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Review

Recycling of Organic Wastes through Composting: Process Performance and Compost Application in Agriculture

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Abstract: Composting has become a preferable option to treat organic wastes to obtain a final stable sanitized product that can be used as an organic amendment. From home composting to big municipal waste treatment plants, composting is one of the few technologies that can be practically implemented at any scale. This review explores some of the essential issues in the field of composting/compost research: on one hand, the main parameters related to composting performance are compiled, with especial emphasis on the maturity and stability of compost; on the other hand, the main rules of applying compost on crops and other applications are explored in detail, including all the effects that compost can have on agricultural land. Especial attention is paid to aspects such as the improvement of the fertility of soils once compost is applied, the suppressor effect of compost and some negative experiences of massive compost application.

Keywords: organic wastes; compost; soil; agriculture; fertilizers

1. Introduction

During recent decades, the generated amounts of solid wastes have been exponentially increased almost all over the world. This increase is attributed and correlated primarily with population growth. However, modern lifestyles and standards due to economic development and the associated increase in urbanization have greatly led in accelerating waste generation [1–3]. It was estimated that about 2 billion tons of solid waste were generated in the world's cities during 2016 [4]. This increase in waste generation has put pressure on or even disturbed the various components of the environmental system. Accordingly, the implementation of an appropriate and environmentally friendly management strategy for solid waste is recognized as an urgent need worldwide [5], whereas reuse and recycling of these wastes are categorized as the most preferable approaches in integrated solid waste management systems in a framework of a circular economy. In this regard, and in an attempt to increase economic sustainability through increased recycling, reuse and resource efficiency, the European Parliament recently adopted a circular economy action plan that includes various legislative proposals, including the EU fertilizer regulation [6]. This proposal aims at encouraging the production and the trade of fertilizing products within the EU market [7]. The new proposal will cover different groups of fertilizers, including organic products, like compost obtained from organic wastes. Actually, this orientation is in the favor of both humans and environmental interests, as it encourages the recycling of organic wastes into nutrients that can be used in agriculture [7,8].

In alignment with this orientation, and since the organic fraction represents a large portion of the generated waste, mainly from domestic wastes, this biodegradable portion could be recycled and used as a potential source of plant nutrients instead of being lost through improper disposal/treatment [9–11]. Nevertheless, it is important to point out that the direct application of fresh organic solid waste to land is not recommended. Particularly, the addition of immature/non-stable organic solid waste to soil might influence plant growth by specific substances or inappropriate growing conditions, including immobilization/imbalance of nutrients necessary for plants, phytotoxicity and the presence of heavy metals, pathogenic bacteria and inorganic salts, which ultimately lead to the inhibition of plant growth [12,13]. Consequently, the application of proper biochemical technologies would lead to the recovery of these nutrients that later might be safely used in agricultural fields [3,14]. Accordingly, composting technology has become an effective management approach for recycling and converting organic waste into a useful "compost" product with a high nutrient content and low prevalence of pathogenic microorganisms [15,16]. This technology provides a promising and sustainable solution as the produced compost would be used as fertilizer and thus improve productivity in terms of quantity and quality of agricultural products [17] and, at the same time, the conservation of natural resources [18], the protection of soil systems and the reduction of environmental impact [19]. Additionally, this technology is marked by its cost-effectiveness compared with other alternative options [20–22]. Importantly, compost can replace inorganic fertilizers, which are used in large quantities in agricultural activities. The continuous and intensified use of inorganic fertilizers can adversely affect soil composition and other environmental components [23]. Therefore, compost application is being promoted as an alternative to heavy chemical fertilization to enhance agricultural sustainability [24], and to restore soil organic carbon and nitrogen and improve soil aggregation [25]. Compost is characterized by a high organic matter content as well as abundance in macro- and micronutrients [26,27]. Positive effects on soil biological and physicochemical properties were recorded with the utilization of compost [28,29]. Additionally, using compost as a valuable alternative to artificial inorganic fertilizers due to their nutrient value, to improve the soil content in organic matter and consequently the long-term soil fertility and productivity, became widespread around the world. Additionally, they suppose a significant saving in fertilizer cost without loss of crop yield.

This review aims to provide information about the composting process as a method for the treatment of organic waste. Furthermore, a comprehensive overview about the characteristics of the final end product and its application in agriculture is introduced.

2. Composting Process

2.1. Process Parameters

Composting is an aerobic process, which requires oxygen, optimal moisture content and porosity to stabilize the organic wastes, and the common control variables are temperature, oxygen and moisture [30,31]. The microbial activity through complex metabolic processes is responsible for the decomposition and fractional humification (biological oxidative transformation) of the organic matter, which ultimately transforms it into a nutritious soil amendment, which is compost, a valuable stable, mature and contamination-free product for crop cultivation and soil fertility [31–34].

Nowadays, composting technology is being presented as an alternative scheme for solid waste management and valorization, especially for the organic fraction and, in general, organic solid wastes of all origins. When it is correctly handled, it provides the option to recover valuable nutrient resources, rather than disposing of them, thus reducing environmental pollution [5,35]. It is increasingly getting attention as an efficient and cost-effective process with minimum environmental risks. The process fundamentally relies on the conversion of organic matter into the stable, sanitized and high-quality end product "compost" through biochemical/biological actions [36].

During the composting process, several biochemical transformations take place. Consequently, a successful operation of the process essentially needs the preparation of the mixture within the recommended values to ensure product value and environmental safety [37–40]. During the process, temperature, oxygen, moisture, porosity and C/N ratio are recognized as important parameters for process control to obtain a good-quality product [30,41–43].

