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Review

Bio-Based Waste' Substrates for Degraded Soil Improvement—Advantages and Challenges in European Context

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Abstract: The area of degraded sites in the world is constantly expanding and has been a serious environmental problem for years. Such terrains are not only polluted, but also due to erosion, devoid of plant cover and organic matter. The degradation trends can be reversed by supporting remediation/reclamation processes. One of the possibilities is the introduction of biodegradable waste/biowaste substrates into the soil. The additives can be the waste itself or preformed substrates, such composts, mineral-organic fertilizers or biochar. In EU countries average value of compost used for land restoration and landfill cover was equal 4.9%. The transformation of waste in valuable products require the fulfillment of a number of conditions (waste quality, process conditions, law, local circumstances). Application on degraded land surface bio-based waste substrates has several advantages: increase soil organic matter (SOM) and nutrient content, biodiversity and activity of microbial soil communities and change of several others physical and chemical factors including degradation/immobilization of contaminants. The additives improve the water ratio and availability to plants and restore aboveground ecosystem. Due to organic additives degraded terrains are able to sequestrate carbon and climate mitigate. However, we identified some challenges. The application of waste to soil must comply with the legal requirements and meet the end of use criteria. Moreover, shorter or long-term use of bio-waste based substrate lead to even greater soil chemical or microbial contamination. Among pollutants, "emerging contaminants" appear more frequently, such microplastics, nanoparticles or active compounds of pharmaceuticals. That is why a holistic approach is necessary for use the bio-waste based substrate for rehabilitation of soil degraded ecosystems.

Keywords: soil degradation; biodegradable waste; compost; biochar; remediation; revegetation; soil organic matter; plant ecosystem restoration contamination immobilization/degradation

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1. Introduction

Soil degradation is the modification of its physical, chemical and biological properties that worsen the biological activity of the environment, with particular emphasis on food production, water quality, ecosystem services, flooding, eutrophication, biodiversity and carbon stock shrinkage. Soil degradation has many forms and genesis: (i) geotechnical soil degradation caused by deformation of the relief resulting from the activities of opencast and underground mining as well as construction (including road, rail and water). This form of soil degradation covers the entire territory, but the greatest damage should be noted in the areas of high concentration of the mining industry and in large urban agglomerations. Soil geotechnical changes are usually accompanied by changes in soil structure; (ii) physical degradation of soils consists primarily of water and wind erosive action. It is caused by negative changes in the soil structure, compaction of the soil mass, excessive soil drainage caused by a depression funnel, defective melioration, waterlogging due to subsidence in mining areas, pressure of above-level dumps, landslides and the impact of water reservoirs; (iii) chemical degradation of soil is associated with excessive acidification or alkalization, destabilization of the ionic balance of soils, excessive salt concentration in soil solutions, toxic concentration of heavy metals, sulfur, fluorine and biologically active compounds (hydrocarbons, pesticides); (iv) soil biological degradation underlies all forms of soil degradation, although it is generally of an indirect nature. It manifests itself in destruction of plant cover (especially forests), which causes deterioration of soil conditions, especially when they are highly susceptible to degradation (loess). The forms of soil biological degradation also include soil fatigue stoppage of soil ammonification, nitrification and organic degradation processes.

Cook et al. [1] estimate that soil degradation affects approximately 15% of Earth's ice-free land surface, and irreversible erosion has occurred in an area of approximately 430 million ha and in Asia, approximately 40% of the soils are classified as degraded. The mean soil loss rate in the European Union's erosion-prone lands (agricultural, forests and semi-natural areas) was found to be 2.46 t ha^{-1} yr^{-1}, resulting in a total soil loss of 970 Mt annually [2]. US Environmental Protection Agency reported that more than 40% of the national priority list sites are co-contaminated with heavy metals and heavy polycyclic aromatic hydrocarbons (PAHs) [3].

The possibility of using biodegradable waste (as a resource of SOM, water and living biota) to increase productivity and soil quality, in accordance with regulations, standards and norms, is still in the center of attention in many research activities, and there is now also great interest in the possibility of carbon sequestration in soils, water availability and climate mitigate, which is closely connected with increasing the organic matter content of soils. The Circular Economy Action Plan adopted by the European Commission in 2015 prefers that after the end of the product's life, by-products or waste be reused for further value. This plan sets out measures to close the product life cycle and lists five priority sectors, including the two sectors most relevant to the topic addressed in the article: food waste, biomass and bioproducts [4]. According to the European Commission Biodiversity Strategy 2030, the Farm to Fork and the European Climate Law written several actions for sustainable soil management. Circular economic utilization of waste streams helps in fulfilling SDG 11 and SDG 15. As mentioned Montanarella and Panagos [5] gaining land degradation neutrality by 2030 (SDG target 15.3) should be a pre-condition for the later achievement of a climate neutral continent in 2050.

Among all the different types of generated wastes, biological ones represent the most environmentally significant since they are continuously and globally produced [6]. The authors noted that the characteristics of organic amendments (both waste and waste-based products) depend on their origin (urban: domestic organic waste and sludges from urban wastewater treatments; other: animal (manure), agricultural or agroindustrial) and determine in part their potential positive or negative effects on the degraded terrains where they are applied. Hence determination of connections between the use of bio-based waste products in soil and its impact on soil characteristic improvement, carbon sequestration, plant growth and productivity, in accordance with standard regulations and environmental risk is the subject of this review. We identify the most import benefits of the use bio-based product for soil remediation/reclamation/revitalization. However application of bio-based substrates onto degraded land also poses a number of challenges for unstable degraded soil ecosystems. Ambitious goals of European countries require specific strategies for management of degraded terrains. Hence important is identification not only all positive aspects, which prevalancing in literature, but also risks connected with environmental hazards.

The objectives of this review are to: (1) deliberate the role of biodegradable waste as a valuable resources for soil restoration in European context; (2) estimate the potential of bio-waste based substrates as additives for remediation/reclamation and revitalization of degraded terrains; and (3) identify chalenges for improving soil quality to mitigate risks of soil degradation.

2. Biodegradable Waste vs. Bio-Waste

European Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste [7] introduced targets for the landfill of untreated biodegradable waste. Further restrictions were subsequently set by prohibiting the landfill of biodegradable waste collected separately for recycling in accordance with Directive 2008/98/EC [8]. Directive 2018/850 [9] of the European Parliament and of the Council (EU) states that the predefined targets should be stronger to better illustrate the EU's ambition to move to a closed-loop economy. By 31 December 2023, EU Member States should ensure that bio-waste is separated and recycled at source or separately collected and not mixed with other types of waste. "*Biodegradable waste*" is defined in the Landfill Directive as any waste that is capable of undergoing anaerobic or aerobic decomposition, such as food and garden waste, and paper and paperboard. In turn "*bio-waste*" is defined in the Waste Framework Directive (WFD), as "*biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, and comparable waste from food processing plants*". It does not include forestry or agricultural residues, manure, sewage sludge, or other biodegradable waste (natural textiles, paper or processed wood).

3. Bio-Based Waste Substrates

Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Towards a circular economy: a zero-waste program for Europe published in 2014 clearly stressed the need to reuse waste in the closed-loop cycle [10]. In 2019 European Commission published a new EU fertiliser regulation [11]. In order to protect primary raw materials, it recommends the introduction of secondary raw materials for fertilizer production in the EU. This is to allow access to the EU internal market for organic fertilizers and soil improvers from recycling (compost and digestate) [12]. However, the list of biodegradable waste could be used as substrate to products for degraded soil fertilization is very wide (Table 1) and after decomposition introduce several valuable compounds such polysaccharides, proteins, polyphenols, lipids, macro and micronutrients and many others (Figure 1).

