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Review

Potential and Constraints of Use of Organic Amendments from Agricultural Residues for Improvement of Soil Properties

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Abstract: Agricultural residues are produced in large quantities and their management is an issue all over the world. Many of these residues consist of plant materials in different degrees of transformation, so returning them back to soil is a management option that closes loops in a circular economy context. The objective of this paper is to summarize current knowledge on the options and effects of reusing agricultural residues as organic soil amendments. The reuse of these residues in soil is a good solution for minimizing the problems associated with their management, while improving soil health and ecosystem functions. While some agricultural residues can be applied directly to soil, others will need previous transformations such as composting to improve their properties. This allows the recovery of plant nutrients and increase in soil organic matter contents, with many positive effects on the soil's physical, chemical and biological properties, and ultimately, crop production, although potential risks derived from some materials must also be considered. The concept of regenerative agriculture and soil management using organic soil amendments contribute to the significant enhancement of soil biodiversity, the protection of the environment and climate goal achievement.

Keywords: soil health; organic residue management; composting; soil management; soil organic carbon sequestration

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1. Introduction

The production and processing of food are essential activities in all societies. Agriculture, animal husbandry and the agro-industry, which conserves, transforms and processes agricultural products, are among the largest economic sectors, and are basic for the development of agriculture-based economy and are strategic for all countries [1]. These sectors are also the source of environmental impacts and a large amount and diversity of related organic residues. Agricultural residues are defined as unwanted waste produced in various agricultural operations. They comprise manure and similar waste from farms, slaughterhouses and poultry houses; harvest waste; fertilizer run-off; salt and silt drained from fields; or pesticides. Most of these materials are made up of organic matter: plant residues from crops, pruning waste, cattle droppings, fruits and vegetables, soilless substrates, wood and pallets, etc. Organic agricultural residues represent an important fraction of all waste produced by human activities. In addition, approximately one-third of all food produced for human consumption in the world is lost or wasted [2].

Regulations in many countries, in particular in the European Union, establish that these organic residues need to be managed and/or treated in a convenient way [3]. However, moving one step further is necessary, as the current food production economic models are predominantly linear and unsustainable and rely heavily on scarce and/or finite resources. Increasing the food demand of growing populations calls for sustainable intensification to reduce the environmental impact of food production. The waste hierarchy promotes prevention of waste production, followed by reuse and recycling pathways. Therefore, finding options for recycling these organic residues at a large scale without harmful environmental effects and with low technology are needed.

A basic principle of circular economy is that organic residues should be re-used or upcycled to materials, and only if this is not possible, should they be considered for energy generation. A further important aspect is that the nutrients and organic matter contained in organic residues should be valorized and used as soil amendments, instead of being wasted, thus contributing to material circularity, soil fertility and improved soil health [4]. The concept of organic recycling and closing nutrients loops in sustainable organic agriculture and waste processing is summarized in Figure 1. The conversion of agro-industrial organic residues to organic amendments for resource utilization and to recover nutrients is key for eco-friendly and sustainable agricultural and food production. Such a solution contributes to closing C, N, and P cycles in organic agricultural residue management and agricultural practices.

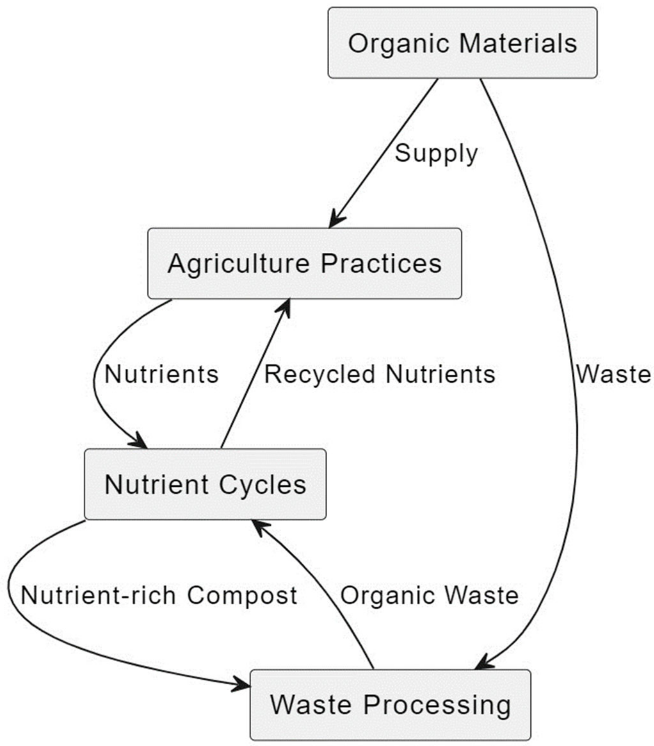

Figure 1. Organic recycling and closing nutrients loops in sustainable organic agriculture and waste processing.

