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Review

Effect of Biowastes on Soil Remediation, Plant Productivity and Soil Organic Carbon Sequestration: A Review

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Abstract: High anthropogenic activities are constantly causing increased soil degradation and thus soil health and safety are becoming an important issue. The soil quality is deteriorating at an alarming rate in the neighborhood of smelters as a result of heavy metal deposition. Organic biowastes, also produced through anthropogenic activities, provide some solutions for remediation and management of degraded soils through their use as a substrate. Biowastes, due to their high content of organic compounds, have the potential to improve soil quality, plant productivity, and microbial activity contributing to higher humus production. Biowaste use also leads to the immobilization and stabilization of heavy metals, carbon sequestration, and release of macro and micronutrients. Increased carbon sequestration through biowaste use helps us in mitigating climate change and global warming. Soil amendment by biowaste increases soil activity and plant productivity caused by stimulation in shoot and root length, biomass production, grain yield, chlorophyll content, and decrease in oxidative stress. However, biowaste application to soils is a debatable issue due to their possible negative effect of high heavy metal concentration and risks of their accumulation in soils. Therefore, regulations for the use of biowastes as fertilizer or soil amendment must be improved and strictly employed to avoid environmental risks and the entry of potentially toxic elements into the food chain. In this review, we summarize the current knowledge on the effects of biowastes on soil remediation, plant productivity, and soil organic carbon sequestration.

Keywords: soil remediation; soil carbon sequestration; plant productivity; biowaste; circular economy; sewage sludge; biosolids; regulations; soil degraded; soil revegetation

1. Introduction

Soil quality worldwide is degrading primarily due to anthropogenic activities but also, to a lesser extent, by natural processes [1]. The development of industries, adoption of new technologies, excessive exploitation of the environment, and improper agricultural management practices as well as excessive fertilization contribute to the decrease in soil quality and, in many cases, this makes the soils unusable [2–4]. The area of degraded soils is continuously increasing globally and hence it is urgently needed to implement actions targeted at protecting the soil from further degradation and to improve its quality [4,5]. In such cases, biowastes are considered as a cost-effective, easily accessible, and effective soil amendments.

1.1. European, and World Standards and Regulations on the Use of Organic Waste in Soil

In the European Union (EU) countries, the EU Directive 99/31/EC [6] strictly regulates this issue, but many EU countries have introduced extra documents regarding the landfill of waste. In Poland, for example, an additional document that regulates the storage of sewage sludge has been introduced [7]. It prohibits any sewage sludge use on agricultural soils, enforcing stakeholders to implement other management measures [8]. The sewage sludge amendment on agricultural land within the EU is controlled by heavy metal concentrations (Cd, Cu, Hg, Ni, Pb, and Zn) which are included in the Council Directive 86/278/EEC [9]. Some critical concentrations of heavy metals controlling the sewage sludge amendment in agricultural soil for selected countries are shown in Table 1. The total heavy metal concentration range in agricultural soils within EU countries is large: 0.5–40 mg kg^{-1} for Cd; 75–1750 mg kg^{-1} for Cu; 0.2–25 mg kg^{-1} for Hg; 30–400 mg kg^{-1} for Ni; 40–120 mg kg^{-1} for Pb and 100–4000 mg kg^{-1} for Zn [10].

Table 1. Limits of some selected heavy metals in sewage sludge for agricultural use in selected countries [mgkg^{-1} DM sewage sludge] [10–13].

Norm/Country	Cd	Cu	Hg	Ni	Pb	Zn	Cr	As	Co	Se
Directive 86/278/EEC	20–40	1000–1750	16–25	300–400	750–1200	2500–4000				
Czech republic	5	500	4	100	200	2500	200	30		
Denmark	0.8	1000	0.8	30	120	4000	100	25		
Finland	3	600	2	100	150	1500	300			
France	20	1000	10	200	800	3000	1000			
Germany (proposed new limits)	2	600	1.4	60	100	1500	80			
Hungary	10	1000	10	200	750	2500	1000-1 (Cr VI)	75	50	100
Luxemburg	20–40	1000–1750	15–25	300–400	750–1200	2500–4000	1000–1750			
Netherlands	1.25	75	0.75	30	100	300	75	15		
Poland	10	800	5	100	500	2500	500			
Portugal	20	1000	16	300	750	2500	1000			
Sweden	2	300	2	70	100	1200	100			
Spain	40	1750	25	400	1200	4000	1500			
Range in Europe	0.5–40	75–1750	0.2–25	30–400	40–1200	100–4000				
Australia	1	100–200	1	60	150–300	200–250	100–400	20		3
United States	85	4300	57	420	840	7500	3000	75		100
Mexico	85	4300	57	420	840	7500	3000	75		100
China	5–20	800–1500	5–15	100–200	300–1000	2000–3000		75		
Japan	5		2	300	100			50		
Russia	15	750	7.5	200	250	1750		10		
India	5	300	0.15		100	1000		10		

All standardization of biowaste for land use has been described by Cesaro et al. [14], but within Europe, individual countries assess the compost quality regulating documents at national levels. The EU-document Directive 2006/799/EC [15] making use of the revised ecological criteria and the related assessment and verification requirements for the award of the Community eco-label to soil improvers is available, but it does not regulate compost quality. It may, however, be useful for the implementation of hygienization rules. The most important regulation is related to the microbial presence in the waste focused on *Salmonella*, *Escherichia coli*, *Campylobacter*, *Listeria*, *Enterococcae*, and others. In most EU countries, a total absence of such bacteria is required (e.g., Austria, Poland). However, a few EU countries accept traces of three species in recycled waste (e.g., UK—*E. coli* < 1000 MPN/g; Latvia—*E. coli* ≤ 2500 CFU/g; Czech Republic—*Enterococcae* < 103 CFU/g) [14], otherwise there is a general zero tolerance for any of these within the EU.

Biowaste land use regulation varies worldwide. For instance, on the more conservative end of the scale are the Indian [13] and the Australian guidelines (Table 1). The Australian guidelines are controlled by the National Resource Management Ministers Council (2004) [11], and these are more restrictive

in comparison to the European guidelines (Table 1). As for China, the application of biowastes on agricultural land and the threshold values for heavy metal content are rather liberal in comparison to the rest of the world, although more restrictive compared to US legal acts. The comparable threshold values for heavy metal concentration in biowaste for agricultural use in the United States on the far high end of the scale (EPA CFR40/503 Sludge Rule) [12]. The Mexican guidelines are similar to the US guidelines [12].

This review aims to provide current knowledge on the effects of biowastes on soil remediation, plant productivity, and soil organic carbon (SOC) sequestration. The review focus on features of biowaste for soil remediation purposes, e.g., in the case of metal contaminated soils, and for support of SOC sequestration.