2.2. Composting Stages

In the composting process, microbial activity is responsible for decomposing organic matter, which finally produces the relatively stable organic end product that is the compost. Under favorable conditions, the composting process proceeds through several main phases, where different communities of microorganisms predominate during each composting phase. These phases include: (i) Decomposition "active" phase: As the microbial population begins to degrade the most readily degradable material and the population increases, the heat generated by the microbial activity accumulates within the pile and the temperature continues to increase steadily, passing from the mesophilic range (25–45 °C) to the thermophilic one (more than 45 °C). The thermophilic temperatures (55 °C and above) are desirable because they kill more pathogens, weed seeds and fly larvae in the composting materials [44]. Because temperatures over about 65 °C kill many forms of microbes and limit the rate of decomposition, compost managers use aeration and mixing to keep the temperature below this point, (ii) cooling phase: As the supply of high-energy compounds becomes exhausted, the compost temperature gradually decreases and mesophilic microorganisms once again dominate the pile, (iii) maturation "curing" phase: This takes place at a lower temperature, but still many naturally occurring reactions occur during this phase, although the microbial activity is relatively low compared with the previous stages. One of the characteristics in this stage is material humification, which gives an interesting value to the produced compost [45].

It is worth remarking that several composting methods can be applied, and the selection of the method is dependent on the capital cost, labor cost, time, the availability of land, etc. These methods include: Passive composting, turned composting, static aerated pile composting and in-vessel composting in all its forms.

2.3. Stability and Maturity of Compost

Among the different characteristics that determine the quality of the compost, especially for agricultural applications, are "stability" and "maturity". During the different composting phases, the degree of organic matter decomposition and humification highly affects the quality of the process end product [46–48]. As documented, mature composts increase soil organic matter (SOM) much better than fresh and immature composts due to their higher level of stable carbon (C) [49,50]. However, the incomplete decomposition and humification of the organic matter would cause the accumulation of harmful substances in soil and produce toxic effects in plants [13,51].

In this regard, and in order to avoid any such side effects, it is recommended to determine the quality of the compost by determining its degree of maturity and stability. Maturity is used to determine the compost suitability for agricultural purposes, considering its effect on plant growth and phytotoxicity aspects [52–54], whereas stability refers to the resistance of organic matter against extensive biodegradation or microbiological activity [55]. Importantly, when compost quality is to be determined, both characteristics (i.e., maturity and stability) are to be viewed and correlated together, because phytotoxic compounds are products of the microbial activity of unstable organic matter [56–58]. In the literature, different tests have been used to assess the stability and maturity of compost [58]. In this context, respiration techniques which are based on oxygen consumption by microbial activity are regarded as the most useful methods for determining compost stability and maturity, but germination tests are also widely used for the determination of compost maturity [59,60]. The respiration index for the degradation of different materials is correlated with the organic matter content and the biochemical reactions by microbial activities. For instance, materials with a respiration index between 0.5 and 1.5 mg O_2 g^{-1} OM h^{-1} are considered stable, while values higher than 1.5 mg O_2 g^{-1} OM h^{-1} correspond to unstable materials [61,62].

3. Application of Compost in Agriculture

The demand on agricultural products leads to the use of intensive agricultural systems, which ultimately deteriorate soil health and bring several environmental problems [3]. Actually, the recycling of organic waste through composting is viewed as a sustainable approach for waste management as it provides a valuable source of organic matter for enhancing soil organic matter content that is being deteriorated due to various anthropogenic activities, and it is recognized as a reliable approach for improving different soil properties. In this regard, the best practices, including fertilizer management with a focus on using organic fertilizers, can improve soil properties and provide various additional benefits to enhance the soil quality [25,63,64]. The effect of compost application onto soil highly depends on both soil and compost (feedstock) intrinsic properties, along with the compost application rate [49,50,65]. However, it is important to mention that the results of the application of this type of fertilizer may not be viewed within a short period due to the slow release of nutrients [66,67]. Figure 1 presents the schematic diagram of compost mineralization after application to soil. The different effects resulting from compost application to soil will be discussed in the subsequent sections of this research.