The key components of the system are represented by rectangles: organic materials, agriculture practices, waste processing, and nutrient cycles. The arrows indicate the flow of materials and processes within the system. The organic materials supply is directed towards agriculture practices to provide nutrients for the crops. Additionally, the organic waste generated from the organic materials is sent to waste processing to be converted into nutrient-rich compost. The agriculture practices and waste processing components are connected to nutrient cycles to ensure the recycling of nutrients. Nutrients from the agriculture practices are recycled back to the system through the nutrient cycles, while the waste processing component receives nutrient-rich compost from the nutrient cycles. This diagram visualizes how organic recycling and nutrient loops operate in sustainable agriculture and waste processing.

By using biotechnological interventions, numerous value-added and by-products can be obtained from agro-industrial organic residues (Figure 2), including organic fertilizers in the form of manure, compost, biodegradable plastics, biofuel and bioproducts [5]. The application of advanced biological and thermochemical methods, such as anaerobic digestion, composting and biocharring, in organic residue treatment can be a proper solution to obtain safe and stable soil amendments. Such processing reduces nutrients leaching and odors and results in the prolonged release of micro and macronutrients. The whole system functions using sustainable organic agriculture and green residue processing strategies. Thus, putting extra effort on recycling organic residues as soil amendments with the double objective of improving soil health and closing matter circles can only be positive.

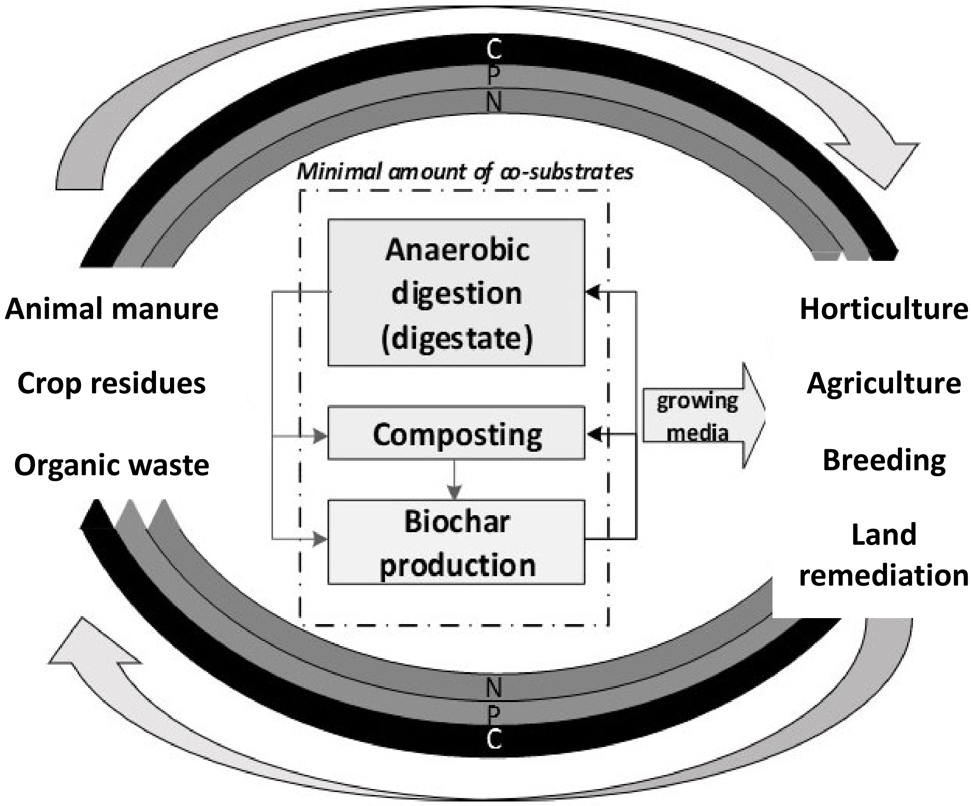

Figure 2. Biotechnological interventions for waste processing as soil amendments.

This manuscript explores the potential and constraints associated with the use of organic amendments derived from agricultural residues to enhance soil properties, focusing on some types of agroindustrial waste: animal manure, crop residue or pruning waste. The authors emphasize the global issue of managing large quantities of agricultural residues. In order to provide a comprehensive summary of their use as soil amendments for minimizing the problems associated with their management while improving soil health and ecosystem functions, the manuscript presents a summary of the techniques currently used for their transformation, as well as the benefits and risks of this practice, from the point of view of physical, chemical and biological soil properties and the carbon cycle.