1.2. Biowastes

Biowastes refer to the biodegradable food residues from private household and food industry, garden industry, municipal wastes, and sewage sludge. Forestry and agricultural residues do not fall into this definition despite being biodegradable. The composition of biowastes strongly depends on their origin, however, the common part for all biowastes is always a relatively large fraction of total solids, a relatively large share of organic matter (34–81% d. w.). The important feature for biowaste determining its biodegradability is C/N ratio is typically in the range of 10–25, whereas the biogas potential range between 0.15–0.60 m^3 kg^{-1} d. o. m. [16]. The moisture is normally >50% by volume.

According to the ISWA report (2015), only about 37% of biowaste is recycled in OECD countries [17]. Their final disposal worldwide is typically composting, biofuels production, incineration, landfilling, and biochar production [18]. The method of recycling determines their applicability for different purposes.

1.3. Remediation of Metal Contaminated Soils

One of the main concerns, closely connected with soil resources, pertains to their contamination, especially with heavy metals and metalloids caused by industrial emissions [19,20]. Urbanization, chemical and metallurgical industries, mining, agriculture, and landfilling activities have contaminated and degraded soils for decades [2]. Heavy metals in the soil are mostly partitioned into inorganic or organic fractions not accessible for living organisms [20]. However, the heavy metal fraction being geochemically active responds to physicochemical changes such as pH and quality of solid and dissolved organic matter, and may thus change its bioavailability. The labile metal species are of biological concern as they may be taken up mostly as free ions or as small labile species [21,22]. The metals accumulation and geochemical conditions in soil may favor metal solubility and ion activity, affecting soil living organisms negatively [23,24]. Many sites around Europe are heavily contaminated by heavy metals, and the biogeochemical impact may be known; but their hazardous impact on short and long time scales are still unknown [25,26]. It has been reported that about 20 million ha of land globally is contaminated by heavy metals [1] and remediation through biological, physical, or chemical stabilization or a combination of the various remediation methods of the contaminated sites are given a high priority. The remediation process may be executed *in-situ* or *ex-situ*. Several soil remediation methods: physical (capping, flushing, thermal treatment, etc.), chemical (adsorption, catalysis, ion exchange, etc.), bioremediation (phytoremediation, bioaugmentation, bioventilation, etc.), and hybrid remediation are proposed [27]. The most cost-effective soil remediation strategy is to apply metal immobilizing soil amendments *insitu* [28].

1.4. Soil Conditioner and Risk of Contamination

The "policy of sustainable development of biowaste", acknowledges the use of biowastes such as sewage sludge and composts as soil conditioner [29,30]. Many degraded soils are typically low in soil organic matter (SOM) and, consequently, often with a poor soil structure. In addition to the introduction of mineral nutrients, the application of organic waste to such soils improves its structure

by facilitating soil aggregation, water infiltration, and water holding capacity, thus reducing the risk of soil loss due to erosion [31]. Moreover, the application of sewage sludge as a soil conditioner contributes to higher NPK uptake by plants which may be caused by better root development [32].

Despite the many advantages of biowaste recycling in soil, the main concern is related to its content of industrial derived contaminants of heavy metals and metalloids [19,33]. Long-term and multiple amendments with soil biowastes thus may lead to secondary contamination of the soil. Biowaste may also contain pathogens and viruses (if not well processed and hygienized) which may even leach to groundwater [34].

1.5. Carbon Sequestration

The capacity of a system to fix CO_2 from the atmosphere by photosynthesis and sequester carbon in deeper soil layers is closely connected to climatic conditions, nutritional status, and soil physical quality. The recycling of municipal organic wastes in soils generally improves nutritional status, improves the soil conditions for soil living organisms, and as a consequence improves the soil structure. This stimulates carbon sequestration and reduces soil erosion. Recycling biowaste in degraded soils can thus be used alone or in combination with other technologies for remediation purposes (Figure 1) [35]. The CO_2 emission is an issue of the major human concerns worldwide [35]. According to the modeled representative concentration pathways (RCP) for global warming, is closely related to high emissions of anthropogenic greenhouse gases (GHGs) such as CO_2, CH_4, and N_2O. Among these gases, CO_2 alone has the potential to increase global warming by about 60% [36]. According to the 2020 Climate & Energy Package (Directive 2009/28/EC of the European Parliament and the Council) [18] and Strategy Europe 2020 [37], European countries have committed themselves to cut greenhouse gas emission by 20% by 2020 to meet the RCP 2.6 goal. According to the EU−28 report, CO_2 emission per capita ranges from about 5 to near 20 Mg CO_2, and the highest rates are emitted in northern Europe (Figure 1).To combat the steadily increasing concentration of CO_2 into the atmosphere, various CO_2 capture technologies are explored. Repeated application of biowaste to particularly degraded soils, may add to this effort by increasing the subsoil carbon slowing down the oxidation of biowaste, but also stimulating plant growth. Increased plant growth will in turn facilitate the development or better soil structure and aggregation. Recycling of biowaste will prime the soil biological activity and in the long term, add to increased storage of recalcitrant organic material in deeper soil layers.

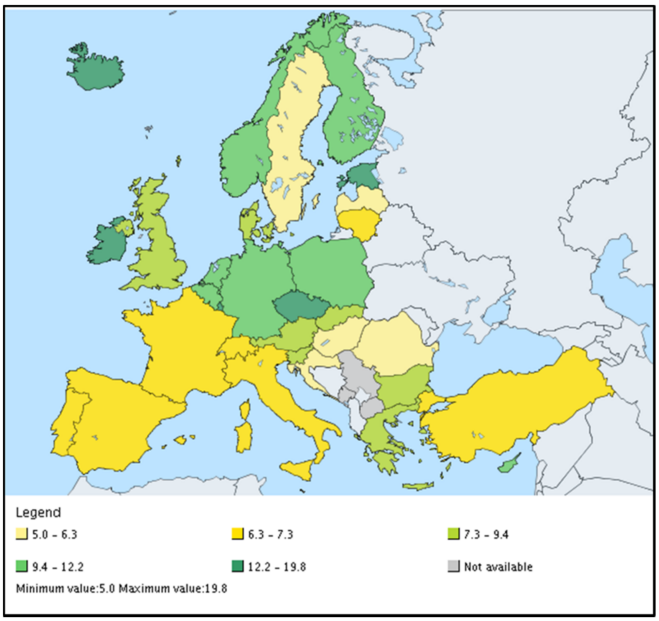


Figure 1. Greenhouse gas emission per capita in EU-28. Mg of CO_2 equivalent per capita—2016 [38].

It has been reported that soil has a high potential for stable and safe carbon storage [36]. Soil carbon sequestration refers to the long-term safe storage of carbon in the SOM in a way that carbon cannot be reemitted. The CO_2 sequestrated into soil via plants or as an effect of deposition contribute to the increase in soil quality and plant productivity as well as supporting ecosystem balance [30,31,39]. SOC sequestration strongly depends on soil texture, profile characteristics, and climate. It has been estimated that SOC sequestration in different soil types may oscillate between 50–1000 kg C ha^{-1} y^{-1} [35]. However, it is necessary to understand all processes in the global carbon cycle, since soil emits GHGs by respiration of SOM. Sequestrated carbon may be stabilized and stored in the soil via many mechanisms such as physical (in soil aggregates, unavailable for organisms), chemical (via absorption into clays or chemical bonds, unavailable for organisms), and biochemical (biologically re-synthesized to complex molecular structures that are difficult for decomposition) [40]. Generally, the post active carbon cycling and carbon sequestration are localized in the topsoil. In turn, stabilized carbon is mainly localized in deeper soil layers, allowing for the safe storage of sequestrated CO_2 [41].