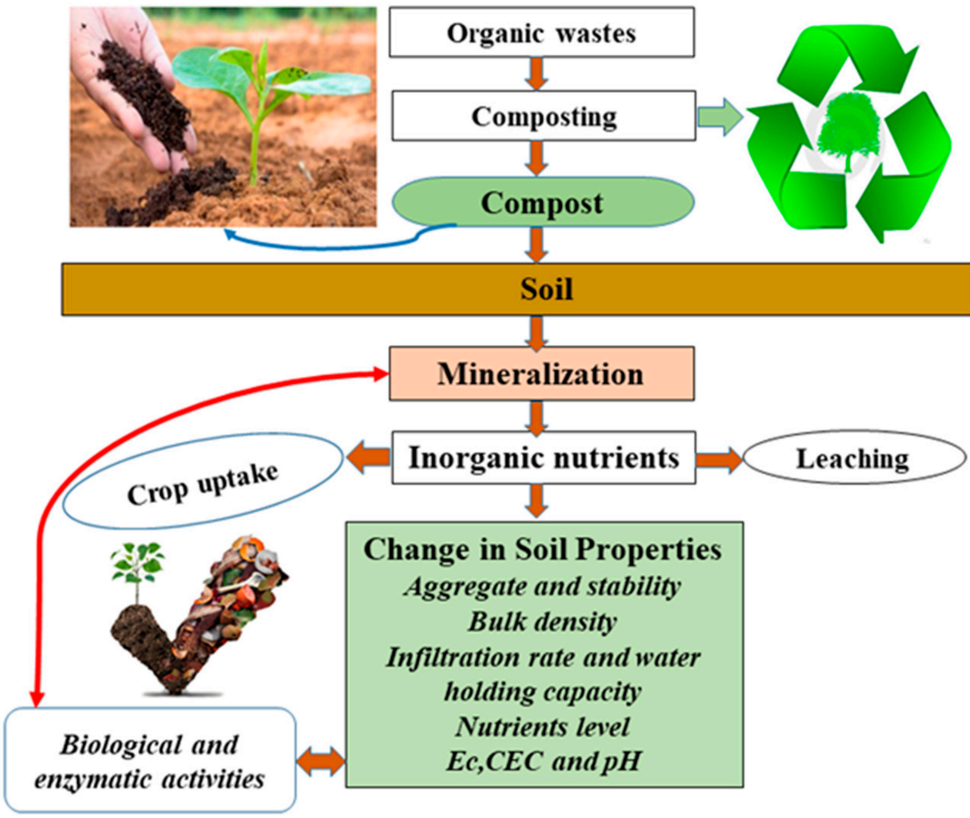

Figure 1. Schematic diagram of compost mineralization after application to soil. EC: Electrical conductivity, CEC: Cation exchange capacity.

3.1. The Ideal Form of Nutrients in the Compost

Composting application on normal and saline soils is an important practice for improving soil organic matter and mineralization, particularly in arid and semi-arid regions [68], which constitutes the bulk cultivable areas worldwide, mainly due to low precipitation and increased alkalinity. Indeed, the organic matter in soil is essential in maintaining the soil fertility and decreasing nutrient losses. In addition, it is responsible for many soil characteristics, including water-holding capacity, soil productivity, medium of biological activity, soil aeration and soil structure [69]. It is well documented that nitrogen is the most needed fertilizer affecting plant ontogeny. In normal soil conditions, 95% of nitrogen and sulfur is available in organic matter, although 25% of phosphorus is also available [69,70]. Since compost consists of decomposed organic waste, it naturally contains a good percentage of nitrogen [71]. Therefore, adding compost to the soil enriches it with the important elements for plant growth and development, such as nitrogen, carbon, sulfur and phosphorus [50].

Composting process conditions and the type of raw organic materials are the main factors affecting the nutrient availability and the stability of the humus-like product form. Indeed, N and C are the most important elements that should be calibrated for the pile maturation period. The C/N ratio should be between 25 to 30 and the average bio-compost must contain about 33.3% organic matter, but not less than 20% [35,72]. Compost should also contain no more than 40% water and nearly 35% water is recommended for market compost. The ideal compost pH to be used for most of the applications in agriculture should be around 7.5. In addition, salt content is also an important parameter; it should be nearly 3.89 g per liter of fresh matter. Phosphate is available in the form of P_2O_5 in compost at around 0.62% DM (dry matter), while potassium content is about 1.01% DM [72].

3.2. Implication of Maturity and Stability on the Compost Quality in Agriculture

Compost quality fundamentally depends on raw composted materials, their nutritional composition, age and the process by which they were produced [73–75]. It is well known that composting products' quality determines their application and any insufficient or unbalanced nutrients in the compost will limit its application. In this context, the assessment of composts basically depends on the determination of physicochemical and agronomical parameters, whereas the evaluation of toxicity endpoints is commonly limited to pathogen content and seed germination [76,77]. Achieving an advanced degree of compost maturity and stability promotes the formation of humic substances, which are believed to build soil fertility and increase the organic matter content of the soil [78] without causing environmental problems, since the produced stable nitrogenous compounds are less vulnerable to volatilization, leaching and denitrification. For instance, nitrate is the most preferable chemical form for plant growth, and is characterized by its high mobility, however, with more stable compost, the risk of groundwater contamination is minimized [79]. Planting crops with high demand for nitrogen, like wheat and maize, is also recommended to minimize any leaching of nitrogen compounds [80].

The phytotoxicity of immature compost is mostly attributed to the production of organic acids, ammonia and ethylene oxide that negatively impact plant growth and inhibit seed germination [81]. For instance, in a study conducted by Alvarenga et al. [82], a lower value of germination index (GI) was recorded with very unstable organic matter. Additionally, it was recorded that applying immature or non-stabilized compost decreases the oxygen concentration and redox potential and increases the mineralization rate of the organic carbon in soil [83,84].