2. Reuse as Soil Amendments

2.1. Direct Application to Soil

Some organic waste can be used directly as amendments in agricultural soils, especially animal manure; crop residue, such as cereal straw; and pruning residue, among others. For instance, vines are traditionally incorporated into vineyard soils in Spain. Manure, which is a collective term for excretions of different animal species in combination with straw and other plant materials but also livestock feed residues, improves soil properties through increased organic carbon and nutrients in soils. However, organic matter in manure may be quickly degraded because of its low carbon-to-nitrogen ratio [6]. Similarly, returning straw to the soil takes advantage of the large contents of organic carbon to improve soil physical and chemical properties, for instance porosity and bulk density [7], benefitting the growth of crops, but it may also have negative effects caused by organic acids production during decomposition [8]. In addition, the high C/N ratio hinders soil organic matter formation due to the lack of adequate nutrient supply. The same reason might lead to limited nutrient supply to plants when straw is applied alone to soils.

2.2. Previous Transformations

While the benefits of direct application of organic waste are many, not all should be applied directly to soil. In some cases, there are potential risks associated with their composition and transformation processes in soils, such as the leaching of readily available nutrients, especially nitrogen in form of nitrate, into the groundwater [9]. Other materials such as manure can also benefit from previous transformation processes to be converted into amendments better suited for soil application, even if their direct application is feasible.

2.2.1. Compost

Composting is a process of biological decomposition and the stabilization of organic matter under aerobic conditions through the action of diverse microorganisms. Although composting is a method that has been used since ancient times for waste transformation and soil fertilization, scientific studies about its fundamentals have only begun to be published in the past four decades. Several methods and systems for composting have been developed, varying in scale and purpose from home-made systems in individual households, over medium-sized, on-site reactors operated by farmers, to large, high-tech systems used by professional producers. The fundamental physical, chemical and biological and aspects of composting are always the same despite different techniques, and knowledge about the interactions and dependence of factors and competing forces within a composting matrix have recently been investigated. These include the suitability of different feedstocks and amendments as well as their adequate composition, porosity and free air space, moisture control, energy balance as well as substrate degradability, decomposition and stabilization [10,11]. This process has three typical phases. The first one is a moderate-temperature (mesophilic) phase and after a few days, a high temperature of over 60 °C is reached (thermophilic phase). This phase is very important to eliminate pathogenic bacteria and seeds. Finally, the last phase is the maturation stage, leading to the final stabilized organic matter.

Composting allows us to stabilize organic residues before application to soil avoiding crop damage that can come from highly biodegradable fresh residues, but it also allows to blend materials that are not easily composted alone. Animal manure is typically composted to improve its properties [12], as well as plant-derived materials such as pruning residues [13], cereal crop residue [14], grape marc and other winery waste [15,16], olive pomace [17] or fruit and vegetable waste [18]. These organic residues are also commonly treated by co-composting processes using more than one feedstock (Table 1). The final product of this biological process is compost, a stabilized substrate rich in organic matter, free of pathogens and plant seeds, which is suitable to be added to the soil as an organic fertilizer. Composted organic residues are typically used in agriculture and horticulture, as well as to produce topsoil for landscaping or land restoration activities, including phytoremediation [19].

A similar technique is vermicomposting, which is a decomposition process involving microorganisms and earthworms. A disadvantage of vermicomposting is that it does not reach high temperatures [20], lacking the proper elimination of pathogens and seeds.

Therefore, vermicomposting should not be used alone. Instead, vermicomposting and traditional composting should be combined, beginning with a partial pre-composting followed by a finishing stage of vermicomposting [21].

Table 1. Examples of co-composting processes of commonly used agro-industrial organic residues.

Main Feedstock Category	Composting Process	Feedstock Used for Composting Process	Ratio (*v*/*v*)	Effects	Reference
Manure	Aerobic reactors	Chicken manure + peanut straw + biochar	2.5:1:0.1	Increased temperature of the process after biochar application	[22]
	Piles	Cattle manure + maize straw	5:1	Amino acid and carbohydrate metabolism were key metabolism pathways	[23]
	Aerobic reactors	Pig manure + wheat straw (+ bean dregs and biochar)	2:1	Bean dregs and biochar promote the decomposition and humification of compost	[24]
	Piles	Straw, draff, horse manure, maize silage, loam, and stone powder + biochar co-composting	1:5:1:5:0.02:1	Biochar compost performed better than compost alone or synthetic fertilizer	[25]
	Aerobic reactors + preheating	Swine manure + food waste + corn stalk co-composting	2:2:0.5	Initially elevated temperature restricted the rebounding of pathogenic bacteria	[26]
	Piles	Cow manure + sawdust	1:1	Cow manure co-composting reduced pathogenic microbes	[27]
	Aerobic reactors	Kitchen waste + pig manure + cornstalks	2.5:2.5:1	Germination index of the inoculated thermophilic compost was higher	[28]
Sewage sludge	Aerobic reactors	Rural sewage sludge and food waste co-composting	2:0.5	Agricultural value of sewage sludge can be enhanced through co-composting	[29]
	Aerobic reactors	Sewage sludge + centrate		Improves yield and rice protein and mineral content; high nutrient content	[30]
	Aerobic reactors	Sewage sludge from food industry + biochar vermiremediation	1:0.1	In vermicomposting of sewage sludge bulking materials can be replaced with biochar	[25]
	Aerobic reactor	Sewage sludge + straw (1 cm) + aerobic microorganism agent + biochar	4:1	Reduction of gas emissions after bacteria and biochar application	[31]
Green waste/Food waste/other organic waste or biomass	Windrow composting	Vegetable biomass	-	Compost based on “heavy” materials the most sustainable	[32]
	Windrow composting	Green waste + food waste	1:1	Compost designed for tropical horticultural crops	[33]
	In-vessel	Food waste	-	Can reduce GHG emissions and eutrophication when compared to	[34]
	Open-air static pile	Food waste + leaves	4:1	Substituting chemical fertilizers with organic compost is a viable option	[35]