2. Soil Amendment with Biowaste

Socioeconomic development is closely related to ecosystem changes. To avoid activities that have harmful effects on the environment, it is necessary to apply methods consistent with the policy of Sustainable Development (SD). Application of biowaste is compatible with the policy of sustainable development, sustainable agriculture, as well as sustainable food production, and it may contribute to the mitigation of climate changes by sequestering carbon in soil [42]. The key aim of SD is to obtain a balance between the exploitation of natural resources for economic development and protecting ecosystem services [43].

Biowastes are produced in large quantities worldwide by anthropogenic activities, but only about 25% of the total production is recycled. Figure 2 shows the recycling of biowaste per capita in European countries [44]. Due to their high content of organic matter, such biowastes may be used for energy production, soil amendments, and fertilizer, as well as for the immobilization of harmful and toxic trace elements in soils [30]. Biowastes, such as farmyard manure, improve nutrient availability either from the manure itself or through altering the soil's geochemical properties [45], and it may lead to the improvement of good soil structure. Moreover, biowastes may effectively reduce the lability of harmful cations in soil by complexation or surface adsorption to carboxylic and phenolic acid groups. In addition, the co-precipitation to precipitants such as Fe and Al oxides used in the production provides metal-binding surfactants [46–51].

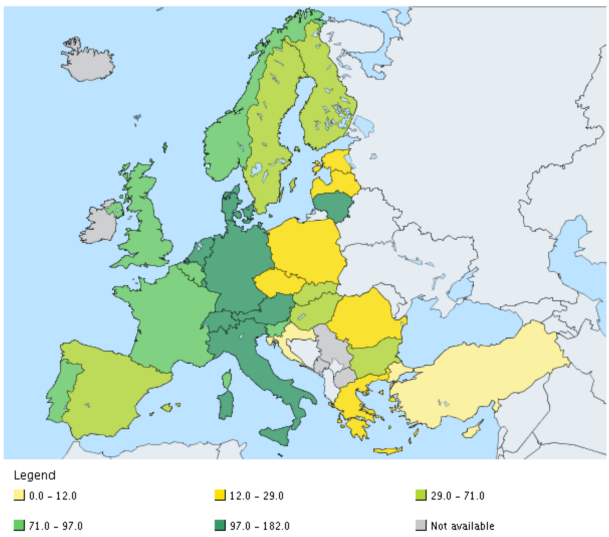


Figure 2. Recycling of biowaste (kg per capita) in different countries in 2017 provided by Eurostat [52].

2.1. Sewage Sludge

Sewage sludge is the most commonly used biowaste in soil remediation practices. Sewage sludge (SS) is a by-product produced in biological wastewater treatment plants and usually makes up about 1–2% of the treated wastewater volume. Production of sewage sludge in 2015 in Poland was 568 Gg, whereas in Germany it was 1.82 Tg [53]. Such large quantities of SS create a problem for their utilization. Moreover, sewage sludge may be problematic in its recycling due to the presence of potentially hazardous trace elements [54]. The substrate of sewage sludge contains both organic and inorganic substances, including pathogens and toxic substances which pose a substantial ecological risk [53]. Sewage sludge also contains organic contaminants that create odors and hygiene concerns [55]. For this reason, sewage treatment systems are designed to stabilize and safely recycle biowaste and to reduce possible environmental risks [53,56]. Applied treatment methods are aimed to recover valuable organic matter fraction and reduction in produced wastes [57].

The final disposal of sewage sludge consists of a major cost in all treatment processes [55]. That is why over many years the treatment and usage of sewage sludge have changed drastically. At present, sewage sludge may be incinerated, disposed of in landfills, treated in anaerobic digestion and composted, spread on agricultural lands, and used for producing biochar by pyrolysis [18,58]. A share of different disposal methods in total sewage sludge disposal in selected European counties in 2015 is shown in Figure 3. In addition to these disposal methods, sewage sludge may also be recycled as a building material [55].

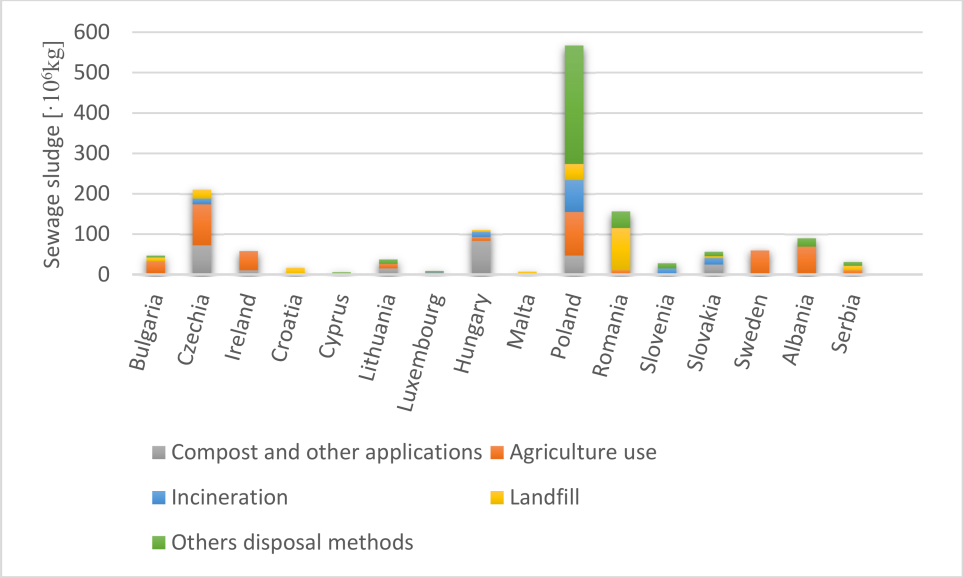


Figure 3. Share of different methods of disposal of sewage sludge in total disposal in selected European countries in 2015 [45].

Sewage sludge has a good fertilizer value due to its high nutrient content made available to plants during the growth period [59]. The sewage sludge is produced in large quantities globally and its amount is increasing year by year. For instance, in Poland, the yearly production of sewage sludge increased by 13% between the years 2006–2015, while in Bulgaria the increase was about 50% between 2006 and 2017. Large quantities of sewage sludge produced in Europe are either deposited or used for different purposes (Figure 3). For example, Germany in 2015 produced 180,299 Mg of sewage sludge, of which 99% was disposed of for agriculture use, landfill, compost, and other application [45].