3.3. Effects of Compost on Biological and Enzymatic Activities in Soils

Compost seems to be an ideal alternative fertilizing material that has a great effect on soil organic matter and soil microorganisms [85,86]. For healthy soil, ensuring soil microbial diversity is considered as a key factor for nutrient cycling and other biological processes [87,88], whereas enzymatic activities that are vital for mediating biochemical process are a good indicator of the ability of the soil to perform biochemical functions and reactions [89]. These enzymatic activities are enhanced when organic fertilizers were used. For instance, β-glucosidase activity was found to be enhanced by more than 200% in organic-amended soil as compared to the non-amended soil [90]. Additionally, manure application increases enzymatic activities and soil organic C, and hence glucosidase activity was enhanced with the increase in total organic C [88,91]. Analysis of enzymatic activities and microbial biomass demonstrated that microbial activities were enhanced and microbial biomass C increased up to 100% [92,93]. Furthermore, compost application on different soils was found to be an effective method for affecting the soil microbial properties (mainly biomass and respiration rate), thereby enhancing almost all stages of plant growth, development and total yield [94,95]. Indeed, compost provides microorganisms (such as bacteria and fungi) capable of transforming insoluble matter into plant nutrients and degrading harmful substances, improving soil conditions and providing carbon to keep the biodiversity of micro- and macro-fauna, such as earthworms [31]. Additionally, it was documented that compost application promotes the activity of diverse groups of rhizospheric microorganisms that promote plant growth [96,97]. In this regard, arbuscular mycorrhizal fungi (AMF) were found to be promoted in such applications, and contributed to increasing P absorption from the soil, as well as other elements with limited availability for the plants [98,99]. The origin of the used organic amendment affects the microbial activities. In this regard, a variation was observed between control soil and soil amended with compost or manure based on the released amounts of CO_2, where the highest values were obtained in soil amended with 120 T/ha of compost (35.8 mg CO_2/kg). The difference was probably due to low biodegradability of the organic matter originating from manure [50]. Other additional benefits of composting are the reduction of bad odors from rotting and the elimination of vectors such as insects and rats.

As highlighted in the scientific literature, the effect of organic fertilizer application is normally seen in the long term, where soil biological properties, such as basal respiration, microbial biomass C and some enzymatic activities, are significantly enhanced by compost. This can be explained by the continuous/slow release of nutrients during organic matter decomposition. Consequently, microbial biomass could be sustained for long periods of time [88,92]. In this regard, it was found that soil microbial biomass C was 20–40% higher in soils amended with compost and manure 4 years after the last application compared to inorganic fertilizer treatments [100]. Importantly, since organic matter mineralization takes place over extended periods, this would enhance plant growth, while minimizing the impact of leaching associated with rainfall and excess irrigation [101].

3.4. *Effects of Compost on Soil Physical Properties*

Soil structure has a vital role in different soil processes [102,103]. Adding compost to soils recovers their structure that allows free gas and water transfer, facilitates soil management for ploughing or seeding and enhances seed germination and root growth, as well as reduces the risk of erosion, reduces water evaporation, regulates moisture and improves drainage [31,69,104].

3.4.1. Soil Aggregate and Stability

The formation of stable aggregates is highly dependent on organic matter contents and dynamics, especially in loam or clay soils, since these soils are poor in mineral-stabilizing agents. Compost texture is humus-like, thus the formation of such stable aggregates is promoted through the binding of mineral particles when compost is incorporated/added into soil [105–107]. Actually, changes in soil aggregates due to compost application are normally associated with a more active specific area that promotes intensive interactions between soil fauna, microorganisms and root hairs under optimum conditions (e.g., sufficient humidity) that ultimately provides optimal soil formation and a positive effect on soil fertility, increasing the stability of soil aggregates and improving soil structure [70,108]. Compost enhances aggregate stability in light- or medium-textured soils, such as loamy or clay soils, but not heavy-textured soils (sandy soil) [105]. Various studies showed that compost increases soil structural or aggregate stability between 29 and 63% [109]. Furthermore, it was reported that the application of manure and crop rotation increased the macro-aggregate (>250 µm) proportion and geometric mean diameter and decreased the proportion of micro-aggregates and silt clay-sized fractions (<250 µm) compared to monoculture crops and conventional fertilizer management [110]. Additionally, Babalola et al. [111] observed that aggregate stability was improved by 15.7% after compost application.

The degree of soil aggregates and stability is highly influenced by rate of application, degree of maturity, intervals of compost application, compost feedstock and soil type. In this context, Bouajila and Sanaa [50] conducted a field trial and demonstrated that the application of manure and household waste compost significantly increased soil structural stability compared with the control. The results also indicated that compost from household wastes was more efficient than manure, and better structural stability was achieved when 120 T/ha of compost was applied. Similarly, Annabi et al. [112]

investigated the effectiveness of repeated applications of municipal compost and manure on silty loam soil. The obtained results revealed that compost derived from municipal organic waste is more effective than manure application in almost all studied cases. Additionally, after two years and using three loads (25 Mg/ha per each) of poultry manure, sewage sludge, barley straw and alfalfa in Arlington soil, Martens and Frankenberger [113] indicated that the change in soil physical properties resulted in significantly increased soil aggregate stability (22–59%) in the organic-amended plots as compared with the unamended plots.

3.4.2. Bulk Density

Increasing the bulk density of the soil is associated with various problems, including excessive soil strength, inadequate aeration and low water infiltration. This would eventually affect the growth of plants, and root penetration and elongation would be restricted [114,115]. Compost application is often used to improve soil structure and decrease the bulk density, which provides a healthy soil environment [116]. This positive effect, which results from the increase in soil porosity due to the interactions between organic and inorganic fractions [70,117], has been observed in most cases under different soil types, different application rates, different incorporation depths and with different compost feedstocks [115]. In this regard, Martínez-Blanco et al. [109] pointed out that compost application on soil reduces soil loss between 5 and 36% and soil bulk density decreased between 0.7 and 23% after compost application. Additionally, the incorporation of 540 Mg/ha of compost 50 cm deep in the soil profile in four soils with different parent materials reduced the bulk densities by 19–21% compared with the control [118]. Somerville et al. [119] studied the effect of sludge compost application (50% *v*/*v*) on three different soil types (two different loamy coarse sands and a coarse sandy loam). The bulk density decreased in all three soils at a rate of 15–26% and 14–25% after 3 and 15 months of application. The continued reduction in bulk density was attributed to the deep tilling method used in this study (20 cm and 50 cm) compared to other studies with shallower tilling depths. In this regard, Crogger et al. [120] demonstrated that the surface application of yard waste compost reduced the bulk density (1.21 g/cm^3), but a significant reduction was observed with compost incorporation 20 cm in the soil profile (1.07 g/cm^3) 3.5 years after the application. The same trend was maintained even after 6 years of application and bulk densities after 6 years were significantly lower than after 3.5 years, which is in accordance with other studies [119,121–123].