2.2.2. Biochar

Charred organic material has been added to soil in ancient agricultural systems all over the world [36], in addition to the Terra Preta phenomenon [37], precedents of the current use of biochar as soil amendment. Agro-industrial residues employed preferentially for biochar production are wood, sawdust and crop residues, including straw and woody materials such as pruning residues. Biochar is produced by the thermal treatment (>400 °C) of organic materials, e.g., by pyrolysis or gasification under oxygen-deficient conditions. Different technologies are available for biochar production: these include charcoal stacks, the traditional way of converting wood to charcoal [38]; rotary kilns, which are cylindrical-shaped pyrolizers, externally heated, where biomass is moving continually via rotating spirals. The Pyreg process is a patented pyrolysis characterized by biomass allothermic gasification. Wood gasifiers produce biochar in a fixed-bed, downdraft, open core, compact gasifier with the main purpose of electricity production; they are normally fed with pure and clean wood rather than on agricultural organic residues. Preferred technologies are pyrolisis systems and gasification because of emissions free of toxic compounds and the beneficial use of released energy, e.g., for electricity production or heating purposes [38].

Biochar has been proven to increase soil organic carbon, nutrient availability, and water holding capacity over a long time period and to sequester carbon [39,40]. Biochar affects crops and soils differently [38], and its addition to soil should be additionally considered as a strategy to mitigate the negative effects of climate change [40,41].

2.2.3. Anaerobic Digestion

Anaerobic digestion is a biological process in which organic matter is decomposed and stabilized in the absence of oxygen. As a result of the decomposition under anerobic conditions, a gas mixture known as biogas is produced, containing essentially methane (50–75%) and carbon dioxide (30–40%), which can be used to generate heat or electricity as a substitute for fossil fuels [42]. Therefore, anaerobic digestion allows the conversion of organic waste into a renewable source of energy. This technology is very useful for those agricultural waste with high moisture, and in particular for liquid manure.

In addition to biogas, the anaerobic digestion of agricultural waste also products digestate, a by-product that can be used as a soil amendment [43]. However, digestate should undergo a composting/stabilization stage before application to soil for easier management and an efficient agronomic use as fertilizer [44], in order to reduce odors, ammonia emission and risk of nutrient leaching. Digestate has been applied to soil proving good fertilizer value, increasing soil organic carbon and stimulating soil biological activity [45,46].

Finally, advantages and disadvantages of the options presented for organic waste use on soil are summarized in Table 2.

Table 2. Summary of advantages and advantages of options for the utilization of agro-industrial organic residues.

	Advantages	Disadvantages
Direct application	- Low cost - Low technology	- Not suitable for all waste - Nuisances for application - Pollution risk
Composting	- Waste volume reduction - Low cost - Hygienization - Easy to manipulate - Applicable to a wide range of waste	- Need of space and time for treatment - Gas emissions
Biocharring	- Fast process - Waste volume reduction - Hygienization - Easy to manipulate	- High level of technology - High cost - Gas emissions
Anaerobic digestion	- Obtention of energy from biogas	- High level of technology - Odors, ammonia emissions

3. Benefits of Organic Soil Amendments

Besides the management and circularity of agricultural activities, one of the main objectives of organic residue recycling is increasing the contents of soil organic matter, which is known to improve soil properties, both physical and chemical, and reversing the ongoing processes of the degradation of agricultural soils. In this section, we will briefly summarize the benefits from the point of view of physical, chemical and biological soil properties and the carbon cycle.

3.1. The Carbon Cycle

Although soils play an essential role in the C cycle, being the major terrestrial global carbon sink [47], agricultural activities contribute significantly to the release of greenhouse gases into the atmosphere. In this context, the promotion of soil C storage and sequestration has a high value in remediating climate change [40,48,49]. Soil C sequestration is a process of C capturing from the atmosphere by living organisms and later, storing it stabilized in soils for a long time, even for centuries [50]. Soil organic amendment increases the possibilities of soil C storage directly [51] and indirectly through plant growth improvement and the activation of the microbial transformations of C [52]. The incorporation of CO_2 into plant biomass represents a major bottleneck of soil C sequestration [53]: as plants are the main source of organic inputs for soils, C storage is ultimately dependent on photosynthesis [54]. In this sense, the application of organic amendments has been found to highly promote plant growth and thus intensify photosynthesis [55], due to the improvement of root's environment and influence on nitrogen and other nutritive elements necessary for plant development [56]. Moreover, higher soil biodiversity and the population of plant-growth promoting bacteria under organic fertilization also contributes to higher photosynthesis [57]. Thus, the improvement of crop production level has been reported to promote soil C sequestration and contribute to carbon neutrality [58].

