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## EXECUTIVE SUMMARY

### Background

The EUCLID project has the ambition to deliver the simultaneous optimization of current pest management methods and the development of novel ones, and to promote their rapid adoption through the design of IPM packages and exploitation by end-users. This will reduce the dependence of European and Chinese farmers on chemical pesticides in selected key farming systems in both regions.

Soil-borne pathogens are among the key problems that farmers are facing worldwide and novel solutions are necessary, within a circular economy and more sustainable approach, such as the use of compost.

### Objectives

EUCLID will contribute to the development of novel solutions for the management of soil-borne plant pathogens, such as the use of compost. Main objective is to provide indications for the optimal use of compost for controlling plant pathogens.

### Methods

Literature review, results from trials carried out in WP1 and expertise from AgriNewTech were used as methods.

### Results & Implications

Compost can be produced from many different type of biowastes, including crop residues, both at small scale and industrial scale. Compost can be applied, at soil level or as a component of growing media, to control soil-borne pathogens. Furthermore, it is possible to fortify composts with beneficial microorganisms to further enhance its suppressive capacity and plant growth promotion. The use of compost as alternative to chemicals should be encouraged, as well as the implementation of systems for composting of crop residues.
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Introduction

The EUCLID project has the ambition to deliver the simultaneous optimization of current pest management methods and the development of novel ones, and to promote their rapid adoption by end-users. This will reduce the dependence of European and Chinese farmers on chemical pesticides in selected key farming systems in both regions. This document aims to provide useful indications for the use of compost for controlling plant diseases, according to a literature review, results from trials carried out during Euclid project and expertise from AgriNewTech.

Vegetable crops are high value production systems, economically important worldwide, facing severe limitations in the use of chemicals and continuous innovations and adaptations to climate change and new diseases (Gilardi et al., 2018). Many new crops and varieties were introduced in the last decades, together with changes in the horticultural industry and in the food market. Potted plants are partially replacing cutted aromatic and ornamental plants, while new products such as ready-to-eat processed salads are requesting improved growing techniques and new production areas. Rapid changes in the production systems are influencing disease development and their management. Together with the phase-out of methyl bromide and the regulatory constraints for the use of soil fumigants, growers are facing also new diseases as a consequence of the introduction of new cultivars and crops and the intensification of the production systems (Colla et al., 2012; Gilardi et al., 2018).

Soil-borne diseases, caused by fungi and nematodes, are major yield-limiting factors and they are difficult to control, taking away approximately 10% of the World’s global agricultural output and causing economic losses valued at over $125 billion each year (Chitwood, 2003). Applied knowledge on suppression techniques seems to be limited. Methyl bromide was one of the most widely used pesticides to control soil-borne diseases, but due to its ozone depleting...
characteristics, The United Nations (Montreal protocol) made the decision to phase out its use in 2010 in developed countries and in 2015 all over the world (Colla et al., 2012). Other soil disinfectants such as chloropicrin, dichloropropene and methylisothiocyanate are also being limited in more and more European countries (Colla et al., 2012). This increases the need for sustainable and economic alternatives.
1. Soil health and soil suppressiveness

1.1. Soil health

The absence of an integrated approach to soil health and soil quality in general is the main cause of problems regarding soil-borne diseases. A lack of awareness and knowledge along the production chain, resulting in a lack of knowledge-based planning, monitoring and a lack of preventive measures leads to a reactive and preventive approach for controlling them.

Soil health is the biological condition of the soil which determines potential yield. Soil health is more than just the absence of disease. It is about equilibrium in the soil: the ability of the soil to cope with new incoming diseases and keep pest and disease population levels sufficiently low so that crops do not suffer damage (Janvier et al., 2007; EIP-AGRI, 2015).

The physical, chemical and biological characteristics of a soil determine its quality. These characteristics are strongly interrelated. Soil is not just a stacking of mineral parts mixed with organic matter. A soil is full of life, it is a complete ecosystem. Species that cause soil-borne diseases are mostly just a minority in the whole ecosystem, which includes many different fungi, bacteria, insects, protozoa and nematodes (EIP-AGRI, 2015). These species interact so it is important to develop a soil health strategy instead of just concentrating on one species which causes a single disease.

Several interactions occur between the populations and the soil which built the soil ecosystem.