3.4.3. Infiltration Rate and Water-Holding Capacity

The ability of soil to retain water is the key factor for water use efficiency in agriculture. Obviously, organic matter in soil is mainly responsible for water retention, hence adding compost is obviously a great way to increase soil organic matter, as it is proven that it also affects the ability of soil to retain water [71,109]. In soils with large granules, like sandy soils, compost is considered as a sponge that saves water, and it helps to add porosity to clay soil, making it drain easier, so that it does not stay waterlogged or dry out easily [69]. Therefore, compost application is ideal and a promising natural fertilizer for facing climate change and water shortage challenges, especially for farmers in arid and semi-arid areas around the world, in which soils have low organic matter content and are subjected to erosion, deterioration and desertification processes [86,124].

Based on the results of different studies, there is a general trend of an increasing infiltration rate when compost is added to soil. This increase is attributed to the increased porosity, reduction in bulk density and microbiological activity [50,115,120]. Additionally, it is well documented that the infiltration rate is also highly dependent on the soil texture being amended [115,120,125]. Results obtained by [50] showed that the application of 120 T/ha household wastes and manure improved water infiltration (549.25 and 596.46 cm, respectively) when compared with the control (332.16 cm). Martens and Frankenberger [113] indicated that the change in soil physical properties resulted in significantly increased cumulative water infiltration rates (18–25%) in the organic-amended plots as compared with the unamended plots after two years and using three loads (25 Mg/ha per each) of poultry manure, sewage sludge, barley straw and alfalfa in an Arlington soil. Logsdon et al. [126] reported 24 and 50% increases in infiltration rate for the two yard waste composts tested, where the shallowest incorporation depth that showed a significant increase in infiltration rate was 5–10 cm. There is also similar trend with infiltration, in which compost addition increases water infiltration rate [69,117].

Among other improvements due to the application of compost is the increase in the water-holding capacity of soils [69,127]. However, it is important to highlight that any change in water-holding capacity is primarily attributed to the water retention characteristics of the amendment, and the potential benefit of different organic amendments in enhancing water-holding capacity is therefore remarkably related to the characteristics of the amendment. Furthermore, the contribution of organic amendments to water-holding capacity would also be expected to change over time, as degradation of the amendment continues in the soil [122,128]. According to Brown and Cotton [117], water-holding capacity was significantly increased ($p < 0.01$) and it was 1.57 greater than in the control treatment. Additionally, compost was found to increase water-holding capacity as well as plant-available water by 50% and 34%, respectively, however, it was less effective than cow dung [109]. Using different rates of mix sources of compost at 15 cm with clay and loam soils also resulted in increasing water-holding capacity, but with higher compost application rates in both soils. However, clay soil recorded higher values at all pressures compared to the loam soil, and compost increased the number of large pores, especially the pores holding water at around 5 kPa tension for water retention [129]. Similar behavior concerning water-holding capacity was also documented in various studies [122,128].

3.5. Effect of Compost on Chemical Properties of Soil

3.5.1. Enhancement of Nutrient Level

Soil physical structure (as mentioned before) and biological activity are highly influenced by the percentage of organic matter, which in turn influences other properties and thereby determines the suitability of the soil for different activities, mainly agricultural ones [130]. It is well documented that compost has a direct relation to organic matter. Indeed, adding compost showed enrichment of organic matter and subsequently soil fertility, thus enhancing the nutrient level in the dry matter of these soils [69]. However, each element from these nutrients has a major or minor role in plant metabolisms. While N, P, K, Ca, S, Mg, C, O and H are the macronutrients that are available in soil for plant health, Fe, B, Cl, Mn, Zn, Cu, Mo and Ni are the trace elements that plants need in specific amounts [131].

Remarkably, compost contains significant amounts of these nutrients, especially the macronutrients [69], in which proportions of C and N materials have a particular importance. Carbon serves both as a source of energy and elemental component of microorganisms, and nitrogen is important for the synthesis of amino acids, protein and nucleic acids [35]. In general, the ideal compost C/N ratio has been reported to vary from 25 to 30 [35,132]. Liu et al. [46] reported that the application of compost to subsoil enhanced the nutrient cycling processes and improved sugarcane growth. After 90 days of experimentation, Masmoudi et al. [133] found that levels of soil organic carbon and nitrogen were higher than that of control soil by up to 29.5% in the upper layer of the compost-amended soil. Similarly, Brown and Cotton [117] reported that soil organic carbon increased three-fold and microbial activity in the soil doubled when compost was applied to farmed land. Compared with nitrogen fertilizers, soil P, K and organic matter increased linearly with increased rates of compost application. Conversely, increased rates of N fertilizer application decreased soil P and K, while having no effect on organic matter [134].