Many organic amendments have been studied for their influence on soil C storage and benefits in C sequestration by plants, among them sewage sludge [59], composted materials [60], cattle manure [61] or horse manure [62]. Although the addition of organic matter, fresh or composted, is also a source of CO_2 due to soil respiration, we should consider the positive benefits derived from the transformation process of the organic matter in the soils, giving stabilized organic compounds (humus) that can be present for decades. A recent global meta-analysis covering 101 studies, including 592 cases showed that manure application increases the SOC stocks of agricultural soils by 35%, corresponding to 11 Mg ha^{-1} [40]. Surprisingly, the applications of manure in conventional tillage systems led to 2 Mg ha^{-1} higher SOC stocks compared to reduced tillage, and it was 3 Mg ha^{-1} higher in soils under temperate climate compared to tropical climates [40].

Soil properties also play a role in SOC storage, soil texture in particular has a great importance, as many studies have demonstrated [63]. For instance, following the meta-analysis by Gross et al. [40], clay soils showed 3 Mg ha^{-1} higher SOC increase rates compared to sandy soils. With respect to soil pH, acidic soils showed a 5 Mg ha^{-1} higher stock than neutral and alkaline soils. Different materials also present different performances: farmyard, cattle and pig manure showed higher SOC increases than green manure or straw. The beneficial role of organic soil amendments for the improvement of C storage has also been observed in degraded soils [64,65].

The overall beneficial influence of organic amendments on SOC is summarized in Figure 3. Only in China, the total SOC accumulation in cropland topsoils has been estimated as 85 Tg C per year under compost supplementation: such sequestration contributes by 4.4% to carbon neutrality [66].

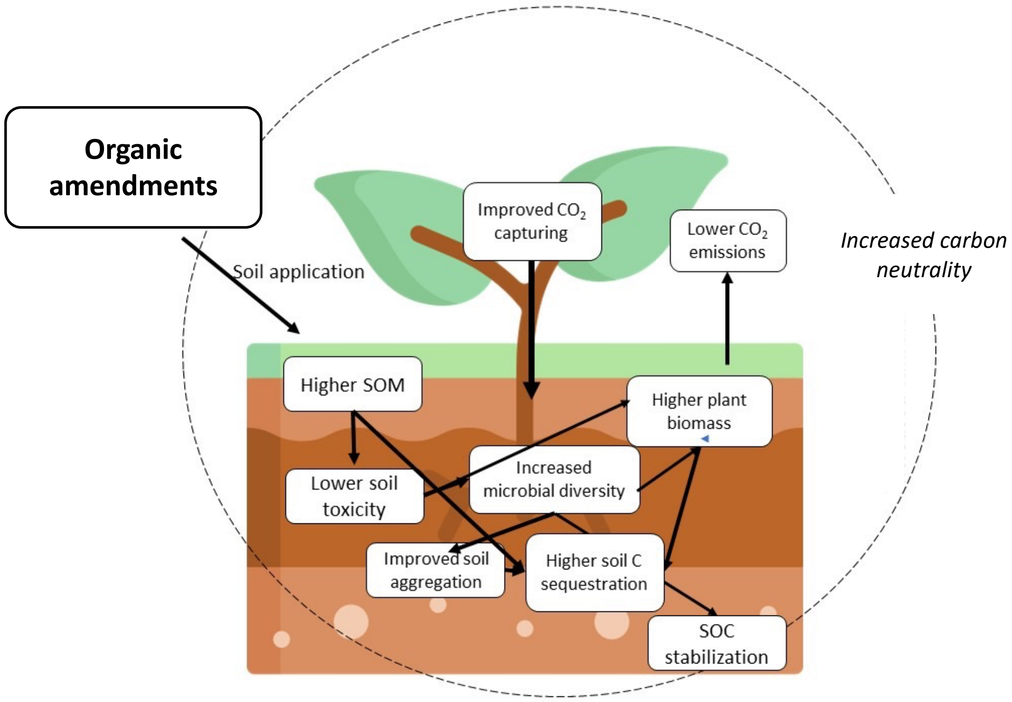

Figure 3. Influence of soil organic amendments on soil C sequestration.