2.2. Composts

Composting refers to the biological process in which organic matter is degraded under controlled aerobic conditions [14]. The product of composting is biologically stabilized material without the consumption and production of phytotoxic metabolites [14]. Different methods are available for composting, including windrows, aerated static piles, bunkers as well as in-vessel systems [60]. A majority of substrates for composting consists of agricultural wastes, agro-industrial wastes, and putrescible organic residues [61]. Composts consist of a uniform structure that is a valuable substrate for agriculture due to its organic origin containing particularly high amounts of phosphorus but also some nitrogen [61,62]. One of the most important advantages of composting when it comes to handling is the reduction in biowaste volume and moisture [63]. The anaerobic digestion of stabilized compost is an interesting treatment pathway, as biogas is produced during the digestion process [64].

In the literature, there are many interesting studies regarding compost enrichment with nutrients to improve compost quality as a soil amendment. For instance, since nitrogen is one of the most important inorganic nutrients, rice straw or coffee pulp was added to the compost feedstock in order to increase N content in the final product [65,66]. Moreover, potassium-rich feedstock (e.g., banana peels) were added to the compost feedstock to enhance K concentration in the final product [67].

In addition to ordinary compost, vermicompost, produced by short duration, viable and cost-effective technique with stabilized and oxidized biowaste can also be used. Vermicomposting is carried out both by microorganisms and earthworms [68]. Vermicompost is a peat-like material with a high concentration of organic and inorganic ingredients, and with large surface area, and high porosity. The application of vermicompost is shown to influence soil quality positively, among others, by an increase in organic matter content as well as permeability coefficient (PC) [69].

2.3. Other Organic Wastes

In addition to sewage sludge and compost mentioned above, animal manures, crop residues, and food wastes are also considered as biowastes. The name "waste" is closely related to the last step of processing but in agreement with the policy of sustainable development, they may consist a valuable primality product in other branches of industry. Animal manure is often used as organic fertilizer.

Biowaste from the wood processing industry is frequently combusted to wood ash which is used as a nutrient source in plantations and cultivated fields. The high content of micro- and macronutrients in wood ash makes it a valuable soil quality improver. Due to its alkaline properties, wood ash application results in raising soil pH [70]. It has also been reported that bioash can improve forest nutrient deficiency [71].

3. Soil Property Changes after Biowastes Amendment

3.1. Physical and Chemical Soil Parameters

There are many studies regarding the change in soil properties after land application of organic waste. Land application of sewage sludge decreases the bulk density of the soil and increases its porosity [72,73]. Moreover, it also alters the aggregate associated organic carbon of soil by its significant increase [72]. In a previous study, it was observed that biowaste fertilization can increase the concentration of dissolved organic carbon and phenolic compounds [74]. Sewage sludge application can lead to an increase in the field capacity and wilting point, but they also found a decrease in the available water in the soil [75]. The effect of sewage sludge application on different soil parameters is shown in Table 2.

Table 2. Changes in soil properties caused by the application of various biowastes.

Organic Additive	Soil Properties	Effect	Reference
Sewage sludge	pH	In H_2O Decrease	[76]
		In KCl Increase	
		Decrease	[29,75]
		Increase	[77]
	Humic acids	Increase	[76,78]
	Organic matter	Increase	[30]
	Dissolved organic carbon	Increase	[74]
	Cation-exchange capacity	Increase	[30]
	Total organic carbon	Increase	[76,78,79]
	N Kjeldhal	Decrease	[76]
		Increase	[30,77]
	N_{total}	Increase	[74]
	NO_3-N	Increase	
	P, K, Fe	Increase	[30]
Compost	Organic matter	Increase	[79]
	$CaCO_3$	Increase	
	pH	Increase	
		Decrease	[80]
	Cation-exchange capacity	Increase	[79,80]
	Soil bulk density	Increase	[81]
		Decrease	[79]
	Soil water content	Increase	[81]
	Humic substances	Increase	[50]
	Electron conductivity	Increase	[50,80]
	Dissolved organic carbon	Increase	[50]
	Soil organic carbon	Increase	[80]
	Total organic carbon	Increase	[50]
	C:N ratio	Increase	[81]
	P	Decrease	
	NH_4-N	Decrease	
	NO_3-N	Increase	

The application of compost to soil significantly increased the saturated hydraulic conductivity by up to 168.4% in clay soil [79]. Composts may also increase soil porosity, decrease bulk density, and improve soil chemical quality (pH, CEC, organic matter content) (Table 2) [79]. It was also observed that compost increases electron conductivity, the concentration of dissolved, and total organic carbon, and humic substances [82]. The addition of compost increased the SOC by 1.7 times, K by 5.5 times, and decreased N by 0.7 times in comparison to the control [80].

3.2. Impact on Biological and Biochemical Parameters

Basal respiration provides proper information about the microbial activity in the soil and it is a sensitive indicator for monitoring SOM mineralization [83]. García-Gil et al. [83] showed that sewage sludge soil amendment influenced the biological and biochemical parameters of soil positively via increase in microbial biomass, basal respiration, metabolic quotient (qCO_2), and enzymatic activities (dehydrogenase, catalase, phosphatase, urease, protease, and β-Glu activity) after 9 months of semiarid soil treatment. Sewage sludge and compost application to soil improved microbial respiration [84,85]. They noticed an increase in CO_2 emission at higher doses of sewage sludge (30 Mg ha^{-1}). Moreover, biowaste is a valuable source of nutrients to stimulate microbial activity in the soil [85,86]. Therefore, compost application to the soil altered the structure of the bacterial community [79]. However, some organic wastes used as a soil amendment may contain a high concentration of toxic trace elements creating a huge threat to biocenosis. Thus, their entrance to soil should be carefully monitored to minimize environmental risk [87].

3.3. Remediation of Degraded Soil Using Biowaste

Organic wastes such as sewage sludge and compost may immobilize heavy metals in the soil [78,86]. Soil application of biowaste may significantly increase the microbial activity and strengthen the remediation process [31]. Hattab et al. [88] and Placek et al. [31] observed that composted sewage sludge decreased the mobility of Mo, Cr, and Co. Jaskulak et al. [89] showed that cattle manure, horse manure, and vermicompost contributed to the decrease in oxidative stress caused by heavy metal contamination. In their study, the addition of biowaste for the cultivation of white mustard (*Sinapis alba*), black locust (*Robinia pseudoacacia*), and yellow lupine (*Lupinus luteus*) contributed to the decrease in glutathione peroxidase activity and phenolic compounds resulting in a significant decrease in oxidative stress.

Biowaste may also immobilize polycyclic aromatic hydrocarbons (PAHs) in the soil and consequently reduce their bioavailability [90]. The increased microbial activity fuels the degradation of organic contaminants such as pyrene [91] and PAHs [92].

Moreno et al. [93] showed that biowastes addition to an arid soil increased and stabilized the dehydrogenase activity indicating higher total metabolic activity of soil microorganisms. Similarly, Meena et al. [94] showed a beneficial role of biowastes soil amendment on microbial biomass carbon (MBC) (up to 1.5 times in comparison to the control) and dehydrogenase activity (up to 2 times higher in comparison to control). It has been reported that the application of poultry manure, straw, alfalfa, and municipal solid waste compost benefited the MBC and dehydrogenase activity in the soil positively [95]. Similar, a positive increase in organic matter and a decrease in bulk density in degraded soils was noticed by Foley and Cooperband [96].