Determining the appropriate application rate of compost depends fundamentally on the mineralization of organic matter and, as a consequence, nutrient release rates. This process is highly affected by environmental conditions and the composition of the organic matter itself [135]. Indeed, most easily convertible nitrogen is lost during composting and the remaining part is normally found in a more stable form with low mineralization rates [135]. In this regard, N availability was only 15% and 40% for compost and manure, respectively, in the first year after application and only 8%

and 18% in the second year [136]. Despite the different documented methods for compost application rates [115], applying 7–10 Mg (dry matter) compost per hectare can fulfill the average soil organic matter (SOM) demand of agriculturally used soils, and more than 10 Mg dry matter compost/ha is recommended for a long-term increase in SOM [70].

It is worth mentioning that the replacement of inorganic fertilizers by organic amendment as the nutrient source for soil would have a positive implication for environmental protection. In this regard, it was reported that no high risks of nitrate leaching from soils after compost application were reported compared to inorganic fertilizers, as only about 5% to 15% of nitrogen in mature compost is available in the first year after application [137,138]. On the other side, Bhogal et al. [139] estimated that, over a 20-year period, the application of garden organic compost at a rate of 10 T/ha will save around 2282 kg CO_2-e greenhouse gases (GHG) emissions. Additionally, Schleiss [140] suggested that GHG emission savings from carbon sequestration are eight times higher than from fertilizer replacement, whereas Smith et al. [141] found that in source-segregated organic composting, carbon sequestration accounted for 39% and avoided energy and materials accounted for 61% of GHG savings per tonne of municipal solid wastes.

3.5.2. Cation Exchange Capacity (CEC) and pH Value

Cation exchange capacity is one of the most important indicators for evaluating soil fertility, more specifically for nutrient retention, as it prevents cations from leaching into the groundwater. In many studies, the application of stabilized organic matter, rich in many functional groups, into the soil increases CEC, especially when high doses of compost are applied [69,142]. This increase in CEC is attributed to the exchangeable base cations resulting from the accumulation of compounds bearing negative charges, such as lignin-derived products and carboxyl and/or phenolic hydroxyl groups in the soil [138].

In a study conducted by Liu et al. [47], the treatments applied with composts resulted in an increase nutrient, organic carbon and the cation exchange capacity. Treatment with aged (mature) compost was the most effective one which improved soil physicochemical properties and reduced the heavy metal immobilization. An increase in CEC was also reported when compost and vermicompost were added to soil, and was CEC increased by increasing the application rate [143]. Similar results concerning the increase in CEC were observed in other studies [122,144–146].

Regarding pH value, it was found that the initial pH of compost has a direct effect on the change in soil pH. Consequently, soil pH is either increased or decreased depending on the initial pH of the compost [122]. Composts that have a near-neutral or slightly alkaline pH with a high buffering capacity usually elevate pH in acid soils. For instance, the application of municipal solid waste compost increases the pH of acid soils [147]. However, other studies reported a decrease in pH after the application of compost and attributed this decrease to the formation of organic acids during the mineralization of organic matter [70,148–150].

Attention should be paid to soils with elevated pH, as high pH values lead to a decrease in the availability of nutrients. Fortunately, the application of stable composts to soils rarely shows a substantial increase in soil pH due to the low buffering capacity of the compost [151].

3.6. Effects of Compost on Crop Productivity and Yield

Generally, plants need nutrients to synthesize proteins, nucleic acids and other materials that are important for plant growth [104,109]. To achieve that, farmers used to add compost either as a liquid (brewing compost in water, which is known as "compost tea") or a solid form to the soil with the purpose of enhancing plant growth, health and productivity. In fact, long-term field trials proved that compost has an equalizing effect on annual/seasonal fluctuations regarding the water, air and heat balance of soils and the availability of plant nutrients and thus the final crop yields. Several studies support this finding on *Zea mays* [69,152], and *Phaseolus vulgaris* [68].

Furthermore, the effects of compost on growth, yield and the essential oil of *Majorana hortensis* showed that the application of compost tea positively increased different growth parameters of marjoram, including plant height, stem diameter, number of branches per plant fresh and dry weight, and also increased the essential oil content [153]. Additionally, protein content was enhanced. On the other hand, compost application also showed changes in gibberellins, nitrogen fixer populations and nitrogenase enzyme activity and, accordingly, augmented plant growth and development. Zhang et al. [11] demonstrated that compost application for three years resulted in increasing grain yield by approximately 7–15%, particularly in the second and third years. It was also found that a 30% replacement of N fertilizer by compost is an effective nutrient management strategy to maintain the N uptake and yield of maize [11]. Results obtained by Cai et al. [63] suggest that manure acts as a better fertilizer than synthetic fertilizer in increasing crop yields by improving soil fertility in Chinese subtropical arable soils. Manure inputs accounted for 39% of the relative influence on relative yield, followed by synthetic fertilizer (21%) and soil fertility (40%). Synthetic fertilizers indirectly affected crop yields by weakly increasing soil nutrients and decreasing soil organic carbon storage and soil pH. Manure indirectly affected crop yields by strongly and positively increasing soil nutrients, soil organic carbon storage and soil pH [63]. Agricultural application of a suitable amount of compost enhanced all yield parameters of maize plants by about 60% [154]. Furthermore, the fertility of the soil was improved due to compost addition and field experiments showed an increase in radish yield by 10%, without noticing any phytotoxic effect on radish growth [155].