Disease potential is not only linked to inoculum density (= population levels of organisms which can cause diseases) but also to the capacity of this inoculum density to provoke the disease on a susceptible crop. The whole microbiota does not only control the inoculum density but also the
inoculum capacity to infect the crop. Soil suppressiveness (the capacity of the soil to suppress the development of crop diseases) most often results from the antagonistic activity of the microbiota suppressing the activity of the inoculum, rather than from a low inoculum concentration (EIP-AGRI, 2015). In other words, other organisms present in the soil can often prevent the organisms that cause crop diseases from actually doing so; these are called antagonists. It is not a question of whether a pathogen is present or not even its abundance, but what matters to farmers is its disease potential in a particular soil under certain circumstances.

Whether damage is caused depends on the amount of pathogens present, abiotic and biotic soil conditions (humidity, pH, oxygen, nutrients, the soil food web, antagonists etc.), the tolerance of the crop and climatic conditions (EIP-AGRI, 2015). Everything that improves the vigour of the crop increases its tolerance to damage. Improving soil health starts with optimising soil conditions in terms of its physical, chemical and biological properties, to optimise growing conditions for crops. Very often however, there is very little knowledge available on the mechanisms of interaction between the different factors. It is especially important to know when a potentially neutral factor becomes a "risk factor", either on its own or when combined with others. When growing conditions are optimised, crops are much more tolerant to soil-borne diseases present in the soil, and as a result their impact on crop growth is minimised, but usually not sufficiently. It is necessary to control soil-borne diseases according to the concept of a soil health strategy.

The amount of disease depends on cropping frequency and on the sequence of crops. This is especially the case for specialised organisms with small host ranges. In the case of polyphagous organisms (organisms which infect many different crops) for example *Rhizoctonia solani* and *Verticillium dahliae*, the decisive element is the sequence of crops and the number of host crops within the rotation. To develop a soil health strategy, thorough knowledge on biology and the epidemiology of the diseases is essential.

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Soil health:

- is the biological condition of the soil which determines potential yield;
- is the ability of the soil to cope with new incoming diseases and keep pest and disease population levels sufficiently low so that crops do not suffer damage;
- depends on the physical, chemical and biological characteristics of the soil.

1.2. Soil suppressiveness

Soil suppressiveness is considered a complex system in which soil, microflora and plants play the main role. Suppressive soils or substrates are those in which the disease development is naturally controlled, even in the presence of a virulent pathogen, a susceptible plant host and with good environmental conditions for the development of the disease (Pugliese et al., 2015). Both biotic and abiotic elements are considered to be important for the suppression of plant diseases, but the microbial activity is considered as a key element. All natural soils have a general disease suppression compared to the same pasteurized soil, and it is directly related to the amount of microbial activity. In cropping systems, due to soil cultivation and management, a specific suppression is concerned, where an individual or group of microorganisms, selected for their antagonistic activity, is directly responsible for disease suppression.

Disease suppressiveness depends on soil or substrate properties, including both abiotic and biotic parameters (Mazzola 2004; Janvier et al. 2007). Regarding the influence of physicochemical properties of suppressive soils and substrates towards diseases, soils with higher pH showed to more suppressive towards Fusarium wilts (Höper et al. 1995) but conducive for nematodes (Rimé et al., 2003). Acidic pH reduce incidence of potato scab caused by Streptomyces scabies (Lacey and
Wilson 2001) or enhance suppression of take-all of wheat with *Trichoderma koningii* (Duffy *et al.*, 1997). Concerning the N content of soil, a positive association was found on the suppressiveness towards *Pseudomonas syringae* on bean and cucumber (Rotenberg *et al.*, 2005), *Fusarium* spp. on asparagus (Hamel *et al.*, 2005), *Gaeumannomyces graminis var tritici* and *Rhizoctonia solani* on wheat (Pankhurst *et al.*, 2002), and ectoparasitic nematodes (Rimé *et al.*, 2003). The form of N, either NO$_3^-$ or NH$_4^+$, is also important (Janvier *et al.*, 2007), and NH$_3$ or HNO$_2$ showed to be able to kill microsclerotia of *Verticillium dahliae* in several soils (Tenuta and Lazarovits 2004). Higher C content showed to reduce incidence of Pythium damping-off of tomato and *Fusarium solani* f. sp. *pisi* on pea and *Fusarium culmorum* on barley, but to positively affect *Thielaviopsis basicola* (Oyarzun *et al.*, 1998; van Bruggen and Semenov 1999; Rasmussen *et al.*, 2002).