4. Plant Productivity in Biowaste Treated Soils—Benefits and Risks

Plant productivity depends strongly on soil quality, and good soil quality promotes plant growth [97]. Soil amendments with organic waste can improve the nutritional status [98], plant growth, and crop yields [99]. All soil properties including pH, the concentration of macro- and micronutrients, soil organic matter and the exposure to hazardous elements strongly influence plant development [80]. Similarly, Vaca et al. [99] found that the application of sewage sludge or sewage sludge compost increased the concentration of N, P, K, and SOM in the soil leading to increased productivity of corn. They achieved more corn cobs yield per plant and higher grain production and a low concentration of heavy metals in applied biowastes. Gold beans (*Vigna radiata* L.) grown in the soil amended with sewage sludge were characterized by increased root and shoot length, leaf area, number of leaves and nodules, and total biomass in comparison to control [100]. The pH of soils amended with sewage sludge resulted in a lowering of pH, an increase in electrical conductivity (EC) slightly, and the content of organic C and P was doubled. The negative side of the sewage sludge amendments was a

slight increase in heavy metals concentration. Soil application of biowaste influences positively many agriculture species such as wheat, mustard, pearl millet, and many others [101,102]. The plants grown on soil amended with livestock compost showed higher leaf length and width, as well as chlorophyll content after 4 weeks of growth [102].

There are many studies on the positive role of biowaste on agricultural production as shown in Table 3. Jaskulak et al. [89] showed that cattle manure, horse manure, and vermicompost have a beneficial role in the growth and development of *Lupinus luteus*, *Sinapis alba*, *Robinia pseudoacacia*. In all plants grown on contaminated soil amended with cattle manure, horse manure, or vermicompost, a higher germination index (up to 5 times higher) in comparison to control soil was observed. They also noticed the increase in root length and chlorophyll content in all treated plants. Such improved plant biomass production was an effect of increasing soil pH from value 5.45 (±0.04) in H_2O to 7.41 (±0.14) in H_2O, and a significant increase in N content, and decrease in Cd, Pb, and Zn concentration in the soil. Waqas et al. [103] showed a 25% higher fresh weight of tomato grown on soil amended with sewage sludge, which caused a lowering of soil pH, high increase in EC, and significant increase in C, N, S concentration. The study also showed a large increase in DOC, from 361 mg kg^{-1} to 5720 mg kg^{-1}, and lowering the concentration of bioavailable PAHs in the soil. Nishanth and Biswas [104] studied the effect of rice straw compost on wheat yield at various growth stages and found that the application of this compost on wheat yield increased the yield in comparison to the control at all growth stages, i.e., CRI (color rendering index) stage, maximum tillering, flowering and maturity. Such influence was visible on all plant parts, e.g., shoots, roots, and grain. They also observed higher potassium uptake by wheat grown in the soil treated with rice straw compost. So, the beneficial impact of compost could be caused by the increased availability of nutrients (e.g., K) in the soil caused by their release from applied compost (at least two times higher in comparison to the control at all growth stages). Nevertheless, the dry weight of wheat was much higher in the soil amended by compost in comparison to that amended by sewage sludge [77,101].

It was found that biowaste application to soil increased the plant uptake of nutrients. Singh and Agrawal [100] showed that the sewage sludge treated seeds of *Vigna radiata* L. were higher in N, P, Fe, K, Ca, Mg, and Na content, which correlated well with the similar changes in soil nutrient content, but the protein content decreased. In wheat grown on soil amended with compost Ca concentration in flag leaves increased while the concentration of other nutrients (Mg, K, N, Fe) was not affected by compost application [105].

Table 3. Effects of sewage sludge and compost on various plant growth, development, and yield.

Plant	Plant Properties	Alternation	Reference
	SEWAGE SLUDGE		
Vigna radiata L.	Root length (cm $plant^{-1}$)	Increase	[100]
	Shoot length (cm $plant^{-1}$)	Increase	
	Leaf area (cm^2 $plant^{-1}$)	Increase	
	Number of leaves ($plant^{-1}$)	Increase	
	Number of nodules ($plant^{-1}$)	Increase	
	Total biomass (g $plant^{-1}$)	Increase	
Zea mays	Height (m)	Increase	[99]
	Stem diameter (cm)	Decrease	
	Number of leaves	Increase	
	Foliar area	Increase	
	Number of nodes	Increase	
	Number of corn cob	Increase	
	Productivity (t ha^{-1})	Increase	
Scot Pine	Root biomass production (g)	Increase	[31]
Giant Miscanthus	Root biomass production (g)	Increase	

Table 3. *Cont.*

Lepidium sativum	Root growth (cm)		Increase	[78]
Sinapis alba			increase	
Sorghum saccharatum			Increase	
Dactylis glomerate, *Festuca arundinacea*, *F. rubra*, *Loliumperene*	Biomass yield		Increase	[106]
Eucalyptus, Poplar, Willow	Root biomass (g plant^{-1}) Stem biomass (g plant^{-1}) Leaf biomass (g plant^{-1}) Aboveground biomass (g plant^{-1}) Total biomass(g plant^{-1})		Increase Increase Increase Increase Increase	[107]
Sunflower	Root biomass (g plant^{-1}) Stem biomass (g plant^{-1}) Leaf biomass (g plant^{-1}) Aboveground biomass (g plant^{-1}) Total biomass(g plant^{-1})		Decrease Decrease Decrease Decrease Decrease	
Tomato	Fresh weight (kg)		Increase	[103]
	COMPOST			
Mustard	Grain yield (t ha^{-1}) Straw yield (t ha^{-1})		Increase Increase	[94]
Pearl millet	Yield (t ha^{-1}) Straw yield (t ha^{-1})		Increase Increase	
Tomato	Leaf length (cm plant^{-1}) Leaf width (cm plant^{-1}) Chlorophyll		Increase Increase Increase	[102]
Chinese cabbage	Leaf length (cm plant^{-1}) Leaf width (cm plant^{-1}) Chlorophyll		Increase Increase Increase	
Scot Pine	Root biomass production [g]		Increase	[31]
Giant Miscanthus	Root biomass production [g]		Increase	
Wheat	Grain yield		Increase	[108]
Wheat (*Triticum aestivum)*	Yield (g/pot) CRI stage	Shoot Root	Increase Increase	[104]
	Yield (g/pot) Maximum tillering stage	Shoot Root	Increase Increase	
	Yield (g/pot) Flowering stage	Shoot Root	Increase Increase	
	Yield (g/pot) Maturity stage	Grain Shoot Root	Increase Increase Increase	
Winter wheat	Grain yield		Increase	[105]
Lupin crops	Grain yield		Increase	
Sorghum	Biomass yield		Increase	

Despite many beneficial effects of biowaste on the plants (including higher crop yield, a decrease in oxidative stress, etc.) there are also some negative effects. For example, land application of biowaste

may affect the quality of water through leaching of excess N and P to lower soil layers [109]. In some cases, biowaste land application may increase the mobility of metals via the formation of metal–organic complexes, resulting not only in increased metal uptake by plants but also in metal leaching to the groundwater [110]. Moreover, biowaste, such as municipal sewage sludge, may contain antibiotic and hormones which may be taken up by plants resulting in their entrance to the food chain [111].