3.7. Effects of Compost on Plant Pathogens and Diseases

Soil-borne pathogens are a major problem that confronts the agricultural sector. Although there are many ways to manage these pests, these methods are still expensive, negatively affect the soil and plants, pollute nature and cause pesticide resistance [104]. Interestingly, one of the most important results of composting is non-pathogenic humus, which is long established. In this context, mature composts demonstrated suppressive effects against phytopathogenic microorganisms [156], where this suppressive capacity of compost is attributed to the microbial activities within the compost [157]. In this case, several presentations of compost can be used for this purpose: Compost as it is [158], vermicompost [159], compost tea [160] and even compost enriched with specific biopesticide properties [161]. Whatever the presentation of compost is, the roles of the physical properties and chemical composition of composts are also important in the suppressive effect, not only because they are responsible for the type and quantity of microorganisms established, but also because of their effects on pathogens, plant root health and leaf nutrient status. The growth of the plant pathogen *Sclerotinia sclerotiorum* and stimulation of the growth of two of its antagonists, the soil-borne fungi *Trichoderma viride* and *Trichoderma harzianum*, were found to be inhibited by humic substances extracted from compost [162]. Importantly, the biotic and abiotic characteristics of compost, in addition to its water-soluble and humic fraction, were found to suppress *Pythium ultimum* in pea plants via reducing the effect of the pathogen incidence, as well as decreasing the number of root lesions and *Pythium* populations, therefore avoiding reductions of plant growth [163,164]. Additionally, different studies demonstrated that compost teas were able to inhibit the growth of *Rhizoctonia solani* [163], *Fusarium oxysporum* and *Verticillium dahliae* [165]. It is worth mentioning that compost suppressive effects against phytopathogenic microorganisms are influenced by nutrient level (mainly OM) and environmental conditions during maturation, which affect recolonization by mesophilic microorganisms [166].

As discussed in the previous sections, the application or incorporation of different types of compost would improve soil properties and, as a consequence, the production yield of crops. More evidence of such improvements is summarized in Table 1.

Table 1. Effects of compost application on different soil properties and crop yield.

Compost Feedstock	Experimental Conditions	Effect	Ref.
Green wastes	Compost was applied at three different rates: 5 kg/each tree, 10 kg/each tree and 15 kg/each tree	Compost improved soil organic matter, available phosphorus and available potassium content. The high-level application amount (15 kg/tree) had the greatest effect on soil improvement. Under this rate and compared with the control treatment, soil pH decreased to 7.28–7.45, soil organic matter content reached more than 35 $g \cdot kg^{-1}$. Soil total nitrogen, soil available phosphorus and soil available potassium increased by 25–28%, 200–400% and 80–177%, respectively. Additionally, the soil microbial structure was changed such that bacterial abundance increased by 12–13%.	[167]
Mix of food wastes, animal bedding and manure	Compost was incorporated in soil for 12 years (33% by volume) with the use of a backhoe, and annual top dressing with mulch	Soils exhibit improved (reduced) bulk density, increased active carbon and increased potentially mineralizable nitrogen. Compared to unamended soils, improvements were found in aggregate stability (72.41%), available water-holding capacity (0.22%), total organic matter (8.43%), potentially mineralizable nitrogen (27.53 mg/kg), active carbon (1022.47 mg/kg) and reduction in bulk density (0.89 g/cm^3).	[168]
Sheep manure and wheat straw	Continuous application of compost for 5 years in the proportion of 60:40 (volume basis)	Higher productivity of *Prunus salicina* (21.4%), greater fruit diameter (7.8%) and heavier fruit weight (22.4%) compared to unamended soil. Additionally, the amended soil by compost increased the SOM and water-soluble C fraction in parallel with an increase in microbial parameters (microbial biomass C, adenosine triphosphate (ATP), basal respiration and dehydrogenase).	[169]
Mixed source and yard waste	Five years' incorporation of compost (40%, *v/v*) with soil	Compost incorporation increased hydraulic conductivity by a factor of 22, but the incorporated yard waste compost treatment tended to show a faster reduction in hydraulic conductivity over time (5 years) than the mixed compost.	[170]
Digestates and compost	Digestate and compost were applied at a rate of 100 m^3/ha for four years	Increased pH of the soil and improved the biological soil activity (e.g., enzymatic activities).	[171]
Dairy waste	Dairy waste compost was applied at a rate of 100 T/ha for 5 years	The dairy waste compost increased organic carbon by 143 and 54% compared to ammonium sulfate and liquid dairy waste treatments, respectively, applied at the same available N level (200 kg N/ha), whereas the C pool was enhanced by 115%.	[172]
Cattle manure	Compost was applied annually for 5 years	Organic C and total nitrogen concentrations were increased up to 2.02t C/ha. yr and 0.24t N/ha. yr.	[173]
Yard waste	Compost was incorporated into soil (21%, *v/v*)	A two-fold increase in plant water availability and an increase in the ability of the plants to access water resources through root proliferation.	[174]
Manure organic wastes	Compost and manure were used at 25 t/ha for a 5-year field experiment with a semi-arid Mediterranean soil	Compost and manure treatments increased available water content (AWC) of soils by 86 and 56%, respectively, as a result of the increase in micro- and macro-porosity. However, total porosity and saturated hydraulic conductivity were highest under the compost treatment.	[175]
Municipal solid waste	Municipal solid waste compost applied annually over 5 years at a rate of 80 t/ha	Wheat grain yield was enhanced on average by 246% compared to the control.	[176]
Different organic wastes	For five years, compost applied annually at an amount of between 30 and 50 m^3 in plots of 25 × 12 m	Compost application resulted in 67% reduced soil erosion, 60% reduced run-off, 8% lower bulk density and 21% higher organic matter (OM) content compared to control plots.	[177]