Table 1. The most frequently used biodegradable waste and products for degraded soils improvement.

Product	Biodegradable Waste
Compost Vermicompost Digestate Organic-mineral fertilizers Soil substitutes Plant growth promoting substrates Biochar Ash Struvite	Food, agricultural, forest waste Pig, cow, poultry manure Sewage sludge Organic fraction of municipal solid waste (ofmsw) Waste from the food (such slaughterhouses, bakeries, dairies, breweries) Pulp and paper mill by-products Wastewater

Chojnacka et al. [13] identified several new technologies available for the production of inorganic/organic liquid/solid fertilizers: (i) liquid/solid separation followed by evaporation/filtration, (ii) ammonia stripping, (iii) liming, (iv) biological treatment, (v) precipitation, (vi) pelletizing, (vii) membrane processes (nanofiltration, reverse osmosis, membrane distillation). However, there are still challenges related to the production of more concentrated and marketable products, storage and handling as well as diminishing losses of nutrients [14].

The literature lacks data on the amounts of different groups of biodegradable waste/product used on degraded soils. According to European Compost Network average value of compost used for land restoration and landfill cover was equal 4.9% in 2005 (Table 2).

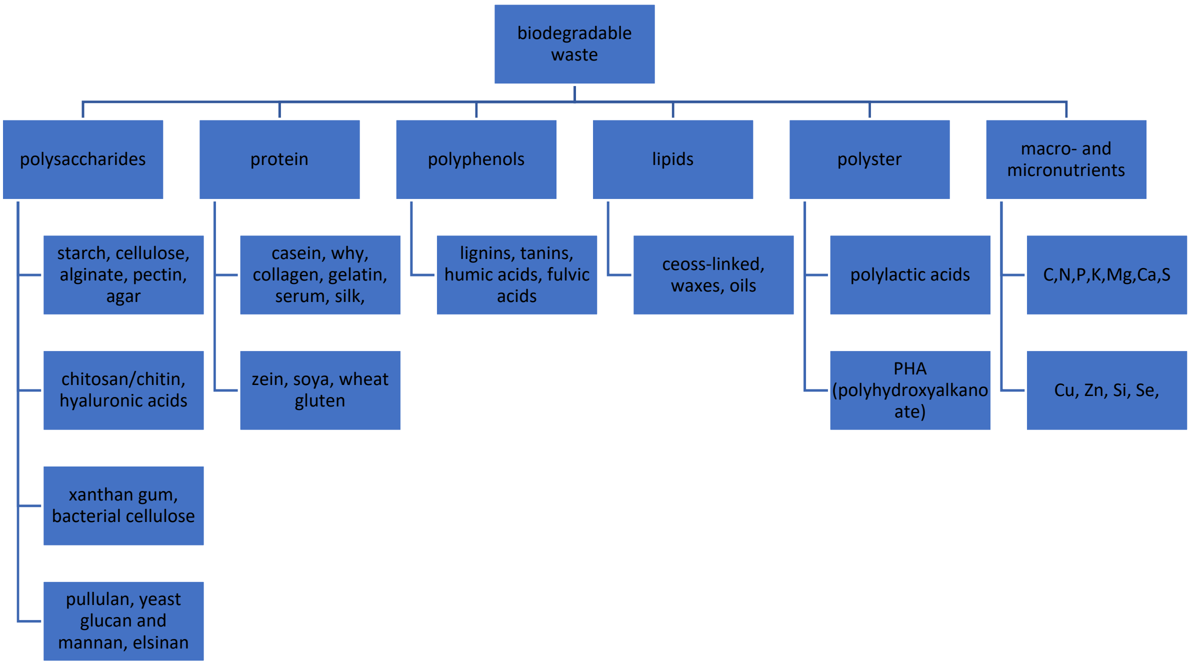


Figure 1. The samples of valuable compounds from biodegradable waste that can be used for degraded soil remediation/revitalization.

Table 2. Land restoration and landfill cover use of compost (%) in major compost producing EU countries [15].

AT 2003	BE/FI 2009 (1)	DE 2005	ES (2) 2006	FI 2005	FR (3) 2005	HU 2005	IE 2006	IT 2003	NL Biowaste 2005	NL (2) Green Waste 2005	PL (3) 2005	SE 2005	UK 2005	Weighted Mean EU
2.0	44	-	-	50.0	-	15.0	38.0	2.0	-	-	100	40.0	16.0	4.9

(1) Data for Wallonia reported in different classification: Agriculture 56.6%; Private 4.4%; Potting compost 13.1%; Green areas 2.1%; Rehabilitation 4.1%; Storage on-site 5.6%; Landfill 2.7%; Other elimination 2.6%; Exported 8.9%. (2) Green waste compost. (3) Mainly mixed waste compost.

In Poland, sewage sludge amount used for the reclamation of degraded lands decreased systematically from 25% (in 2005) to 2.6% (in 2019); (Figure 2).

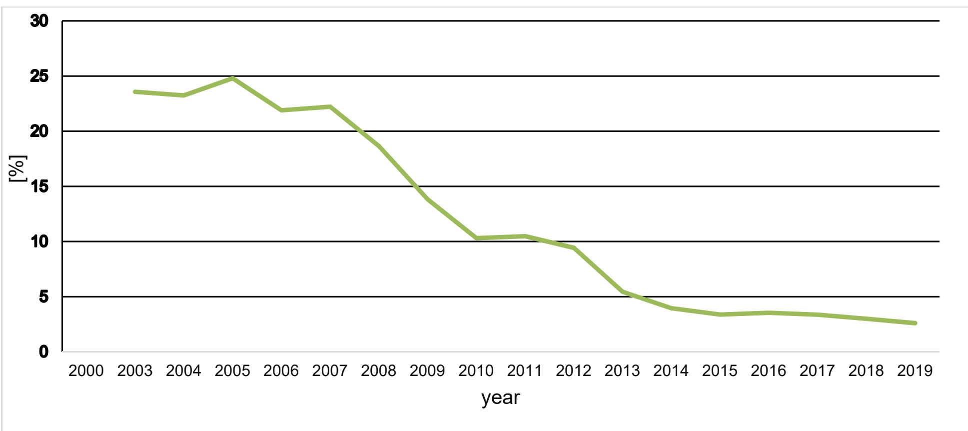


Figure 2. The use (as % of total mass) of sewage sludge for reclamation purposes between years of 2000 and 2019, performed their own study based on Statistics Poland data, (https://stat.gov.pl/en, accessed on 28 November 2021) [16].

3.1. Compost

Biological methods are most often used to transform and utilize biodegradable waste: composting and/or fermentation. It is estimated that out of the total mass of bio-waste, about 30 ÷ 50% is suitable for composting. The composting process is a very effective way of transforming and neutralizing various bio-waste, and then reusing the final product. It is an aerobic process during which microorganisms (aerobic bacteria, nematodes, fungi, etc.) break down biodegradable organic compounds, leading to the formation of compost—an organic fertilizer used to improve soil fertility and the quantity and quality of crops [17]. Composting is carried out both on an industrial scale (in reactors, tunnels, containers or prisms) and, on a much smaller scale, in domestic composters.