Other physicochemical characteristics are also important, like soil texture, cations and oligoelements. Suppressiveness to Fusarium wilts of flax and Armillaria root disease on lodgepole pine was found to be reduced in sandy soils (Höper *et al.*, 1995; Mallett and Maynard 1998). Higher clay content was associated with less *Gaeumannomyces graminis var. tritici* on wheat after treatment with *Trichoderma koningii* (Duffy *et al.*, 1997). No correlation on fusarium wilt of banana (Dominguez *et al.*, 2001) and Fusarium root rot of asparagus (Hamel *et al.*, 2005) were found between soil texture and suppressiveness instead. Higher levels of Mg and K were found to reduce incidence of fungal disease (Duffy *et al.*, 1997; Peng *et al.*, 1999) and suppressiveness of nematodes (Rimé *et al.*, 2003), providing contrasting results depending on the pathogen. Al, Fe, Na or Zn contents generally reduced disease levels (Oyarzun *et al.*, 1998). After analyzing 28 physical and chemical properties of 10 soils, Ownley *et al.* (2003), found that 16 soil properties were correlated with disease suppression and proposed a model including 6 key soil properties (N–NO$_3^-$, CEC, Fe, % silt, soil pH and zinc) to explain the variance in take-all disease of wheat treated with phenazine-producing *Pseudomonas fluorescens*. 

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The application of organic amendments is a strategy commonly used in traditional agricultural systems for providing nutrients to the crops and for improving soil fertility. Several chemical and biological changes in the soil are associated with the incorporation of amendments and correlated to the control of soil-borne diseases, with a good potential for their management thus reducing chemical inputs (Bailey and Lazarovits 2003; Bonanomi et al., 2007; Bonilla et al., 2012). However, a widespread use of organic amendments for disease control is still not being achieved, due to many factors such as the type of amendments, the lack of standardization, the inconsistency in their efficacy and the complexity in their use. In most cases, the application rates effective under controlled conditions are too high for field crops, in others prior crop management practices do not allow a proper use of amendments. A gap between good results observed in laboratory and greenhouse compared to few promising results in the field is still relevant today, as mechanisms of action are largely unknown and risk avoidance is too much limited compared to other disease control strategies. Some studies indicate that the effectiveness of organic amendments is variable and, in some cases, can enhance severity of some diseases (Mazzola 2007).

Organic amendments include manure, crop and food residues, compost, organic fertilizers etc. Their use can help to control soil-borne pathogens in vegetable and ornamental crops, especially when applied in conjunction with other management practices and considering a system approach. The aim is to maintain the soil stable and resilient and to promote a self-regulation and self-balance of the agro-ecosystem. Such an approach is very interesting in the case of organic farming, where the use of amendments, in combination with mulching and other cultural practices, is effective against many soil-borne pathogens.

Amendments can be applied together with other methods, like soil solarization, anaerobic soil disinfestation and soil fumigations, to reduce the density of pathogens. When added to soil,
amendments such as cow or poultry manure, cruciferous residues are subjected to microbial degradation that results in the generation of both toxic and volatile compounds directly affecting soil-borne pathogens propagules or indirectly increasing microbial antagonistic activity in the soil. Positive effects of solarisation integrated with organic amendment have been observed for several soilborne fungi (Rhizoctonia solani, Pythium spp., Fusarium oxysporum, Verticillium spp., Sclerotium rolfsii), nematodes and also many weeds (Gamliel 2000; Mattner et al., 2008). However, released toxic compounds may result in phytotoxic effects on crops and some limitations to practical applications. In other cases they are applied integrated with agronomical strategies, like the use of resistant grafted plants, in order to delay the root infections and provide additional times for the establishment of disease suppressive microbial communities in the rhizosphere. The application of organic amendments can further promote the re-establishment of a more balanced and suppressive soil microflora, when combined with cultural practices like no-tillage and soil mulching. Furthermore, the development of plant disease is reduced thanks to the good root systems growing in a soil rich in organic matter and managed accurately (Chellemi 2010).

Among organic amendments, composts are considered those more promising (Pugliese et al., 2015).

A suppressive soil or substrate is:

- the one in which the disease development is naturally controlled, even in the presence of a virulent pathogen, a susceptible plant host and with good environmental conditions for the development of the disease;
- a complex system in which both biotic (microflora) and abiotic elements are important.
2. Compost

2.1. Compost production

Compost is a product that results from microbial decomposition of organic matter, such as recycled plant waste, biosolids, fish or other organic material, under aerobic conditions (Pugliese et al., 2015). Composting is a process which turns biomass into compost with the use of oxygen and certain microorganisms. Increasing the opportunities to use compost in agriculture and in particular in horticulture as a (potting) substrate for plants would contribute to the recycling of wastes and to reducing the use of non-renewable fertilizers.

Depending on composting method, size, intensity of the operation and the input material, a large range of qualities can be produced.