Singh and Agrawal [100] observed that beetroot (*Beta vulgaris*) grown on soil amended with 20% and 40% of sewage sludge showed a higher concentration of heavy metals (Pb, Cr, Cd, Cu, Zn, Ni) which was an effect of increased concentration of these elements in the soil amended with sewage sludge. Soil amendment with biowaste characterized with such high concentration of heavy metals showed toxic influence not only on heavy metals accumulation but also on essential plant process-photosynthesis influenced by a significant decrease in chlorophyll content. The slight increase in heavy metals in *Zea mays* grains were also observed by Vaca et al. [99]. They noticed that soil application of sewage sludge compost increased Zn and Cu concentration in the soil as well as maize grain in comparison to inorganic fertilizer (180 days after sowing), and decreased protein and starch content, thus limiting its commercial value. Although the application of sewage increased the growth and yield of *Vigna radiata* L., it resulted in a higher content of nutrients and heavy metals, for example, Cu, Mn, Zn, Cr, Cd, Ni, and Pb were increased by 4.6, 2, 2, 4.5, 7,13 and 8 times, respectively, as compared to control (Table 4) [100]. Such changes may create a major concern for the risk to human health. Despite increased yield of tomato grown on soil amended with sewage sludge, Wasqal et al. [102] noticed a much higher increase in the content of organic matter, N, P, Ca, Mg, K, and Na as well as the concentration of available Zn and Ni in the soil with any change in soil pH. However, they found a much higher concentration of PTEs, such as As, Cd, Cu, Zn in tomato tissues, which exceeded the maximum permissible limits for PTEs (As, Cd) in food plants. Hoitink and Kuter [112] noticed that the stabilization of biowastes is a bottleneck for composting and usage of compost. The heat treatment and maturity time of compost have a direct influence on the quantity of soil-borne diseases. The current knowledge on this topic is still limited. For instance, the tobacco mosaic virus may not be inactivated even if the composting temperature exceeds 60 °C. It has been suggested that properly conducted composting leads to pathogen-free products [112]. A few studies indicate the pathogenic potential of compost, e.g., wilt of flax (*Fusarium*) [112]. However, more resistant pathogens may still survive or not be inactivated [112].

Table 4. Variations in heavy metal uptake rate and translocation factor of beetroot (*Beta vulgaris*) grown in unamended and sewage sludge-amended soils [100].

Metals	Heavy Metal Uptake (μg plant^{-1}d^{-1})			Translocation Factor		
	Unamended Soil	20% Sewage Sludge Amendment	40% Sewage Sludge Amendment	Unamended Soil	20% Sewage Sludge Amendment	40% Sewage Sludge Amendment
Ni	0.10 ^{c}	0.16 ^{b}	0.31 ^{a}	0.14 ^{c}	0.89 ^{a}	0.73 ^{b}
Cd	0.04 ^{b}	1.34 ^{a}	1.37 ^{a}	0.96 ^{a}	0.78 ^{b}	0.91 ^{a}
Cu	0.80 ^{c}	1.17 ^{b}	1.66 ^{a}	1.23 ^{b}	1.5 ^{a}	0.46 ^{c}
Cr	0.19 ^{c}	0.28 ^{b}	0.32 ^{a}	0.32 ^{a}	0.34 ^{b}	0.29 ^{b}
Pb	0.08 ^{c}	0.16 ^{a}	0.12 ^{b}	0.92 ^{a}	0.40 ^{b}	0.60 ^{b}
Zn	2.15 ^{c}	5.88 ^{b}	6.90 ^{a}	0.83 ^{a}	0.58 ^{b}	0.35 ^{c}
Mn	3.18 ^{a}	2.00 ^{b}	1.41 ^{c}	0.99 ^{a}	0.90 ^{b}	0.67 ^{c}

Different letter in each group shows a significant difference at $p < 0.05$.

5. Effect of Biowaste on Soil Organic Carbon Sequestration

5.1. Soil Organic Carbon Sequestration

Carbon sequestration refers to a long-term capturing and storing of atmospheric carbon dioxide by photosynthesis [113], as illustrated in Figure 4. Sequestered soil organic carbon in the net result

from the gross primary production (NPP = GPP-R_{phd}) not respired by plants (p), herbivores (h), and decomposers (d) [36]. Facilitated by solar energy and H_2O, atmospheric CO_2 is built into the biomass. The dead plants, or residues of plants, provide energy and nutrient-rich substances for a respiring living organism, whereas the slowly decomposable residues add to the humic fraction in soil [113]. The respiration release CO_2 (or CH_4 under anaerobic conditions) to the air. The amount of carbon being sequestered as stabile organic matter depends on several factors affecting photosynthesis and respiration such as temperature, humidity, access to particularly soil N, but also soil texture. e.g., adsorption to clay and oxide minerals reduces microbial respiration and increases soil organic matter stability in soil. The quantification of soil organic matter in the soil is mostly achieved by measuring the content of organic C. In addition to C, the soil organic matter is composed of H, O, N, S, and various amounts of other components. The stoichiometry of elements in soil organic matter varies, but fraction C is the dominating element and, as a rough estimate, C accounts for about 50% of soil organic matter. Hence, soil C is measured as an indication of soil organic matter (SOM) content [114].

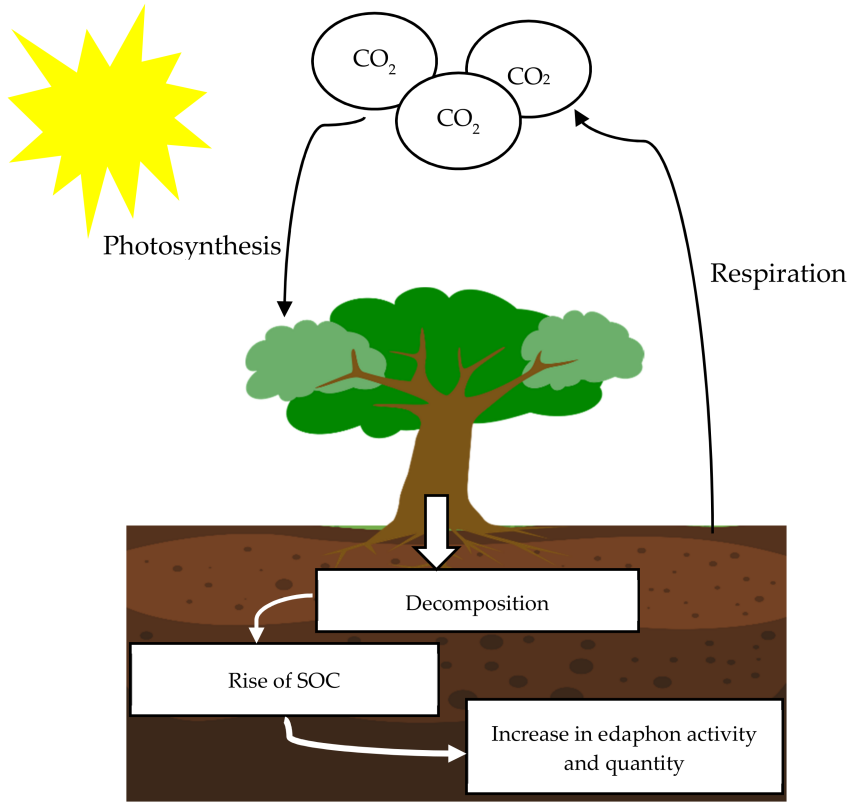


Figure 4. Simplified scheme for the fate of CO_2 in air-soil medium sequestrated by photosynthesis.