Many different substrates are used in the process of composting (Figure 3), mainly waste materials, which are produced both in industry, agriculture and municipal management.

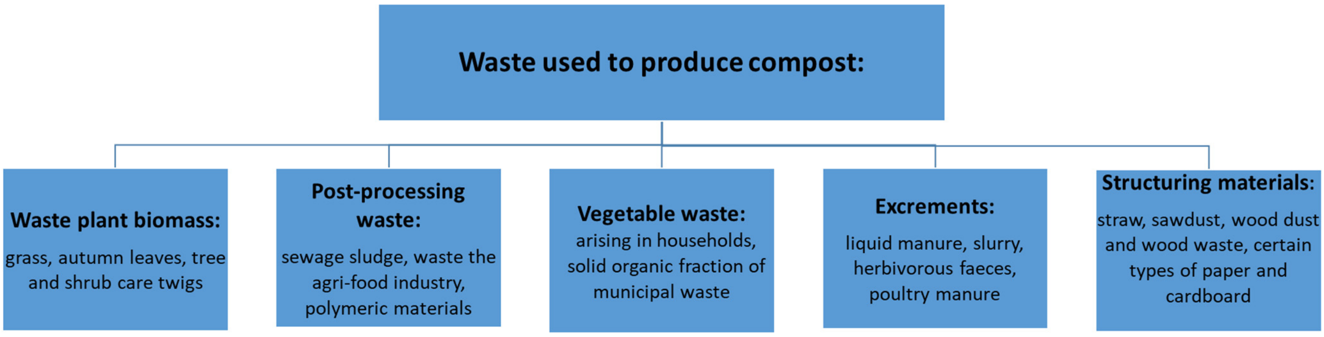


Figure 3. Materials used in the composting process [18–23].

Several factors influence the correct operation of the composting process. The input material must have an appropriate carbon/nitrogen (C/N) ratio, moisture content and structure, while maintaining the correct process conditions (aeration, moisture content, obtaining and maintaining the right temperature) allows the production of high-quality compost [24]. The basic parameter which determines the correct progress of the process and the quality of the resulting product is C/N—mass ratio of organic carbon to total nitrogen. Carbon is a source of energy for microorganisms while nitrogen influences the growth rate of their populations (Figure 4).

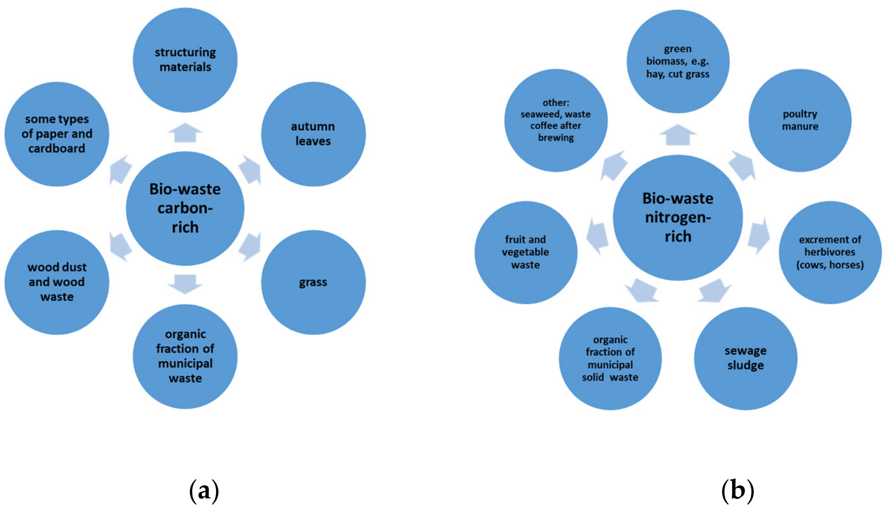


Figure 4. Carbon-rich materials used in the composting process (**a**) and potential nitrogen sources for compost mixes (**b**) [25–29].

If the nitrogen content is too high, its excess is released into the atmosphere during composting and can cause odor problems. In the opposite situation, the process slows down rapidly because of the insufficient amount of nitrogen needed for the microorganisms to grow properly. After mixing all the selected waste to be composted, the C:N ratio should be between 25 ÷ 35:1. In addition, it is important that the batch mix has a moisture content of approximately 55% and a minimum organic matter content of 30%. An incorrect C/N ratio during the process can degrade the quality of the compost and decrease its fertilizer values. Any biodegradable material can be used for composting as long as there is sufficient time for decomposition [30]. However, not every raw material is suitable for the production of compost of a good quality, e.g., because of its above-standard heavy metal content (a common problem with sewage sludge). In addition, the compost mixture, in which the temperature during the thermophilic phase (according to various authors 60 ÷ 65 °C) necessary for the hygienization of the final product is not achieved, may cause the occurrence of harmful microorganisms in the finished compost [31]. Therefore, animal manure, meat residues and milk products should only be composted under an appropriate technological control. The base for obtaining good quality material for the composting process is the separate collection of bio-waste [32]. Good quality compost was produced using selectively collected green waste [33,34], vegetable waste [35–38] or agricultural waste [20,39,40]. In comparison, composts made from sewage sludge or the biodegradable solid fraction of municipal waste require more attention in both production and application [41–44].

Between years 1995 and 2020 in EU countries, was noted significantly increase (approximately 200%) the ratio of composting process in municipal waste management (Table 3).

Table 3. Municipal waste landfilled, incinerated and composted in European countries in years 1995–2020 [45].

	1995	2000	2005	2010	2015	2020	Change 2020/1995 (%)
				million tonnes			
landfill	121	112	88	79	57	52	−58
incineration	30	36	45	53	57	61	105
material recycling	23	38	46	55	63	67	192
composting	14	23	26	29	33	40	186
other	10	12	16	6	4	5	−50
				kg per capita			
landfill	266	262	202	178	127	115	−60
incineration	70	84	103	121	126	137	97
material recycling	54	87	105	125	141	151	177
composting	33	53	59	66	75	90	171
other	23	27	37	13	9	11	−52

3.2. Organic–Mineral Fertilizers

Processing of biodegradable waste into organic–mineral fertilizers or plant growth promoter products are technological solutions exist on commercial market as an alternative way for composts. The production of such fertilizers requires the addition of a significant amount of inorganic substrates. These can be calcium compounds, sulfuric acid, magnesium and potassium compounds or fly ashes from the combustion of hard coal or brown coal. Their role is primarily [46]:

- Elimination of pathogens, as the product for natural use should be safe in terms of sanitation;
- Correction and harmonization of the chemical composition and physical properties, as sewage sludge is a variable substrate;
- Giving the fertilizer mixture a practical, usable and storable form.

Usually the process is based on the adding significant amount of quicklime (containing active calcium oxide CaO):

$$CaO + H_2O \rightarrow Ca(OH)_2 + heat \quad (1)$$

The amount of heat generated by a strong exothermic reaction is directly proportional to the amount of water needed for evaporation and the amount of added quicklime CaO (Equation (1)). According to the fertilizer manufacturers, the resulting slaked lime can react at a temperature elevated to 135–140 °C with the presence of, for example, amorphous silicic acid or aluminum compounds present in the sediments. In addition, lime used as a fertilizing component also has an added value in the form of a positive effect on acidic soils, where it will provide not only lime as a fertilizing element, but also increase the pH of such soils, improving their fertility.