3.2. Soil Physical Properties

Many agricultural soils in the world present poor physical properties, as a result of degradation processes derived from long periods of cultivation, the use of heavy machinery and SOM decline. These processes negatively affect soil structure, reduce porosity, increase compaction, produce surface crusts and sealing and, as a result, create poor conditions for plant growth and increased erosion [7]. The addition of organic amendments shows positive effects on soil physical conditions, caused by increased SOM contents [67]. The reduction in bulk density, increase in porosity and amelioration of structure and aggregate stability are highly associated with SOM contents. Other properties, such as water holding capacity, compaction, runoff, infiltration and protection against erosion are frequently improved.

Bulk density decreases in agricultural soils with the application of many organic amendments, for example, manure [68,69], composted crop residues [70], green waste composts [68,69] and biochar [71]. This is a direct effect of the higher porosity and low density of organic amendments compared to soil and an indirect effect of soil structure amelioration. The improvement of soil structure induced by organic matter has been observed in many studies that report increase in aggregate stability after the addition of manure [72], rice straw [73], fresh or composted crop residues [70,72], green cutting composts [68] or biochar [71].

The highly porous structure of organic matter allows the reorganization of soil pore size distribution, increasing soil water retention as observed after the addition of farmyard manure or crop residues [72] and compost [69,74]. Many research articles reported how biochar amendment also improves soil water retention and reduces plant hydric stress during prolonged dry periods [75–77]. However, the results obtained are variable, also showing cases with no increase in water retention [69,78]. Jeffery et al. [79], for example, applied herbaceous plant cuttings biochar to a sandy soil at 1–50 Mg ha^{-1} and found no increases in water retention capacity despite soil porosity increase. Liu et al. [80] found a doubling of water retention after the addition of 20 Mg ha^{-1} biochar in combination with compost, compared to compost alone, in a sandy soil in Northern Germany. Moreover, Aluko and Oyedele [81] and Paradelo et al. [69] reported improved soil workability after the application of composted green cuttings and farmyard manure.

3.3. Soil Chemical Properties

Maintaining soil fertility and the absence of soil/water pollutants are essential aspects for sustainable agriculture. The objective is an adequate supply of nutrients to crops, avoiding the pollution of soils and waters that results from the excess of nutrient and fertilizers. By modifying chemical properties including pH, cation exchange capacity or nutrient contents and availability, the addition of organic residues also contributes to this aspect.

The addition of organic amendments may lead to increased buffering capacity and soil pH. This can be very important in acid soils. These changes have been shown to increase nutrient availability, especially P and N. The long-term application of compost and manure was found to increase [82] or decrease [83] soil pH, depending on their initial value. Butler and Muir [82] observed an average increase in soil pH by 0.5 units with increasing rates of dairy manure compost from 11.2 to 179.2 Mg ha^{-1}. Biochar application was also found to increase soil pH buffering capacity and pH values, leading to the higher retention of basic cations in acid soils and thus improving crop nutrition by increasing P and K availability [76,84]. The opposite effect was observed when soils were alkaline, where the addition of compost can favor the acidification and, thus, the availability of nutrients for plants [85,86].

Cation exchange capacity is essential for the retention of nutrients and reducing leaching and thus making them available to plants [67,87,88]. Long-term fertility experiments have shown increased soil cation exchange capacity after the application of organic amendments such as manure [89], composts [90] and biochar [76]. In this sense, organic waste also provide nutrients in different forms. Studies proved that compost supplementation provides macro- and micronutrients to soil and enhances crop yield [91–93].

In this sense, Blanchet et al. [94] found in a 50-year long-term study that manure application improves soil chemical properties providing significant amounts of P and K. Also, Scotti et al. [95] found that total nitrogen was increased by 60 and 40%, respectively, in soils treated with municipal solid waste compost and manure, after one year of study, compared to untreated soils. Increases in available P content, which was a 36% higher than in the untreated soil, were also observed, which can be explained by a higher activity of phosphatases. Nest et al. [96] reported that manure application increased soil pH as well as extractable P by two to four times, as compared to a mineral P fertilizer application, after a long-term (40–50 years) experiment, proving that the application of manure can be more effective than mineral fertilizer. Schmidt et al. [97] summarized available meta-analyses on biochar effects on soil chemical properties. They showed that all investigated soil chemical properties significantly improved when biochar was added to soils.

Finally, a very important aspect is the potential positive effect of organic amendments produced from agricultural residues in reducing pollutant mobility. The application of organic amendments contribute to the immobilization of potentially toxic elements in soil, reducing their bioavailability to plants [98]. This is due to the presence in organic matter of acidic groups that can bind a wide range of metal(loid)s such as cadmium, lead, copper or chromium [98] and is considered as an important absorbent and complexer for soil metal ions, with a 4–50 times higher cation exchange capacity than clay [99,100]. This effect of organic amendments is also important for their potential use to remediate degraded and polluted soils [19,101].