Soil contains the biggest terrestrial reservoir of carbon, and soil carbon constitutes approximately two-thirds of total carbon in ecosystems [36,115]. The organic carbon content in the topsoil in selected countries (Figure 5) is shown by de Brogniez et al. [116].

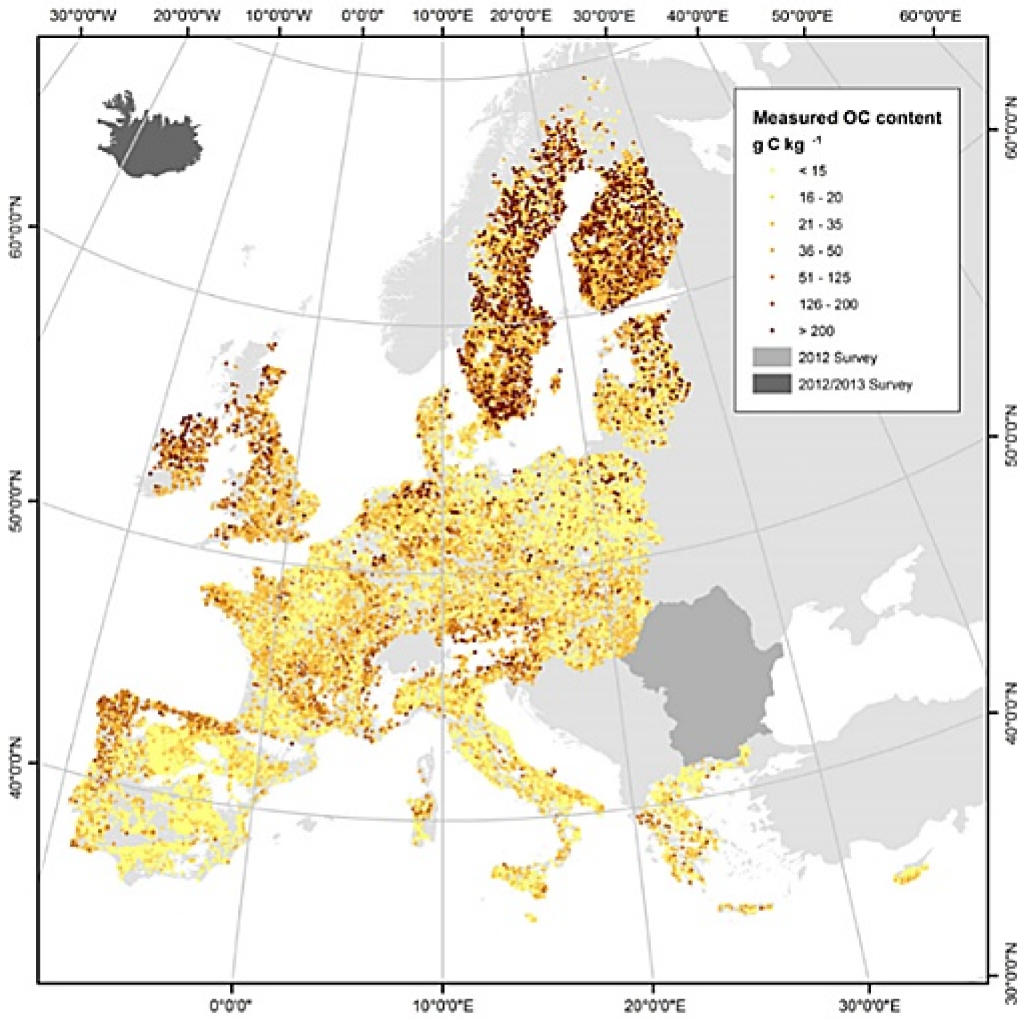


Figure 5. Measured organic carbon content at Land Use/Cover Area frame statistical Survey (LUCAS) topsoil survey (2009) sampling locations. Results of the laboratory analysis for Romania, Bulgaria, and Iceland are awaited [116].

Many studies have shown higher biomass production in soils treated with biowaste [36,117,118]. Placek et al. [31] found an increase in SOC in soil amended by lake chalk and other biowastes. Placek et al. [31] reported that the application of sewage sludge from the food industry to soils from zinc smelter and coal mine showed higher SOC content after 18 months. The beneficial effects of biowaste in this experiment were assigned to the immobilization of toxic heavy metals in the soil allowing for proper growth and development of plants and soil activity, and finally increased SOC. Hemmat et al. [119] studied the long-term impact of biowaste on soil quality including SOC of calcareous soil. They showed that the application of all tested biowastes, municipal soil waste compost, air-dry sewage sludge, and cattle farmyard manure, significantly increased SOC content after 7 years of experiment. Moreover, they noticed a close relationship between the rates of biowaste application and SOC increase rate. Aggelides and Londra [79] reported that compost produced from town wastes and sewage sludge showed beneficial effects on SOC in loamy and clay soils. Similarly, Hemmat et al. [21] found increased SOC after compost application. In the study on the effect of compost, green manure, farmyard manure, and sewage sludge on topsoil and subsoil, it was found that the addition of biowaste significantly increased SOC content. Kätterer et al. [120] noticed that the highest increase in SOC in 0–40 cm deep soil was achieved by the application of compost. Meena et al. [94] also noticed the increase in SOC by application of a municipal waste compost to soil. An increase in SOC contributes to decreased soil

degradation, increased productivity, and remediation of soils. Thus, it is very important to supplement soil with biowaste [35]. However, in some studies, the effect of sewage sludge application depended on initial SOC value, as the application of sewage sludge to soil with a high initial SOC concentration resulted in the decrease in SOC [121]. On the other hand, sewage sludge application to 60 agricultural soils showed an increase in short-term SOC pool in a majority of the soils [121].