Another possibility is technology using roasted magnesite and sulfuric acid. In this method, calcined magnesite with a high MgO content and then sulfuric acid are added to the waste. As a result of an exothermic reaction (temperature above 100 °C), excess heat escapes in the form of water vapor (Equation (2)):

$$MgO + H_2SO_4 \rightarrow MgSO_4 + H_2O + heat \quad (2)$$

The reaction also results in binding the water contained in the waste into the water of crystallization of magnesium sulphate (Equation (3)):

$$MgO + H_2SO_4 + nH_2O \rightarrow MgSO_4 + (n + 1)\ H_2O \quad (3)$$

In this technology, the process is carried out in such a way as not to fully saturate the water with magnesium sulphate, which protects the product against caking and is easily granulated. The fertilizer is an additional source of magnesium and sulphur for plants.

In turn, the fly ashes from biomass combustion is one of the oldest natural mineral fertilizers. Generally, ash from biomass has a much higher content of components such as CaO, MgO, Na_2O, K_2O, P_2O_5 and, at the same time, a lower content of SiO_2, Al_2O_3 and TiO_2 compared to ash from coal combustion. The pH of ashes from the combustion of various types of biomass ranges from 9.3 for oat grain ash to 13.9 for oak wood ashes. Due to its alkaline properties, these ashes can act as a hygienising substance of biodegradable waste (pH of aqueous extracts approx. 13, high content of reactive CaO). The condition for full hygienization of the waste is to maintain a high temperature of the mixture of 55–70 °C for 24 h and at the beginning of the process—a high pH of min. 12.5 As a result of homogenization of the mixture a number of exothermic reactions which lead to physicochemical changes [47]. Fertilizer contains significant amounts of calcium, magnesium and potassium as well as microelements, which are an important nutrient for plants. Moreover, due to high alkalinity it has de-acidifying properties and can be a substitute for calcium.

3.3. Biochar

Biochar is obtained in the pyrolysis process, i.e., thermal processing of biomass without oxygen at a temperature of 350–700 °C, which produces oil (mixture of hydrocarbons), synthetic gas (mixture of gaseous hydrocarbons) and biochar (solid residue). Generally, biochar can be obtained from all types of biodegradable waste. The most frequent waste used in the production of biochar include: forest waste, residues from agri-food processing (e.g., fermentation oats, rice husks, nut shells, coconut and bagasse), sewage sludge, organic fraction of municipal waste, poultry processing waste, chicken manure, cow manure and waste algae biomass. The selection of appropriate substrates depends on the physicochemical properties (including water and carbon content, particle size), potential applications of biochar and the parameters of the pyrolysis process.

The great advantage of processing waste into biochar is also the creation of a product with a uniform structure and stable properties. The obtained biochars are characterized, among others, by high content of organic carbon in the stable form, presence of mineral active chemical groups, developed porosity and large specific surface area (1 g of the material has a surface area of 400 to 800 m^2), negative charge, alkaline reaction and resistance to degradation. It is assumed that the higher the pyrolysis temperature, the greater the specific surface area of the resulting biochar, although there is evidence that at very high temperatures some pores collapse and the surface area diminishes. The negative charge on the surface of biochar attracts positive charged metal ions and organic compounds from the soil solution, which significantly reduces their bioavailability to living organisms. The sorption capacity of metals increases with the pyrolysis temperature until it reaches a maximum at about 350–400 °C, then sorption decreases. The surface of biochar produced at such temperatures is rich in "oxygen-containing functional groups", which enable the formation of complexes with cations, e.g., Cu^{2+}, Ni^{2+}, Cd^{2+}, Pb^{2+} or Zn^{2+}. Metal sorption is the effect of ion exchange with functional groups such as hydroxy-, carboxy- and phenols. In contrast, at high pyrolysis temperatures, the C/O ratio increases, and the surface becomes more electronegative. As a result, metal sorption is the effect of the electrostatic interaction between positively charged metal ions and the negative charge related to the delocalization of π-electrons on aromatic structures (Figure 5). The chemisorption of metals is generally much stronger than their physical sorption. However, it is believed that biochars produced at higher temperatures have a greater ability to absorb hydrocarbons.

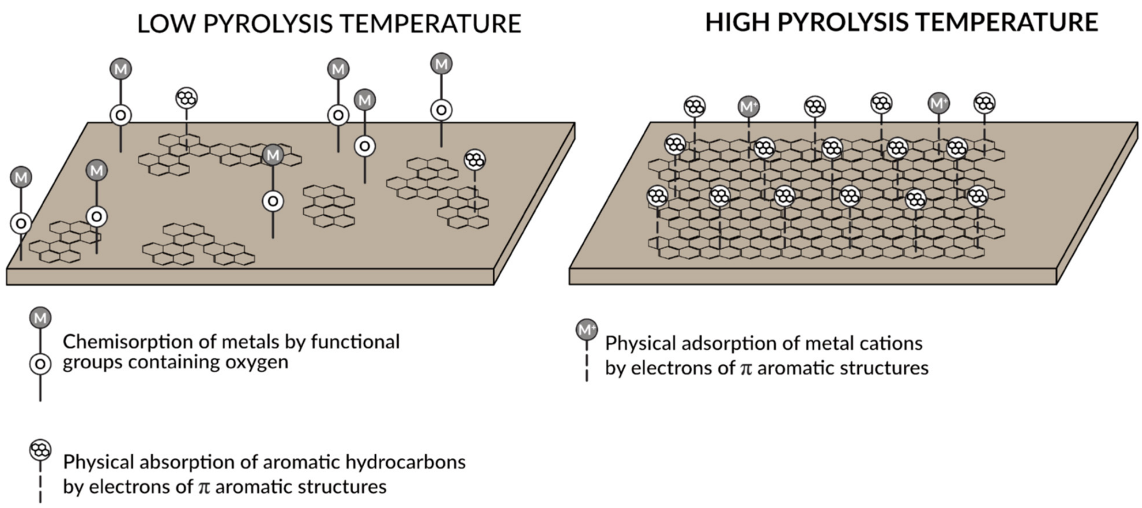


Figure 5. A schematic diagram showing the mechanisms of sorption of organic and inorganic pollutants on biocarbons produced at high and low temperatures [48], modified.

Generally, biochar has a high value of pH. This is due to the formation of metal oxides from basic cations (e.g., K, Ca, Si and Mg) during pyrolysis. Moreover, some biochars contain a lot of mineral ash (up to 50% for animal waste and up to 85% for bone meal materials). The minerals present in the ash, such as carbonates, phosphates and sulphates, can cause precipitation of some toxic elements e.g., Pb in the form of insoluble salts.