Sources of organic matter for compost are numerous: urban organic wastes, industrial wastes, manure, crop wastes. What is important for all type of compost is to begin the process with a high C/N rate, increase the plant fiber content to increase this rate and to obtain a final product rich in humic substances. However, the most important subject related with quality will be the absence of different physical, chemical and microbial contaminant (Channarayappa and Biradar, 2018). Compost can be produced locally or at farm level using simple methods. This process contributes to a sustainable agriculture production.

Compost is:

- produced from sources of organic matter;
- locally, at farm or at industrial scale.
2.2. Compost quality

Quality aspects of compost are of most importance in order to ensure a proper use in agriculture. Compost quality refers to the overall state of the material with regard to physical, chemical and biological characteristics (Pugliese et al., 2015). These parameters are indicators of the ultimate impact of the compost on the environment. In particular, the most important parameters from the point of view of environment protection standards, public health and the soil are those related to pathogens, inorganic and organic potentially toxic compounds (heavy metals) and stability. Within the EU, standards on the use and quality of compost exist in most Member States, while there is not yet a comprehensive European Community legislation. Most regulations in the EU only apply to the nutrient and heavy metal content, beside of some other chemical characteristics (pH level, electrical conductivity etc.) (Pugliese et al., 2015). Moreover, common analysis are not enough to assess compost quality according to specific uses, such as for potting mixes, vegetable and ornamental crops, soil-less systems and for suppressing plant diseases. Consequently, it is important to define and use also agronomical tests to assess compost quality and compost suppressiveness to plant pathogens.

Farmers’ willingness to use compost is strictly connected to various quality aspects of compost. Compost is commonly used as a soil amendment to increase organic matter content and fertility by improving physical, chemical and biological soil conditions (Hoitink and Fahy 1986). The nutritive value of composts and their potential to enhance soil quality makes them ideal for agriculture but may unnecessarily increase the heavy metal content of the soil when applied at high dosages (Ramos and López-Acevedo 2004). Composts have the advantage to significantly increase soil organic matter contents, a key soil quality indicator that is on the contrary declining in many regions of the world (Bellamy et al., 2005). Additional benefits of compost addition to soil are promotion of soil biological activity, reduction of erosion losses, decrease of bulk density,
improvement of structural stability, nutrient availability and plant uptake, increase of water holding capacity (Shiralipour et al., 1992; Tejada and Gonzalez 2007). Compost is also interesting as a peat substitute, in particular after recent increasing concern of the environmental impact of peat extraction and the damage of peat lands natural habitats by the horticulture industry that lead to the adoption of alternative substrates (Silva et al., 2007). Also in field horticulture, there are great market opportunities for compost, although its use on leafy vegetables is unlikely due to the potential for microbiological contamination by human pathogens, especially in the case of municipal solid waste compost (Farrell and Jones 2009).

Compost most important quality parameters are:
- physical, chemical and biological;
- the nutritive value;
- the stability;
- the absence or limited content of pathogens, inorganic and organic potentially toxic compounds (heavy metals).
2.3. Compost use according to specific applications

The specific applications for the compost use are soil improver, growing media, plant disease suppression and also other applications. Compost is commonly used as a soil amendment to increase organic matter content and fertility by improving physical, chemical and biological soil (Pugliese et al., 2015). The nutritive value of composts and their potential to enhance soil quality makes them ideal for agriculture, but may unnecessarily increase the heavy metal content of the soil when applied at high dosages. Composts have the advantage to significantly increase soil organic matter contents, a key soil quality indicator that is on the contrary declining in many regions of the world. Additional benefits of compost addition to soil are promoting soil biological activity, reducing erosion losses, decreasing bulk density, improving structural stability, nutrient availability and plant uptake, increasing the water holding capacity (Channarayappa and Biradar, 2018). Crop growth or yield is usually increased by compost amendments in the field (Channarayappa and Biradar, 2018). Compost obtained from the organic fraction of municipal wastes (biowaste) can be used as an organic fertilizer on agricultural soil; his high level of organic matter and nutrients guaranteed benefits such as higher porosity and structural stability. The addition of compost into soil, has a positive impact on soil structure because it resist compaction and increases water holding capacity (Channarayappa and Biradar, 2018). If the content of humus is high, the soil will be more resistant to erosion. The increase of soil porosity affects oxygen availability in soil thus reducing the incidence of anaerobiosis in soil and then the production of greenhouse gases, and stimulating soil activity and root respiration (Channarayappa and Biradar, 2018). Applying a stable source of organic matter such as compost will result in a net accumulation of organic matter on the long term. There are many compounds within compost that influence the biological process in soil, improving the physical and chemical characteristics. Humates improve the soil structure which enables the roots to penetrate the soil. Improving root growth, the stability of trees increases and
the water stress decreases. The organic molecules increases the adsorption and retention of nutrients in the soil and the micro-nutrients added to the soil by compost could replace a fertilizer.