5.2. Assessment Methods of Soil Organic Carbon Sequestration

The simplest method for calculation of soil organic carbon sequestration is a comparison between changes in the SOC stock in an ecosystem [122]. The assessment of carbon sequestration is one of the most difficult scientific issues due to the impact of many variables. One of the methods for estimation of SOC sequestration at the ecosystem level are eddy-covariance and agricultural life cycle analysis [123]. The eddy-covariance is a micrometeorological technique that allows the quantification of CO_2 exchange between the atmosphere and several hectares area of forest or grassland, as well as shrubland [124]. The quantification of SOC as well as TOC in soils currently may be conducted via many available methods, including wet digestion and dry combustion, as well as the loss-on-ignition (LOI) technique for TOC [123]. All mentioned methods have been previously well described by Nayak et al. [123].

Evaluation of the Effectiveness and Stability of Assessment Indicators and Modeling of the Degree of Organic Carbon Sequestration (SOC) of Soils

Climate change and increasing area of degraded soils require stable indicators and models for SOC sequestration [125]. Thus, SOC modeling is one of the most essential tools for determining the effects of organic material management on carbon sequestration [126]. Generally, all long-term fields are aimed to monitor SOC dynamics as affected by management practices. The large dependency of SOC dynamic on the climate conditions and soil type may cause that the accuracy of the monitor of SOC dynamic may not be enough to properly assess the post-future influence of soil management practices [126]. The main advantages of SOC modeling are an explanation of processes and relationships in the soil–plant–atmosphere system and improvement of the clarity of SOC dynamics. Above all, SOC modeling is useful to study the effects of various management scenarios on carbon sequestration and hence, mitigation of climate change [127].

Considering the above facts, SOC dynamics and distribution may be indirectly estimated by modeling. The models for soil organic carbon should provide accurate and transparent data about the carbon sequestration in the soil as well as predictions of SOC content in the soil [126]. Many models are available for the estimation of organic carbon stock, and among them the most widely used are: RothC and CENTURY models with a high potential in application to predict SOC stock on regional as well as an national level [128–132].

Rothamsted carbon model (RothC model) refers to the organic carbon turnover in the non-waterlogged topsoil that allows for the effects of soil type, temperature, soil moisture, and plant cover on the turnover process. RothC is freely available for non-profit scientific research [133]. The main advantage of RothC model is the necessity to provide only basic input data that are readily available, such as monthly rainfall, average monthly air temperature, and others [134,135] (full description is available by Coleman and Jenkinson [133]). RothC model has been widely used in many countries for many years [136,137]. However, the sub-model for plant production has not been included in the RothC models, as it refers only to the soil processes [133]. RothC model can estimate C sequestration under different soil treatments (including soil amendment with biowastes) in long-term experiments [126]. Farina et al. [135] noticed that the simulation of C cycling in dry regions using RothC is not accurate. This simulation required the introduction of unrealistically high C input data to fit the modeled data to the measured. In their study, RothC model has been modified in order to improve SOC dynamics prediction in dry/semi-arid regions and hence requires more realistic C inputs to the soil. Moreover, for amended soils, there are two major limitations for using commonly available carbon models [138]. The actual models do not effectively and clearly describe the variability of exogenous organic matter

(EOM) quality [139]. The RothC model modified by Modini et al. [139] is available that provides addition of EOM pools as well as its parametrization by model fitting to the respiratory curves of amended soil [139]. The modified RothC model is an important tool to evaluate SOC storage in amended soils because of the influence of many differences between laboratory and field conditions. Mondini et al. [140] showed that the modified RothC model may be useful for the long-term modeling of SOC in the soil amendment with EOM at the regional level under climate change [140]. Generally, the modification consisted of supplying additional pools of decomposable (DEOM), resistant (REOM), and humified (HEOM) exogenous organic matter. All of them have been specifically characterized by partitioning factors (F) and decomposition constant rates [140].

Despite many possibilities of this model, it does not include all data for all soil types; thus, for many cases, the model must be properly validated and modified. For example, the RothC does not work properly for Andosols due to the active Al formed in the weathering process of volcanic ash which binds organic matter strongly that thus this form of OM cannot be considered in RothC model [126]. Moreover, in the literature, many extensions of the models have been proposed. For example, Bolinder et al. [141] proposed a reference depth of 40 cm for below-ground residues (Equation (1)) where *RBFplot* consist root biomass for the measured depth of the tested soil, and *RBFref* is the root biomass for the reference depth of 40 cm—both described as: $RBF = 1 - \beta d$. Another extension of the RothC model was provided by Franko [140] for carbon input residues in combination with the crop yield in mixed topsoil of 30 cm depth, where *K* is yield-independent, and *F* is the yield-independent carbon input (Equation (2)).

$$C_{in_{BGB}} = C_{yield} \cdot \frac{fr_{root} + Fr_{exud}}{fr_{yield}} \frac{RBF_{plot}}{RBF_{ref}} \left[\text{Mg C ha}^{-1}\right] \quad (1)$$

$$C_{in} = (K + yield \cdot F)\left[\text{Mg C ha}^{-1}\right] \quad (2)$$

The CENTURY simulation model developed by Parton and co-workers [142] used a four-pools SOM submodel (production submodel, SOM submodel, N submodel, and soil water balance submodel), and allows us to predict long-term SOC trends that are based on the mathematical representation of C-cycling processes in the soil-plant system [140]. The basic idea of the CENTURY model shows similarity to the RothC model. CENTURY model allows for simulations of C, N, P, S dynamics for various plant-soil systems [142]. It provides a possibility to assess climate change and it is usable for ecosystem management [134]. This model is successfully used in simulations of long-term SOM dynamics across a wide range of ecosystems under various environments and management [143]. CENTURY has been validated for various types of ecosystems in order to provide proper information. CENTURY model uses a monthly time step and works well for simulations of long- or medium-term changes in SOC as a response to climate changes, as well as land management including the remediation of degraded soils with biowastes.

Similar to the RothC model, many different modifications of the CENTURY model are available. The CENTURY model has been developed for grasslands, but due to many modifications, it is extended to cropping systems, forests, and savanna systems [132].

6. Conclusions and Research Perspective

Biowaste applications in soil have been shown to improve soil quality, and thereby conditions for effective photosynthesis and other soil biological processes. Improved biomass production promotes the development of stable organic matter in the soil, which improves the cation exchange and water holding capacity in soil. These are essential factors to promote and stimulated for effective soil remediation to happen. Moreover, high organic matter content in biowastes contributes to the immobilization of heavy metals in soils. In degraded and poor fertility soils, the use of biowaste may improve their quality and productivity. Moreover, biowastes have shown a high potential for carbon sequestration and its storage in the soil, thus contributing to the mitigation of climate change. Higher microbial activity and plant productivity being an effect of improved soil quality with biowastes, contributes to the higher

CO_2 sequestration and storage in the soil. Care should be taken on the quality assessment of biowaste, as such material may contain PTEs and pathogens, generating a huge risk for biodiversity and human health through their entrance into the food chain. Therefore, regulations regarding the use of biowastes in the soil should be improved and extended for their use as agricultural fertilizer or soil amendment in the soil remediation process to avoid an enhanced accumulation of PTEs and other contaminants. Furthermore, it is important to understand the processes and mechanisms involved in the use of biowastes (sewage sludge and compost) and organic matter dynamics to enhance SOC sequestration.

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