4. Advantages of Use the Biodegradable Waste on/to Degraded Soil

In the literature many studies have demonstrated that organic substrates added to degraded soil improve quality, resulting first at all in increase of organic matter content and stabilize soil structure. Garcia et al. [6] identify some main functions of organic amendments in soils: (1) promotion of soil aggregation; (2) provision of plant nutrients; and (3) a reduction in water content loss, in addition to other beneficial functions. The many other authors find several samples described in literature which confirm the positive effect on soil physical, chemical and microbiological properties (Table 4). The study of Soria et al. [49] evaluates the effects of technosols made with different organic amendments (waste of gardening, greenhouse horticultural, stabilized sewage sludge and two mixtures of sludge with both vegetable composts) to restore degraded soils in a semiarid limestone quarry. Amended technosols after 6 and 18 months increased water retention capacity, electrical conductivity, total organic carbon and nitrogen, as compared to not amended and natural soils. In turn Arif et al. [50] carried out 5-year consecutive application of fresh industrial sludge (FIS) and composted industrial sludge (CIS) to restore soil functions at surface (0–15 cm) and subsurface (15–30 cm) of the degraded agricultural land. The authors found that sludge amendments increased such soil parameters like total organic carbon (TOC), soil available nitrogen (SAN), soil available phosphorus (SAP) and soil available potassium (SAK) at 0–15 cm depth. Taking into consideration of microbial activities they noted significant increase of value of dehydrogenase (DHA), β-glucosidase (BGA) and alkaline phosphatase (ALp) after FIS and CIS applications. However, other enzymes, such as urease activity (UA) and acid phosphatase (ACp), were significantly reduced compared to control soil. Moreover, sludge amendments significantly increased microbial biomass nitrogen (MBN) and microbial biomass phosphorus (MBP). Significant changes were noted in the increase population of soil culturable microflora (bacteria, fungi and actinomycetes) after sludge application into soil [50,51]. Composts produced from biodegradable waste not only help to improve soil fertility and plant yield, but also are able to control of soil erosion, biocontrol of diseases and bioremediation [52]. The optimal rates (not greater than 50 t ha^{-1}) of different organic amendments can improve physical (soil structure, permeability, water holding capacity, etc.) and chemical (pH, cation exchangeable capacity, etc.) soil properties, favoring plant growth and microbial activity, without any risks for the environment (subsoil and groundwater contamination) [53]. Other studies have indicated the effectiveness of organic matter addition on increase surface roughness resulting in a large decline in soil erosion rates [54]. The use organic matter on salt-degraded soils caused following benefits: (i) aggregate formation, (ii) pores: soil aeration and plant root prolongation, (iii) water leaching [55]. Several advantages of using of biochar on degraded land identified IPCC special report [56]: (i) improved nutrient use efficiency due to reduced leaching of nitrate and ammonium and increased availability of phosphorus in soils with high phosphorus fixation capacity, (ii) management of heavy metals and organic pollutants: through reduced bioavailability of toxic elements, (iii) stimulation of beneficial soil organisms, (iv) improved porosity and water-holding capacity, (v) amelioration of soil acidification.

Table 4. Effects of the organic amendments on the properties of degraded soil [6,49–59].

Properties	Effect
Physical	pH ↑↓, Soil aggregate stability ↑, Bulk density ↓, Water holding capacity ↑, Porosity ↑, Erosion ↓, Humic content ↑↓, Sorption capacity ↑, Electron conductivity ↑
Chemical	Soil organic matter (SOM) ↑, Total organic carbon TOC ↑, Humic acids ↑, N, P, Ca, Mg ↑, Salinity and sodicity ↓, Total heavy metal ↑↓, applicable heavy metal ions ↓, Organic contaminants ↓
Biochemical and microbial	Microbial activity ↑, Dehydrogenase activity (DHA) ↑, β-glucosidase (BGA) ↑, Alkaline phosphatase (ALp) ↑, Basal respiration ↑, Microbial biomass ↑, Pathogens ↑↓,

4.1. Soil Organic Matter (SOM)

Healthy soils are able to store significant quantities of carbon (C) in the form of soil organic carbon (SOC) or soil organic matter (SOM). Navarro-Pedreño et al. [60] noted that around 45% of the mineral soils in Europe have low or very low organic carbon content (0–2%) and 45% have a medium content (2–6%). SOC is included as a metrics for the regular assessment of land degradation in reporting for SDG target 15.3 [5]. The source of carbon in the soil is above and below ground plant biomass, animal residues, organic products of edaphone and biomass introduced in the form of fertilizers (manure, slurry, compost or green fertilizers). As a result of the mineralisation of organic compounds in the soil, under aerobic conditions, the available nutrients for plants are created, but at the same time the production of CO_2 increases. However, in the process of humification, i.e., chemical, biological and biochemical transformations of various degrees of advancement, humus and other non-humus substances (fats, carbohydrates and lignins) are formed. One should strive for humification processes (accumulation of organic matter) to prevail over mineralization processes. Soil organic matter (SOM), and in it organic carbon, determines the physical, chemical and biological properties. It is one of the main components of forming soil fertility and influences the formation and durability of soil aggregates. Its content determines soil sorption capacity, water retention, biodiversity and soil density. Organic fertilisation is necessary to maintain and improve soil fertility, although affects yields more slowly and to a lesser extent [61]. Ngo et al. [62] compared several additives (mineral fertilizers, buffalo manure, compost, vermicompost and biochar) to check effect on degraded soils. They found the synergistic effects between plants and different organic amendments on carbon storage and soil organic matter composition. The biowaste compost (BWC) amended soils were assessed during 180 days under arid ambient conditions and in comparison with control soil [63]. It was shown a significant increase in SOM and SOC in dependence on used BWC quantities to 120 days, and then decrease in SOM and SOC levels.

4.2. Carbon Sequestration and Climate Mitigate

Increasing the organic matter content in soils can be fundamental in reducing CO_2 concentration in the atmosphere. Two processes can be defined: carbon biosequestration in plants and carbon sequestration in soil. Photosynthesis reduces the amount of carbon dioxide in the atmosphere: thanks to chlorophyll, plants absorb CO_2 from the atmosphere and as a result of biochemical transformations convert it into organic compounds necessary for their life processes. Increasing the yields of selected plants with appropriate agrotechnology helps to reduce CO_2 emissions into the atmosphere (biosequestration). An effective reduction of the carbon dioxide content in the atmosphere can be achieved by sequestering CO_2 in SOM [64]. An increase in soil organic matter content in Europe is estimated to have the potential to absorb about 0.8% of the current CO_2 emissions from the burning of fossil fuels in the world, improving compliance with the international Kyoto Protocol [65]. Figure 6 shows the good agricultural practices described in the literature that influence the SOM content of soils.

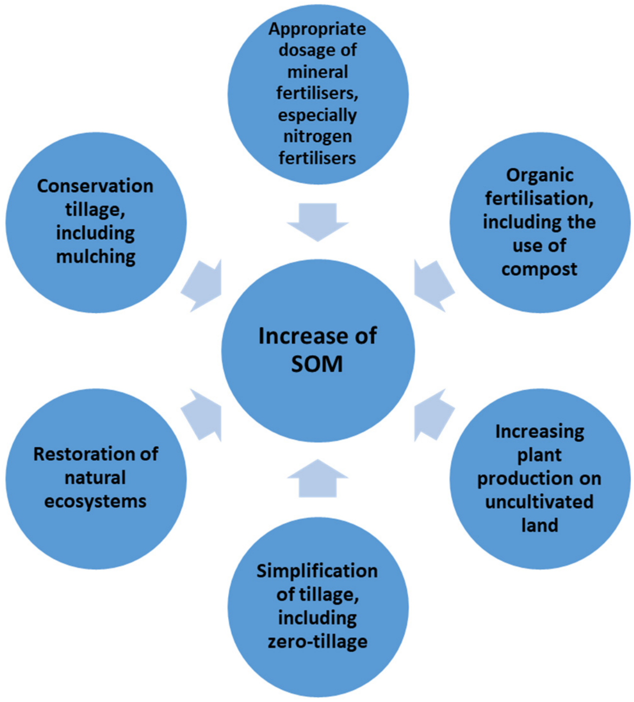


Figure 6. Methods of increasing carbon deposit in the soil [66,67].