The use of very large amounts of compost is not good practice, especially on well-drained soils and when the plants are unable to retrieve the nutrients from the soil. C:N content and K-content are important indicators of how well composts could supplied the soil with nutrients and the content of K and P and the content of metals are good guides to what amounts need to apply. Large amount of compost can satisfy a plant’s need for nitrogen and the contents of P could be the constraint determining the application of compost. High concentrations of metals such as Fe or Al, could not make available P to the plants because of immobilization (Channarayappa and Biradar, 2018). The rate that gives the best results may be very different from one plant species to the next. Generally the average doses of application vary from 5 t/ha to 30 t/ha according to soil and crop uptakes, and spring is the best time for applying compost. Before applying compost it is necessary to prepare the soil for example by removing weeds and during application of the compost it is advisable to plow the soil to a depth of 30-40 cm. It might be possible to achieve good results also with minimum-tillage techniques. It is possible to apply compost to the soil using compost-spreaders, or if the surface is not too extensive as in the case of a small greenhouse, it is possible to spread it by hand.

The use of compost is also interesting as a peat substitute, in particular after recent increasing concern on peat extraction and the damage of peat lands natural habitats by the horticulture industry that lead to the adoption of alternative substrates. Also in field horticulture, there are great market opportunities for compost, although its use on salads is unlikely due to the potential for microbiological contamination by human pathogens, especially for municipal solid waste compost (Franceschini et al., 2016).
However, composts can hardly be used alone as a growing media; it is necessary to do a germination test or compost analysis to determine the suitability because of possible damages on plants due to excessive salinity.

Mature composts are characterised by the absence of substances inhibiting seed germination and plant growth. Acetic acid is one of the damaging organic acids released from fresh compost, but there are also other compounds such as acetaldehyde, ethanol and acetone that can cause phytotoxic effect.

Mixing compost with other materials such as soil, sand or peat could modify the pH, and nutrient concentration, improving the physical properties. When compost is used as a part of the organic fraction of growing media, it has been shown to reduce fertilizer and liming needs, to improve crop vigor, to reduce the need for fungicidal drenches, and to improve root growth. For example, organic stable products such as composted softwood bark and biowaste compost contain essential plant nutrients. If biowaste feedstock changes, the quality of the compost will be different. The variations in texture, size and mineral composition, have a great importance when compost is use with other constituents in a plant container. The variability in the growing substrate could cause problems if it affects growth rate, nutrition or plant form. The use of compost provides environmental and economical benefits because wastes are re-used and costs are lower than the other conventional materials.

In conclusion, compost can be used as growing media only if <1000 µs/cm electrical conductivity, otherwise it has to be mixed with other materials, such as peat, up to 20% volume/volume. It is recommended not to sterilize the compost, in order to avoid the loss of beneficial microorganisms and part of the nutrients, and, when mixed with other materials, to wait at least 48 hours before using the growing media.

Compost can be used also to reduce soil erosion, the act of exogenic processes possibly reducing the ability of plants to establish, grow and remain healthy in the soil.
Compost can be used:

- as soil amendment for increasing crop growth or yields, promoting soil biological activity, reducing erosion losses, decreasing bulk density, improving structural stability, nutrient availability and plant uptake, increasing the water holding capacity;
- as soil improver, as a peat substitute.
3. Compost suppressiveness