3.4. Soil Biological Properties

Biological activity is essential for biogeochemical cycles, residue degradation and, of course, for biodiversity, all of which is important to sustain agro-ecosystems functioning [102]. Soil microbial populations play a key role in nitrogen fixation, in the decomposition of organic substances and in nutrient cycling. Organic residues can modify biological properties of soils in positive ways via several mechanisms. First, increasing organic matter contents, including sources of energy for microorganisms. Second, most organic waste is already colonized by microbial communities, which are then transferred to the soil. In addition, organic residues provide space for colonization and form habitats for microorganisms, potentially protecting them from predation and desiccation.

The application of organic amendments to soil has been widely acknowledged to promote microbial population levels, which are driven by physicochemical soil alterations [103]. Studies demonstrated that compost stimulates microbial activity and its biodiversity [104] and suppresses soil-borne pathogens [105,106]. Some studies observed that soil microorganisms respond to compost addition in a dose-dependent way [107,108], reporting that compost may have either positive [109], neutral [110] or negative effects on soil biological activity and biodiversity [111]. In other investigations, the application of biochar to soil has also been proven to increase microbial biomass and enzymatic activities [76].

The application of organic amendments also affects the composition and structure of microbial populations [112]. Throughout the limitation of bioavailability of soil pollutants, soil organic matter allows for increased soil microbial diversity and enhance the dynamic of soil processes [113]. Soil enzymes are highly sensitive to soil nutritional changes and the increase in SOM is considered to influence their activity [114]. Tang et al. [115] showed an activation of soil enzymes induced via the application of compost from agricultural waste, whereas biochar showed its inhibition. Similar interactions between organic amendments and soil enzymes were noticed by Hazrati et al. [116]. They observed the positive effects on β-glucosidase and acid phosphatase activity, which increased by 246%, and 223%, respectively after 60 days from the agricultural residue application. This effect has been attributed to a decreased bioavailability of heavy metals. It has been also reported that organic materials contain a high biodiverse microbial population and are the main reason for improved soil activity and biodiversity [117].

Organic waste also produces modifications in the use of carbon sources that can lead to substantial changes in microbial functional activity and diversity, as well as in the taxonomical composition of microbial communities. The long-term study of repeated organic amendment showed the promotion of microbiome diversity [118]. Manure has been proved to highly promote soil biodiversity, whereas the bacterial community has been found to be more sensitive to disturbances in comparison to fungi [119]. Zhang et al. [120] reported that application of manure to tea plantations improves bacterial biodiversity and stabilizes the structure of soil bacterial communities. Li et al. [121] reported an increase in bacterial abundance by about 161% when straw- and wood-derived biochar was applied to soil, whereas Liao et al. [122] observed that biochar addition made plant-derived C assimilable to a larger number of microbial species, affecting the bacterial community structure and rhizosphere diversity.

Another positive aspect is the suppressive effects on diseases and pathogens observed in relation to compost and biochar. The long-term application of compost for five consecutive years decreases the abundance of plant pathogens in soil [106,123,124]. The capacity of compost to suppress plant diseases, as well as its efficacy, risks and benefits, have been widely recognized, studied and critically reviewed by many authors [118,125,126], and compost amendment has been proposed for the biocontrol of several species, including Pythium irregulare and Pythium ultimum [127,128], Phytophthora nicotianae [129], Rhizoctonia solani [130], Fusarium oxysporum [131] and Verticillium dahlia [132]. The ability of biochar to suppress soil pathogens and diseases has also been proved [76], including the disease caused by foliar fungal pathogens in tomato, pepper [133] and strawberries [134]; the suppression of Fusarium crown and tomato root-rot [135]; or the sensitivity of rice plants to root knot nematode infection [136].

3.5. Soil Health

Soil health is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans, providing essential ecological functions for all forms of life [137]. The increase in soil organic matter plus the simultaneous improvement of soil chemical, physical and biological properties due to organic amendments results in the amelioration of soil functions such as regulation of nutrient cycles, the water cycle or biodiversity and, consequently, the improvement of agricultural soil health [4,138,139].

4. Constraints of Organic Soil Amendments

Although the benefits associated with the agricultural utilization of these residues are many, in some cases they can also create adverse impacts on the environment and, therefore, some risks must be considered for a successful recycling and recovery without environmental harm or hampering soil health (Table 3).

Table 3. Summary of risks and benefits of utilization of agro-industrial organic residues.

Benefit	Risk
C cycle - Increase in SOM content Physical properties - Increased porosity - Improvement of structure - Increased water retention	Processes related to decomposition: (production of toxic substances, organic acids, O_2 consumption) - Immature compost - Fresh residue
Chemical properties - pH buffering - Increased fertility - Reduction of pollutant mobility	N immobilization - Fresh residues - Immature compost - Biochar
Biological properties - Increased biological activity - Increased microbial biomass - Disease suppressiveness	Potentially toxic trace elements - Animal manure Antibiotics and similar - Animal manure

Some observed negative effects are related to the decomposition and application of fresh materials. The direct application of some untreated agricultural residues or immature composts may have negative impacts on plant growth due to relatively the high contents of soluble organic compounds. Straw incorporation can also have negative effects due to the organic acids produced during decomposition, which are harmful to crop root systems. Moreover, an unbalanced C/N ratio can increase organic matter decomposition rates with the higher production of dissolved organic carbon compounds when it is low, or decrease the mineralization and increase demand soil N for decomposition when it is high, depleting available N for plants and soil microorganisms [140]. Unbalanced C/N ratios can be overcome by avoiding the direct application of these residues and by composting mixtures of materials with high and low C/N values.