The initiative to increase the global soil organic matter resource by 0.4% (four per mille) per year as compensation for global greenhouse gases (GHGs) emissions from anthropogenic sources was initiated during COP 21. Most carbon sequestration research only considers 30 cm of topsoil because it is considered that farming techniques have the greatest impact on this layer. It is estimated that agricultural land accumulates around 600 Gt C in a 1 m thick soil layer. Increasing SOC inventories by 4 per mille (around 2.5 Gt C per year) could offset about 30% of global greenhouse gas emissions [68]. It has been found that by using best land management practices, a C absorption rate of up to 10 per mille can be achieved in the first 20 years for soils with low initial SOC resources [64]. Earlier investigations on impact of biosolids on soil organic carbon buildup in calcareous strip-mined land in soil was done in Illinois [69]. Biosolids were applicated at a cumulative loading rate from 455 to 1654 Mg ha $^{-1}$ (dry wt.) for 8 to 23 yr in rotation from 1972 to 2004. Over a 34 years reclamation period, mean net soil carbon accumulation rate was 1.73 (0.54 to 3.05) Mg carbon ha $^{-1}$ yr $^{-1}$ in biosolids amended fields compared with 0.07 to 0.17 Mg carbon ha^{-1} yr^{-1} in fertilizer controls. Soil carbon accumulation rate was significantly correlated with biosolids application rate, expressed as (Equation (4)):

$$y = 0.064\,x - 0.11 \quad (4)$$

where:

y is the annual net soil carbon sequestration (Mg C ha $^{-1}$ yr $^{-1}$),
x is annual biosolids application (Mg ha $^{-1}$ yr $^{-1}$, dry wt.).

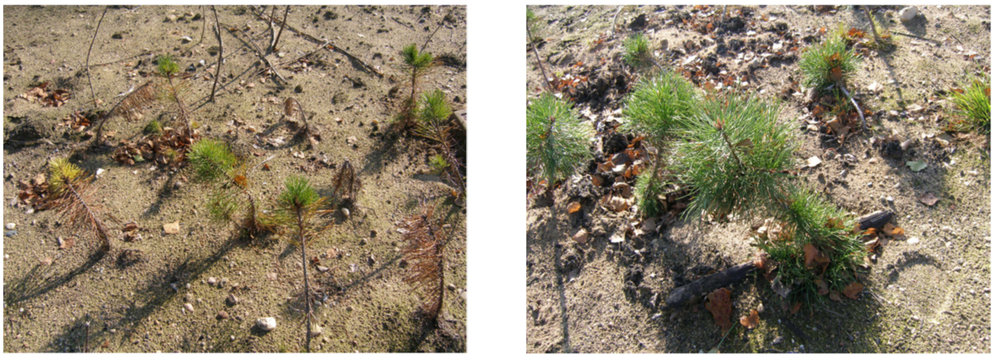
Placek et al. [70] proposed several factors for calculating of carbon sequestration in degraded soil of zinc smelter and post-mining areas: (i) carbon management index (CMI), (ii) carbon lability (L), (iii) soil organic carbon (SOC) pool; (iv) carbon stock (C stock); (v) carbon sequestration rate (C sequestration); (vi) soil organic carbon build up rate (SOC build up rate). The authors used municipal compost, lacustrine chalk and coal slurry, the improvement of soil fertility and soil quality (increase value of total Kjeldahl nitrogen TN, total carbon TC, total organic carbon TOC). They found that CMI and SOC sequestration rate were the best methods to determine carbon sequestration in the soil during conducted pot experiment.

4.3. Biodiversity and Microbial Activity

Soil inhabiting microorganisms play an important role in organic matter mineralization and nutrient cycling. The activity and diversity of microorganisms are crucial for the stability and function of soil ecosystems. Usually the addition of organic matter restored the microbial activity over a long time period, and also increased the diversity of soil communities. The positive effect on the growth of both the biomass of microorganisms and their activity after the application of waste origin substrates with high organic matter content to soils is widely described in the literature, although the results are quite difficult to interpret. In the previous studies, a significant increase in the number of soil bacteria and fungi was observed as a result of the application of sewage sludge to soil [71,72]. The qualitative differences in the communities inhabiting the substrates enriched with additives resulted mainly from the presence of the so-called yeast-like fungi of the genus *Saccharomyces*, *Candida*, *Rhodotorula*, members of the *Mucoraceae* family (*Mucor*, *Absidia*) and the genus *Trichoderma*. However, this impact is highly dependent on climatic conditions and time. One of the causes of significant fluctuations in the number of individual groups of microorganisms is the rapid uptake/depletion of one or several essential nutrients, production of toxins antibiotics and "devouring" of bacteria and fungi by protozoa. On the other hand, the activity of soil dehydrogenases, related mainly to the catabolic processes of heterotrophic prokaryotic cells and fungi, generally reacts strongly to changes in soil oxygenation, although it is not the only factor modifying the activity of these oxidoreductases in such a biodiverse environment as soil. Similarly, significant effect of the introduction of N-rich sludge into the soil on the enzymatic activity was observed, although a significant decrease in activity 90 days after the application of the sewage sludge was noted [73].

4.4. Plant Ecosystem Restoration

Brownfield sites are usually devoid of vegetation. There are many publications in the literature confirming the fact that organic fertilization usually creates favorable conditions for plant growth and vitality [58]. Due to the fact that organic amendments provide both nutrients and water, the plants have better conditions to adopt to live in difficult degraded soil ecosystems. Usually many benefits are noted, such as an increase of total biomass weight, root and stem length and diameter, the number of leaves and foliar area. Some authors describe specific reactions of plants for organic amendment to degraded/contaminated soils. Khan et al. [74] used hard wood biochar (HWB), bagasse (BG), rice husk (RH) and maize comb waste (MCW) to chromite mine degraded soil containing Cd. The results indicated that the biochar added to soil, significantly increased chlorophyll contents (20–40%) and biomass (40–63%) of tomato and cucumber. Moreover, HWB was the most effective at reducing Cd bioavailability and significantly decrease Cd levels in vegetables. Good sample of such effect was induced phytoremediation carried out on degraded terrain around zinc mill (Miasteczko Slaskie, Silesia Region, Poland). The soil is characterized by extremally high concentration of heavy metals (mainly Zn, Pb, Cd) and totally degraded. Addition of sewage sludge in the dose 30 t ha^{-1} boosted the survival of trees such as Scots pine, birch, beech and oak (Figure 7). Similar results were obtained with use of municipal green waste (MGW) on degraded former opencast coal land on the margins of UNESCO's Blaenavon Industrial Landscape World Heritage site in southeast Wales [75]. The application of MGW into soil significantly supported the growth of Silver Birch (Betula pendula, Roth) and European Larch (*Larix decidua*), but no Common Alder (*Alnus glutinosa* (L.) Gaertn.) [75]. There are many advantages of use the so called "aided phytostabilizaion technologies". The technologies are widely proposed as a suitable strategy ecosystem plant revegetation. As a results of organic additives, metals bioavailability can be reduced. At the same time tolerant plant species find the suitable conditions to growth and further improves the soil characteristics boosted by the increase soil organic matter and biological activity [76].



(**a**) (**b**)

Figure 7. Mycorrhized Scots pine growing in a plot in the field growing on control soil (**a**) and on soil enriched with sewage sludge (**b**), (photo M. Kacprzak).