3.1. Compost quality in relation to compost suppressiveness

The suppressive capacity of compost against soil-borne pathogens has been demonstrated in several studies, and, consequently, the use of disease suppressive compost can reduce crop losses caused by soilborne diseases and benefit growers (Hoitink and Fahy 1986; Hoitink and Boehm 1999; Noble and Coventry 2005; Pugliese et al., 2007; Hadar 2011; Pugliese et al., 2015). Compost showed to be the most suppressive material, with more than 50% of cases showing effective disease control, compared to other amendments such as crop residues and peat (Bonanomi et al., 2007). In field trials compost showed, in most experiments, to be suppressive when an application rate of at least 15 t/ha. Compost prepared from cannery wastes was able to suppress anthracnose caused by Colletotrichum coccodes and bacterial spot caused by Xanthomonas campestris pv. vesicatoria on tomato in soil (Abbasi et al., 2002). Lower applications, like 4 t/ha, has also been reported to be sufficient for reducing dry root rot of bean caused by Macrophomina phaseolina (Lodha et al., 2002). In other cases, repetition for five consecutive years of compost at 10 t/ha was necessary to suppress damping-off of cucumber and lettuce caused by Pythium ultimum and Rhizoctonia solani (Fuchs 1995). Suppressive effect of compost is generally proportional to the inclusion rate in soil, like in the case of damping-off of cress by P. ultimum and wilt of flax by Fusarium oxysporum f. sp. lini (Fuchs 1995; Serra-Wittling et al., 1996), but not always. Application of compost suppressed root rot of chile peppers caused by Phytophthora capsici when applied at 48 t/ha, but at higher rates (72 t/ha) promoted the disease, probably by increasing soil salinity (Dickerson 1999), and suppressed damping-off caused by R. solani. However, disease promotion of root rot of bean caused by R. solani on soil amended with dairy manure compost has also been observed (Voland and Epstein 1994). In the case of vascular diseases caused by Fusarium species and root rots and damping-off caused by Pythium species, compost amendment of soil generally suppressed or unaffected the diseases (Noble and Coventry 2005). Different results can be obtained...
by different composts on the same pathosystem. For example, verticillium wilt of potato caused by *V. dahliae* was promoted by dairy manure compost but suppressed by vegetable waste compost (Noble 2011). Soil type and conditions, like texture, pH and moisture, can also influence suppressiveness to soil-borne pathogens (Bruehl 1975). Coventry *et al.* (2005) found that vegetable waste compost was ineffective against *Sclerotium cepivorum* in a silt soil, but suppressive on the same pathogen, causal agent of *Allium* white rot, in sandy loam and peat soils.

In container experiments using soil or sand, compost derived from green wastes and/or dairy cow manure generally showed a suppressive effect on *Pythium* species and *Rhizoctonia solani*, but results did not necessarily translate into the field (Noble and Coventry 2005). Compost equally suppressed white rot of onion caused by *Sclerotium cepivorum* in pot tests and in the field (Coventry *et al.*, 2005). In other experiments composites suppressing *Phytophthora* on citrus seedlings in pot experiments was ineffective in field trials with the same soils (Widmer *et al.*, 1998). Compost suppressiveness also showed to be dependent on the type of wastes used for preparation. For example, bark compost suppressed *Pythium* root rot, while grape marc showed neutral or promoting effects to disease (Erhart *et al.*, 1999), and vermicomposted animal manure suppressed infection of tomato seedlings caused by *Phytophthora nicotianae*, but not root and stem rot of cucumber caused by *Fusarium oxysporum* f.sp. *radicis-cucumerinum* (Kannangara *et al.*, 2000; Szczech and Smolinska 2001).

Low rates of compost in growing media are generally indicated, in order to avoid negative growth effects and phytotoxicity caused by high pH and electrical conductivity, and other phytotoxic compounds present in composites (Sullivan and Miller 2001). However, it is generally necessary to include at least 20% v/v of compost in containers in order to observe a suppressive effect. Lower rates are successfully applied for few specific cases, like *Ralstonia solanacearum* and...
Rhizoctonia solani (Voland and Epstein 1994; Islam and Toyota 2004). Cases of increase of disease severity caused by composts used in containers have also been reported. A 50% spruce bark compost increased black root rot caused by Thielaviopsis basicola in poinsettias and Fusarium wilt of cyclamen, compared to a peat substrate (Krebs 1990). Highly saline composts were reported to enhance Pythium and Phytophthora diseases, while composts with higher nitrogen or ammonium content enhance Fusarium wilts (Hoitink et al., 2001). Among soil-borne pathogens, Rhizoctonia solani is considered to be the most difficult one to be controlled with compost (Scheuerell et al., 2005; Bonanomi et al., 2007). Variability also depends on the pathosystem. A compost from wood chips and horse manure stimulated disease caused by Rhizoctonia solani on cauliflower, but suppressed it on pine (Termorshuizen et al., 2006). Success or failure of compost for disease control depends on the nature of the raw materials from which the compost was prepared, on the composting process used and on the maturity and quality of the compost (Termorshuizen et al., 2006). Composting temperatures are important also for the eradication of plant pathogens and nematodes and the sanitization of compost (Noble and Roberts, 2004).

For the issue of soil-borne diseases the most critical ingredients are the organic matter (including humic substances, humic and fulvic acids) and the microbial community and its activity.