Other residues can contain toxic elements in higher concentrations than the normal concentrations in soil, so the possibility exists of buildup in soil when they are repeatedly applied, and they might enter the food chain if taken up by plants, causing concern for human health and food security. The accumulation of toxic metals in soils depends on the amounts of organic amendments applied, as well as of their source and soil properties. Although this is a not an extended problem in agricultural waste, some materials such as animal manure from intensive production can present high concentrations of certain metals due to their presence as feed additives [141,142]. In this sense, metal contents increase in soils treated with animal manure have been reported in the literature, especially in the long term. For example, increases in soil Cd, Pb and As have been observed after three years of the continuous application of chicken and swine manure; six-year consecutive applications of a swine compost also resulted in significantly higher concentrations of Cu and Zn compared to the control [143]. Zhen et al. [144] reported increases in soil Cd, Cu and Zn after 15 years of application of chicken and cattle manure, whereas in a longer study, van Oort et al. [145] observed the progressive accumulation of Zn in a soil affected by manure for 90 consecutive years. In turn, in another long-term experiment, Erhart et al. [146] observed no variation in either total heavy metal concentrations or available fractions after 10 years of application of high-quality biowaste compost. In any case, the mobility of metals and their concentration in the soil solution rather than their total concentrations are determinant factors for their environmental impacts.

Finally, care should be taken with potentially pathogenic microorganisms in some cases, as well as antibiotic resistance transferred from animal manure. Veterinary pharmaceutical products and hormone-linked compounds as well as (micro)plastic residues might accumulate in soils with slurry or manure applied. In a global meta-analysis about antibiotic residues in manure, slurry, soils, plants and water, Frey et al. [147] reported that fluoroquinolones, sulfonamides and tetracyclines used in animal husbandry contaminate the environment, exceeding the EU threshold values for veterinary antibiotics in soil in many countries [147]. Therefore, it is urgent to significantly reduce the use of veterinary antibiotics in order to diminish their contents in manure and other waste and, thus, their environmental pollution potential.

5. Future Challenges and Conclusions

One of the most important challenges in the nearest future will be the transformation of the agriculture sector from synthetic based fertilizers agri-model into regenerative agriculture with the integrated use of manure and organic residues combined with smaller amounts of fertilizer. The reuse of residues as soil amendments, either directly or after transformation, must be kept as the first option for most agricultural and agro-industrial organic waste. Following the logic of the waste hierarchy, burning or disposal can only be considered the final option. Thus, recycling in soil is an obvious choice for these organic residues that will allow us to reverse the trends of soil degradation and unsustainability and provide opportunities to transform residues into valuable resources.

However, to achieve this objective, large transformations are necessary: this will require not only changes in soil, waste and crop knowledge but also social and economic revolution. In recent decades, we have observed a significant increase in synthetic fertilizers utilization and stagnant soil application of manure as a source of nitrogen, resulting in stagnant crop productivity and deteriorating soil health in many parts of the world. Future research needs to focus on closing N, P, K and C loops, providing balanced fertilization for nutrient rich food for animal and human health. One of the reasons is economic: the high-energy demanding sector of synthetic fertilizers needs total revolution. The limited availability of fertilizer raw materials for political reasons also forces the search for new sources of fertilizers, mainly of organic origin. Future research will also focus on safe food production, without any emerging contaminants like pesticides or even microplastics.

Another potential problem is that many farms do not have enough land available to reuse the organic waste they produce or the technology necessary for biological or thermal transformations. Therefore, full process systems must be implemented for the management of these wastes at a larger scale, including collection, treatment and/or distribution from areas of excess production to areas where they are needed. The implementation of farmers' cooperatives for waste transformation could be a good solution for the large-scale processing of waste. These residues and derived amendments could also be used in non-agricultural soils, although it would be more interesting to close circles within the agricultural system based on a circular economy. Appropriate planning in this sense will probably need a new regulatory context in many countries.

To achieve regenerative agriculture, a better understanding of the interaction of soil additives such as composts, manure or other additives such as biochar is needed, and the identification of soil parameters that will determine whether the additives used will have a positive and sustainable impact on the soil environment in agricultural practices and different environmental conditions. The study of such interactions and the dissemination of knowledge concerning them should be included in the management of agro-ecosystems, which will help to mitigate climate change and in the necessary adaptation to it.

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