Application of organic fertilizers to degraded soil caused that the plants receive better conditions to develop and produce better defense responses, then are in general less susceptible to infection by phytopathogens such *Pythium*, *Phytophthora* and *Fusarium* spp. [77].

4.5. Water Availability

Degraded soils are frequently poor in water content. The loss of organic matter usually led to disturbances in biogeochemical cycles and loss of soil stability. In the long-term, lower water holding capacity led to dramatic decrease in infiltration rates and absence of available water in the soil profile. Cover vegetation will not be able to re-establish resulting in high rates of overland flow and sediment yield [54]. They found in literature several positive samples of using the organic amendments for increase of porosity along the soil profile, the number of aggregates and their stability (Table 5). Moreover, organic matter increases the soil water holding capacity and availability of water. The impact of organic amendments on water content has greater significance in degraded sandy soils than finer-textured soils, the latter having greater intrinsic water-holding capacity [59]. Moreover, use the organic on the dry degraded terrains can protect soil from rainfall and runoff forces when vegetation is absent [54].

Table 5. Positive effect of use of organic matter on hydrology of degraded terrain.

Effect	Literature
Overland flow decrease Erosion decrease Soil moisture increase Splash effect reduction Soil roughness increase Soil sealing decrease	[54]
Saturated hydraulic conductivity and pore size distribution Soil water retention Water stable aggregates	[78]
Gravimetric water retention Water infiltration Saturated hydraulic conductivity Occlusion of pores by coarse organic matter and increased hydrophobicity	[59]

4.6. Immobilization/Degradation of Contaminants

Methods such as: immobilization, bioaccumulation, phytostabilization and rhizodegradation, supporting processes occurring spontaneously in the natural environment (NA—natural attenuation, MNA—monitored natural attenuation and ENA—enhanced natural attenuation) allow not only to reduce the content of pollutants, but also create conditions for ecosystem revitalization. Immobilizing contaminants such as heavy metals does not remove them from the soil. First of all, immobilization is a process of modification of physical and chemical parameters aimed at increasing the sorption capacity of the soil complex. The process includes complexation in the internal sphere with the ligand exchange mechanism, covalent and hydrogen bonds and the formation of hydrogen bridges. The functional groups of humic compounds, especially humic and fulvic acids, with free negative charges, directly participate in metal complexation. With a higher humus content in the soil, less soluble chelates with heavy metals are formed. This is achieved by adding natural inorganic minerals or organic substances, often waste. The metals occurred in the sludge (bound by organic matter) are less digestible than their equivalent amounts in inorganic salts and the sewage sludge has metal release buffering properties. The application of sewage sludge containing various concentrations of Cu, Ni and Zn to soils may increase the leachability of nickel and zinc, while the concentration of copper should be kept constant [51]. Although in the case of this type of research, the obtained results are not homogeneous. The addition of a large dose of organic matter (e.g., grape pomace compost, cultivated mushrooms or crop residues) to contaminated soils resulted in the immobilization of Cd and Ni, but increased the availability of Zn [51]. The addition of sewage sludge, compost from kitchen waste and a mixture of compost and horticultural soil to contaminated forest soils reduced the concentration of exchangeable forms of copper, but had no effect on microbiological activity, bacterial tolerance to copper or the structure of microorganisms directly involved in the remediation process [51]. Moreno et al. [79] demonstrated a reduction in cadmium toxicity as a result of the use of sewage sludge. In the case of cadmium, no risk of this metal for groundwater was observed, but increasing the concentration of this element in plants grown on soils enriched with sludge [80]. The combined use of compost and biochar to soil polluted by polycyclic aromatic hydrocarbons (PAH) and NSO-substituted PAHs caused increase its sorption [81]. However higher degradation of contaminants was observed only after compost addition.

5. Challenges of Use the Biodegradable Waste on/to Degraded Soil

5.1. End of Use Criteria

Environmental law establishes permits must be obtained before certain activities may be performed. Local governance can use the remediation criteria to determine the severity of the pollution, and whether a site needs urgent remediation. In Europe first the Soil and Groundwater Quality Standards (SQSs) were formalized in the Netherlands in 1994. The permissible dose of waste has been determined taking into account the fertility of the soil, the method of its use, the quality of waste and the plant's demand for nutrients [82]. Waste should be applied in such a way that its application does not cause deterioration of the quality of the soil, soil and surface water and underground even for long-term use. In China a comprehensive soil management system is constructed on risk-based control [83]. In turn, in European Parliament resolution of 28 April 2021 on soil protection (2021/2548 (RSP) in some points are dedicated degraded soil remediation and organic matter improvement [84]:

> *" . . . 19. Considers that the CAP should provide conditions for safeguarding the productivity and ecosystem services of soils; encourages the Member States to introduce coherent soil protection measures in their national CAP Strategic Plans and to ensure the wide use of agronomic practices based on agroecology; invites the Commission to assess whether CAP National Strategic Plans ensure a high level of soil protection and to promote actions to regenerate degraded agricultural soils; calls for measures to promote less intensive tillage practices which cause minimum soil disturbance, organic farming, and the use of organic matter additions to soil; . . .*

30. Welcomes the Commission's commitment in the context of the circular economy action plan to revise Council Directive 86/278/EEC on sewage sludge; calls on the Commission to ensure that the review contributes to soil protection by increasing organic matter in soils, recycling nutrients and reducing erosion while protecting soils and groundwater from pollution; . . .

31. Calls on the Commission to task the European Soil Data Centre with monitoring pesticide residues as well as assessing the amount of carbon stored in European soils and setting targets for soil restoration and quality improvement, including through an increase in soil organic matter, in line with IPCC recommendations and SDG requirements . . . "

By 2050, the EU aims to become a climate neutral continent. The European Green Deal is a series of activities that enable more efficient use of resources thanks to the transition to a circular economy (circular economy), counteracting the loss of biodiversity and reducing the level of pollution. The circular economy in the field of waste management is primarily the minimization of the storage of biodegradable waste. One of the limiting factors of use the biodegradable waste product is quality of the used substrate. For example, sewage sludge is a rich source of not only organic carbon, but also nitrogen, phosphorus and many micronutrients, such as zinc and copper—this fact is well known. Typically, 59–88% of the mass of the sludge is biodegradable organic matter, which gives a solids basis of 2.4–5% nitrogen and 0.5–0.7% phosphorus, respectively. The criteria determining the land usage of municipal sewage sludge are defined by the directive EEC/1986 [84]. However, EU countries have introduced more stringent requirements in comparison with the directive, and have adopted limits for concentrations of other heavy metals, synthetic organic compounds and microbial contamination. It has been proposed the following complementary elements that should be combined in a set of end-of-waste criteria [83]:

- ➢ Product quality requirement;
- ➢ Requirements on input materials;
- ➢ Requirements on treatment processes and techniques;
- ➢ Requirements on the provision of information;
- ➢ Requirements on quality assurance procedures.

