however available. Third, I would recall again that the use of on-farm compost by agricultural residual biomass in horticultural farming systems represents a better way to solve the dual concerns of the agro-wastes disposal and high-value added formulates production by implementing the biorefinery approach. Fourth, several critical factors as: availability of technology suppliers and authorities, low energy and water requirement, low bio-fertilizers prices, and existence of renewable residual sources in global frameworks have been identified and discussed here. Fifth, economic factors affecting the farmer's decision about composting management and compost application on larger scale are depending on the density and intensity of the farming system in a specific area. In perspective, is strongly recommended the creation of farm's networks to optimize all steps of the composting chain. However, centralized on-farm composting sites that allow optimization of the logistic of whole chain should be implemented in the near future.

Declaration of competing interest

The author declares there are no any actual or potential competing interests including any financial, personal or other relationships with other people or organizations.

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