Compost quality in relation to soil-borne diseases depends on:

- Resources
- Production process
- Production technology
- Management and process controlling
- Storage conditions
- Use and application

Physical-chemical properties (pH, CE, CIC, OM content, humic substances, porosity, C/N rate, nutrient content, ...) are very important for plant growing, microbial developing, plant pathogen
survival, and relation with other factors very important for all these mentioned, such as water drainage, temperature soil control, or macro and micronutrients availability.

Microbial properties (microbial richness, diversity,...) is a quality parameter for soil-borne disease suppression, and for movement or recycling organic matter, induced resistance to plant pathogen in plant.

Absence of Human pathogens is a quality parameter of compost to be added in crop soil, overall when products are consume as fresh products. This is from food security point of view. Very important when compost is made with urban organic wastes or manure.

Absence of plant pathogens is a quality parameter of compost to be added in crop soil, when it has been made with plant wastes.

Limits of heavy metal contamination is a quality parameter since environmental and food security point of view, very important in compost obtained from industrial and urban organic wastes).

Limits of chemical contamination (pesticide residues) is a quality parameter since environmental and food security point of view.

Other concerns with compost application are related to solid contaminants (glass, metal, plastic, etc.), which should be limited or completely avoided, costs for process and application, costs for technical equipment, quality control and certification.
3.2. *Mechanisms of action of compost suppression and enrichment with microbials*

In the case of suppressive composts, higher rates of CaO, MgO, K₂O and N–NH₄ and a higher CEC showed to suppress *Rhizoctonia solani* more than the control soil (Pèrez-Piqueres *et al.*, 2006). A loss in the disease suppressive effect of composts following sterilization or heat treatments has been demonstrated in several papers (Hoitink *et al.*, 1997; Cotxarrera *et al.*, 2002; Reuveni *et al.*, 2002; Chen and Nelson 2008; Pugliese *et al.*, 2011). A declining of microbial activity after long periods of maturation and, consequently, a reduction of disease suppression has been also reported (Zmora-Nahum *et al.*, 2008).

Also the use of water extracts from composts showed to suppress several soil-borne pathogens (El-Masry *et al.*, 2002), indicating a predominant biological component rather than chemical or physical in the suppressive effect. Compost acts as a food source and shelter for the antagonists that compete with plant pathogens or parasitize them, for those beneficials that produce antibiotics and for those microorganisms that induce resistance in plants: high-quality compost should contain disease-suppressive microorganisms (Noble and Coventry 2005; Hadar 2011). Fortifying composts with beneficial microorganisms is also one possible factor that can help in the success of compost, increasing the efficacy and reliability of disease control (De Clercq *et al.*, 2004).

According to Hoitink and Boehm (1999), the following biological mechanisms are involved in compost suppressiveness:

a. competition for nutrients by beneficial micro-organisms;

b. parasitism against pathogens by beneficial micro-organisms;

c. antibiotic production by beneficial micro-organisms;

d. activation of disease-resistance genes in plants by micro-organisms (induced systemic resistance);

e. improved plant nutrition and vigour, leading to enhanced disease resistance.
The mode of actions a, d and e generally occur when disease suppressiveness is not accompanied by a reduction in soil-borne pathogen inoculums (Lumsden et al., 1983; Lievens et al., 2001).

Bacteria belonging to genera Bacillus spp., Enterobacter spp., Pseudomonas spp., Streptomyces spp., Penicillium spp., as well as several Trichoderma spp. isolates and other fungi have been identified as biocontrol agents (BCAs) in compost-amended substrates (Chen et al., 1987; Boehm et al., 1993; Hoitink et al., 1997; Boulter et al., 2002; Pugliese et al., 2008). The isolation from roots of eggplants grown in compost of strains of Pseudomonas fluorescens and of Fusarium oxysporum controlling Verticillium wilt, and the presence of microbial species that interact at rizosphere level and suppress the disease of plants germinated in compost indicate that suppression is related to microorganisms, rather than to the growing substrate (Malandraki et al., 2007; Chen and Nelson 2008). Microorganisms, selected from a compost suppressive against fusarium wilts, controlled Fusarium oxysporum and few of them other soil-borne diseases like Phytophthora nicotianae and Rhizoctonia solani (Pugliese et al., 2008). The addition of such microorganisms and BCAs might be considered a good strategy to increase compost suppressiveness and to partially restore disease suppressiveness of steam sterilised compost (Pugliese et al., 2011).