5.2. Chemical Contamination

There are 100,000 registered compounds in Europe, most of which will eventually end up in the water cycle; however, they are not limited according to regulations. Among the risks of using bio-waste, belongs: GHG emission, metal contamination, salinity, N immobilization, NO^{-3} leaching and P leaching, toxic compounds [85]. The data from literature suggest that most processed biodegradable waste contains toxic compounds, at least at trace level [85]: nanoparticles, heavy metals (Pb, Cd, Zn, Cu, Ni, Hg and Fe), physical impurities (glass, metal and plastic > 2 mm), organic pollutants (polycyclic aromatic hydrocarbons PAH, polychlorinated dibenzodioxins (PCDD), polychlorinated dibenzofurans (PCDF), polychlorinated biphenyls (PCB), fluorosurfactants (PFC), nonylphenol, polybrominated diphenyl ethers, polycyclic musks, pesticides and chorophenols). After application of sewage sludge in soil organic acids acidify soil and increase the effectiveness of heavy metals (HMs) [86]. In longer time the humus substances produced by the long-term application of sewage sludge in soil immobilize the HMs and reduce their effectiveness in bioavailability. However, when fresh sewage sludge is continuously applied to a tract of land, due to the mineralization of organic substances and the oxidation of metal sulfides, the release of metal ions and the production of sulfuric acid increase the effectiveness of HMs again. Duan et al. [87] analyzed the ecological risk of land use of sewage sludge from municipal wastewater treatment plants (WWTPs) in Shanxi, China. The authors ranked mean values of the geoaccumulation index (Igeo), heavy metals in the following order: Cd > Zn > Cu > As > Cr > Ni > Pb. They indicated that the potential risk of land exposure to heavy metals in sewage sludge was relatively low, except Zn and Cd. In turns, so-called "emerging" contaminants that are detected in waste divided into three categories: pharmaceutical products (such as anti-inflammatory drugs, antibiotics, beta-blockers), personal care products (such as steroids, painkillers, synthetic hormones, fragrances, cosmetics, sunscreens, lipid regulators and shampoos) and chemicals that disrupt the functioning of the endocrine system (including estrone—E1, 17-estradiol—E2 and 17-ethinylestradiol) [88]. Its serious threat to the environment is mainly due to the hydrophobicity or tendency of pollutants to adsorb to solid particles for example during treatment processes in wastewater treatment plants and enter the environment during use a sewage sludge as fertilizer. Nizetto et al. [89] estimated that between 125 and 850 tons microplastics (MP)/million inhabitants are added annually to European agricultural soils either through direct application of sewage sludge or as processed biosolids. Microplastics affect soil microbial community, surface adsorption, soil aggregations, soil bulk density, soil water holding capacity, soil enzymes activity and soil nutrients availability [90]. In turn, taking into consideration nanoparticles it was noted for Europe and the U.S., the annual increase of ENMs on sludge-treated soil ranges from 1 ng kg^{-1} for fullerenes to 89 µg kg^{-1} for nano-TiO_2 [91].

5.3. Microbial Contamination

During a pandemic, more attention is also paid to pathogenic organisms in environment. Sewage sludge can be a reservoir of drug-resistant bacteria (e.g., resistant to vancomycin), which can then be isolated from fertilized soils. The highest ampicillin resistance bacteria was isolated from soils fertilized with sewage sludge and manure (about 100% drug-resistant forms) [92]. Antibiotic resistant bacteria may become more abundant in contaminated soils due to co-selection pressures from pollutants such as metals and hydrocarbons [93]. Use of biosolids and manure may be a source of pathogenic microorganism such *Campylobacter*, *Escherichia coli*, *Salmonella* and *Yersinia* [6]. The presence of SARS-CoV-2 coronavirus RNA was also found in the sewage sludge. Analyzes performed in the spring of 2020 for 10 weeks in New Haven (WWTP, New Haven, CT, USA) indicate that the coronavirus in sewage sludge was detected even before a positive test was performed on human samples. Such analyzes show the usefulness of monitoring the presence of viral RNA in sewage and municipal sludge for the surveillance of SARS-CoV-2 infections at the level of the entire population and for quick information on the dynamics of infection [94].

5.4. Long-Term Effect

Application of stable soil amendments is often the key to successful phytostabilization and rehabilitation of degraded terrains Blends of lime stabilized municipal biosolids and compost were analyzed 4 and 10 years after application [95]. The addition of biosolids materials to the thick compost cover at rates higher than 100 tonnes ha^{-1} significantly reduced C: N ratio of the substrates, available phosphorus and some of the nutrient cations, while notably increasing inorganic carbon and the potential solubility of Ni and Cu. Increasing biosolids application rates may not equivalently ameliorate soil quality and geochemical stability. Moreover negative impact of higher doses of biosolids on microbial activity visible in reduce of cellulose, hemicellulose and lignocellulose decomposers was noted. In turn Montiel-Rozas et al. [96] analyzed both a microbial diversity and community structure 13 years after the first application of two organic amendments (leonardite and biosolid compost) at different doses, in an area contaminated by trace elements. They concluded that long-term effects of this practice on Mediterranean soils are controversial and were still very evident in soils treated with the highest amendment dose. Shorter effect of waste organic matter application on microbial activity and soil respiration rates in degraded soil was observed after the amendments application, microbial activity, which increased rapidly but ceased 18 months later [49]. The composition of bio-based waste substrates may change with time, and the decomposition of organic matter released into solution contaminants, such metal ions previously bound to the organic fraction. The bioavailability of metals contained in sediments after their introduction to soil changes depending on the physicochemical properties of the soil (such as pH, Eh and clay content). Several ecological risks connected with the transformation of dissolved fraction of biochar consists of dissolved salts, minerals and dissolved organic matter (DOM) within the use of biochar for soil remediation purposes. It could compromise the stabilization of contaminants by competitive sorption, solubilization, blockage, facilitated transport or stimulated activity of soil microbes. It is evidently strongly dependent on soil condition and type of contamination/degradation. 2A twenty-five-year experiment performed on poor post-mining soil confirmed that application of organic amendments in doses of 100 Mg ha^{-1} and biofertilizers had positive effects on the restoration of plant ecosystem and soil characteristics [97]. However, mechanisms interactions between different moieties of biochar-derived DOM, inorganic soil components, indigenous microbes, soil organic matter and coexisting inorganic/organic contaminants under the complex and field-relevant application conditions are not clear [98].

6. Conclusions

The continuously amended waste legislation provides for a systematic reduction of the possibility of depositing biodegradable waste and a constant improvement of the effectiveness of its separate collection. The proper quality and purity of the biosubstrate and the correct composition of the conditions of the treatment process ensure that the product is produced in accordance with EU and/or Member State requirements. Undoubtedly, degraded areas need an inflow of organic matter, as this gives an opportunity to initiate biological reclamation processes and revitalization of the soil ecosystem. Biodegradable waste/products even heavily contaminated with metals added into soils improve physico-chemical properties (in optimal dose) and give a chance to create a plant cover, which in turn accelerate the remediation processes due to the intensity of the processes taking place in the rhizosphere. The application of recycled compost to soils has the same effect as fertilisation with organic natural substances. Moreover, enrichment of soils with organic substances results in an improvement in their quality and increased growth and yield of plants, and consequently an increase in the possibility of CO_2 sequestration in soils and biosequestration in plants. Organic recycling as an important part of the circular economy has great potential to protect primary raw materials and reduce greenhouse gas emissions.

However, the application of biodegradable waste to degraded soils is also a number of challenges: (i) establishing appropriate end-of-waste criteria, (ii) loss of organic matter resulting from fast mineralization and too slow humification and (iii) avoiding chemical and microbiological contamination, especially so called “emerging” contaminants.

Due to the accumulation of contaminants, some areas have not been rehabilitated for many years, despite numerous attempts to date. Hence the final goal should be to adopt a holistic approach to degraded terrain remediation and management. That means that due to the quality and concentration of pollutants, the physical, chemical and biological state of the ecosystem and the way of management, an individual technological solution should be prepared.

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