4. Application of Compost as Growing Media

Growing medium substrates have to provide adequate physical and chemical properties for plants [178]. Since compost is believed to provide such properties, more attention is being devoted toward using it as a growing medium and to replacing peat, as some composts have physical and chemical characteristics similar to peat [178,179]. Furthermore, this orientation is derived by both ecological and economic considerations [180,181]. However, and despite all advantageous effects associated with compost application mentioned in this review, it is important to point out that some problems might be encountered with compost as a standalone growing medium. For instance, some composts are moderately or highly saline or have a high level of heavy metals, which restrict their application as a growing medium, and others might be unstable and shrink with time, resulting in low air-holding capacity and excessive water retention [182–184]. A wide variation in compost quality due to the large number of organic feedstocks, different composting approaches and different approaches for identifying compost maturity and stability are also recognized as obstacles against the application of compost as a growing medium [181,185]. Consequently, a relatively small selection of organic materials has been adopted to be used as growing media during the last 25 years based on relatively simple requirements of the commercial sector [186]. For instance, winery–distillery composts were applied as substitute growing media for the cultivation of thyme, showing significant influence on the production of essential oils from thyme plants [187]. Additionally, plants were grown successfully in growing media containing up to 50% composted sewage sludge and demonstrated that it can provide advantages such as increased nutrient provision [188].

5. Compost Application as Bioremediation Agent for Contaminated Soil

As a result of various human activities, a wide variety of pollutants including, but not limited, to petroleum and related products, pesticides and chlorophenols, are continuously entering the soil, thereby posing a huge threat and risk to human health and natural ecosystems. Although a complete review of this topic is out of the scope of this paper, it is worthwhile to comment that compost can also be added for the bioremediation of other hazardous materials typically found in soil. The scientific literature is full of studies at different scales, where a wide variety of pollutants are considered. For instance, these include hydrocarbons, chlorinated compounds or pesticides [189], and emerging contaminants such as plastics [190]. In some cases, it is particularly remarkable that some compost applications, coupled with phytoremediation, resulted in promising results [191]. Compost application to contaminated soils was proved to be a cost-effective and environmentally friendly approach for bioremediation of polycyclic aromatic hydrocarbons (PAHs)-contaminated soils [192]. Furthermore, the addition of compost resulted in decreasing the levels of heavy metals in soil solution due to precipitates or increased metal sorption (immobilization) since organic matter has the tendency to form strong complexes with heavy metals [193–197]. In this regard, the concentrations of Cd and Ni in soil solution were decreased with high organic matter content [198]. Furthermore, results obtained by Angelova et al. [197] indicated that in most cases, the application of compost and vermicompost decreased extractable levels of heavy metals in the soil as a result of heavy metal immobilization by humic substances. The same trend was observed with lead and cadmium when different types of organic amendment were used [199,200].

6. Potential Risks of Compost Application in Agriculture

As indicated in several studies, compost can improve soil properties and fertility, which, as a consequence, enhance crops yield. However, and in order to assure the safe and optimum application of compost, knowledge about the best application rates and timing are needed to reduce or even avoid negative impacts on soils and the environment. Compost quality should fulfill certain characteristics including, but not limited to, organic matter content, heavy metals, nutrient content, pathogens, maturity and stability [82,201–203]. The following are the potential risks associated with compost application in agriculture:

- Increasing the salinity of the soil: It was reported that high salinity of compost introduced in soil caused a delay in the germination of plants [204–206].
- The possibility of heavy metal accumulation in soils and plants [15,207] could occur when heavy metal concentrations exceed the allowed limits and compost is applied at high rates [208,209]. However, it is important to point that the type of soil, compost type and the irrigation system are important factors affecting this type of pollution.
- Leaching of nutrients: When large amounts of compost are applied in a relatively small area, this would increase the possibility of nutrient leaching, especially during autumn and winter. High concentrations of nitrate can be leached from soils and contaminate the surface and underground water [79,206]. Additionally, nitrate leaching in the presence of other nutrients like phosphorus could contribute to water eutrophication [210,211].

- Composts derived from sewage sludge could promote ammonia emissions, mainly when they have high concentrations of ammonium. Furthermore, these types of compost are characterized by their high potential contamination with pathogenic microorganisms.
- The breakdown of soil aggregates as a result of soil colloid breakdown in the case of high concentrations of cations like Na^+ and K^+ [212]. Additionally, other contaminants like persistent organic pollutants (POPs) and potentially toxic elements, among others, could be released from some types of composts [207,213].

It is worth mentioning that these risks could be minimized by considering the compost rate of application, soil type, time of application and compost stability and maturity. Additionally, pollutant migration and transformation could be explored before compost application. However, more studies are still needed to give a clear image about these issues. In any case, research has powerful tools, such as life cycle assessment, to decide on the advantages/disadvantages of compost application "from cradle to grave". However, it is important to highlight that, although a considerable number of works have been evaluated composting technology in terms of emissions or overall impact [214,215], it is still relatively difficult to find studies where all the aspects of compost application are considered using reliable and experimental data [216].

7. Conclusions

This review shows the positive results of compost when applied in agriculture. The general conclusion is simple, if the composting process is correctly performed and compost is stable and mature, compost is a supply of macro- and micronutrients, which can substitute chemical fertilizers. Compost has other effects, such as suppressing plant diseases, among others. In general, the results presented in this review point out that the applications of compost are adequate from the environmental point of view, with a wide variety of uses and purposes, such as bioremediation of several hazardous pollutants. Several new formulations of compost, such as compost tea, vermicompost or tailor-made compost with different biopesticide products, are emerging fields of research that must be considered in the future.

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