The presence of toxic or volatile compounds in compost, sometimes correlated with changes to the physical properties of the growing medium or soil or to soil pH and conductivity, are other possible mechanisms (Noble 2011), suggesting compost use as alternative to chemical fumigants for managing soil-borne pathogens, also integrated with soil solarization (Katan 2000). Immature composts release volatile compounds containing sulphur, organic acids, and ammonia that may be
responsible for disease suppression (Scheuerell et al., 2005; Coventry et al., 2006). Phytotoxic compounds produced by soil microorganisms after application of farmyard compost was found to suppress apple replant diseases (Gur et al., 1998). Investigating a wide range of biological and chemical characteristics of composts and compost-peat mixtures in relation to plant disease suppression, Termorshuizen et al. (2006) demonstrated that only pH increase resulting from compost amendment showed a consistent relationship with the suppression of some diseases, such as *Fusarium oxysporum*, but that there is no single factor conferring suppressiveness to composts.

Functions of compost in respect of soil-borne disease can be summarized in three groups: biological, physical and chemical properties.

- **Biological properties:**
  - Micro-organisms (e.g., bacteria, fungi, protozoa, nematodes): compost acts as a food source and shelter for the antagonists that compete with plant pathogens or parasitize them, for those beneficials that produce antibiotics and for those microorganisms that induce resistance in plants.
  - Macro-organisms (e.g., earthworms) breed microorganisms in their gut and feed them through mucus: They also provide physical properties like porosity and biological fixed soil aggregates. The chemical characteristics (availability of nutrients for plants, plant growth substances etc.) of their fecal is changed compared to the input material.

- **Physical properties:**
  - Soil texture and structure (porosity, water storage capacity) significantly influence the development of root disease. Well-aerated, well-drained soils create conditions that discourage root diseases. Soils that drain poorly, however, tend to favor the survival and distribution of soilborne pathogens such as *Pythium* and *Phytophthora*. Only a few root
diseases are favored by drier soils (for example, common scab of potato caused by Streptomyces scabies).

- **Chemical properties:**
  - pH, EC: for example clubroot disease of crucifers caused by *Plasmodiophora brassicae* is a major problem in acidic soils (5.7 pH or lower). The disease is dramatically reduced when the pH rises from 5.7 to 6.2 and is virtually eliminated at soil pH values greater than 7.3 to 7.4. Similarly, common scab of potatoes is favored by a pH of 5.2 to 8.0 but is reduced dramatically by soil pH values lower than 5.2.
  - Micro- & macronutrients. High levels of soil nitrogen increase the growth rates of crops, prolong the plants vegetative phase and enhance the growth of succulent plant tissue. Plants in this condition are more vulnerable to attack by some soilborne pathogens. On the other side, low levels of soil nitrogen weaken plants and may predispose them to attack by some pathogens.
  - Organic carbon.

Direct inhibitory effect of compost on soil-borne diseases are related to competition for nutrients, Humic substances content, Toxic volatiles, victim-predatory relationship. Indirect effect via the plant are related to: plant growth (compost delivers nutrients for the plant); reduction of common plant stress; induced resistance for plants; enhanced soil structure.
3.3. Use of compost to control soil-borne pathogens

Compost application to control soil-borne pathogens can be carried out at soil level or with growing media.

For soil applications, it is recommended to proceed in this way:

- Soil preparation by mechanical ploughing up to 30-40 cm depth.
- Spreading of compost with compost-spreader or manure-spreader at 10-30t/ha according to crop uptakes and soil conditions. To be carried out in autumn or, if the compost is mature, 3-5 days before sowing/transplanting.
- Tilling with a mechanical cultivator and sowing/transplanting.
- Do not disinfect the soil after the application.
- It is possible to integrate it with soil solarization, biofumigation, grafting and other agronomical practices.

For applications as growing media, it is recommended to proceed in this way:

- Mix it to the growing media up to 20% v/v, at least 48 hours prior to sowing/transplanting.
- Do not steam sterilize it.
4. Conclusions

Control of soil-borne diseases with organic amendments must be viewed not as a stand-alone management approach but rather part of a system approach where several aspects of the impact of crop production practices on resident soil microbial communities are addressed. Compost suppressiveness can be used both for potted plants and for field crops, combined with other management strategies like soil solarization and grafting. Induce resistance by compost has also been observed, and consequently used for the control of other pathogens or pests. However, quality standards are required in order to avoid phytotoxicity effects on plants and reduce the variability in the control of diseases.
**Glossary**

ANT  Euclid project partner AgriNewTech srl

IPM  Integrated Pest Management, a combination of methods to achieve pest control efficiently
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EUCLID - Europe-China Lever for IPM Demonstration
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