Biodegradable Waste and Degraded Soil

Subjects: Soil Science

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

1. 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 [1]. In 2019 European Commission published a new EU fertiliser regulation [2]. 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) [3]. 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**).

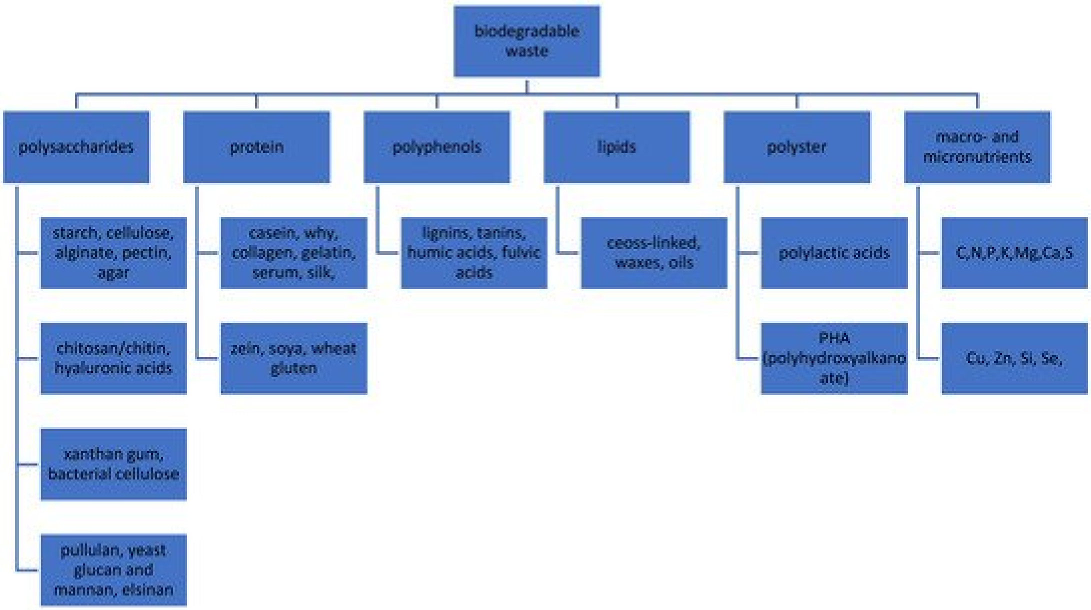

Figure 1. The samples of valuable compounds from biodegradable waste that can be used for degraded soil remediation/revitalization.

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

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

1.1. 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 [4]. 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 2**), mainly waste materials, which are produced both in industry, agriculture and municipal management.

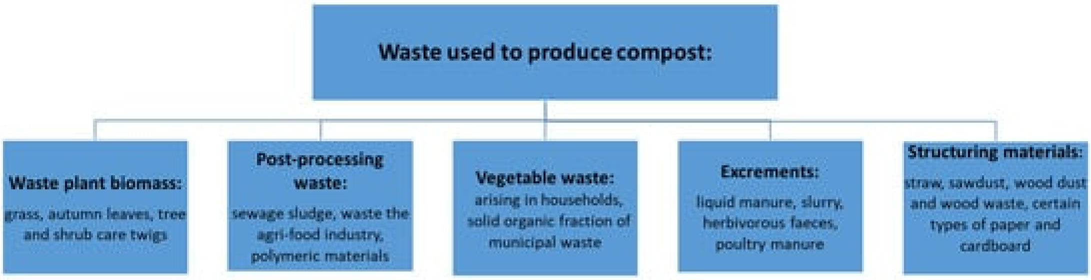

Figure 2. Materials used in the composting process [5][6][7][8][9][10].

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 [11]. 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 3**).

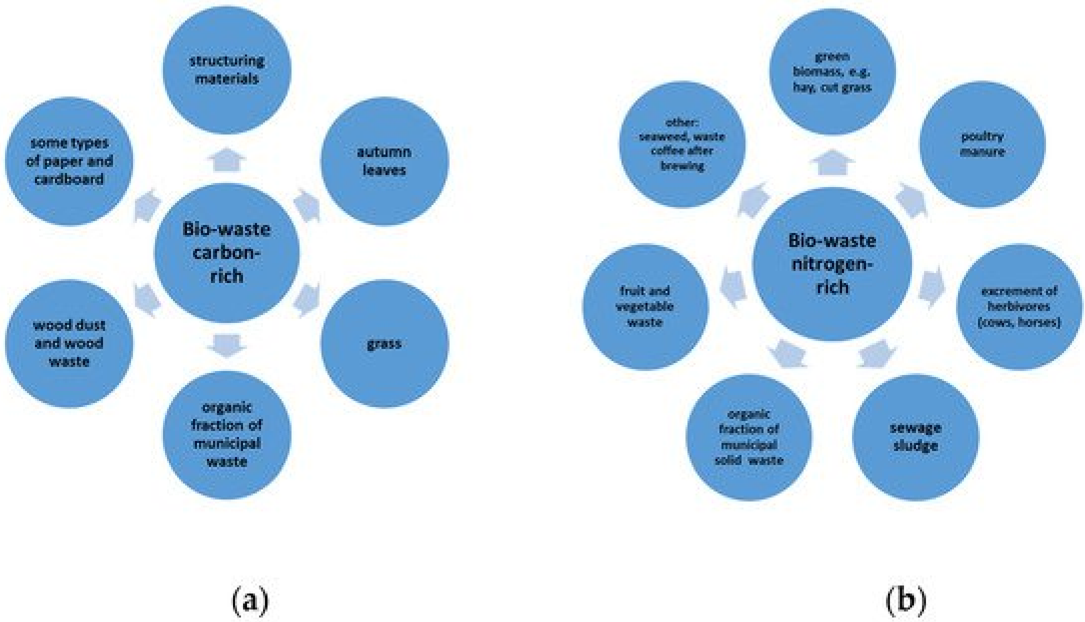

Figure 3. Carbon-rich materials used in the composting process (**a**) and potential nitrogen sources for compost mixes (**b**) [12][13][14][15][16].

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 [17]. 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 [18]. 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 [19]. Good quality compost was produced using selectively collected green waste [20][21], vegetable waste [22][23][24][25] or agricultural waste [7][26][27]. In comparison, composts made from sewage sludge or the biodegradable solid fraction of municipal waste require more attention in both production and application [28][29][30][31].

1.2. 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 [32]:

- 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):
$CaO + H_2O \rightarrow Ca(OH)_2 + heat$

(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)):

$MgO + H_2SO_4 \rightarrow MgSO_4 + H_2O + heat$

(2)

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

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

(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 [33]. 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.

1.3. 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.

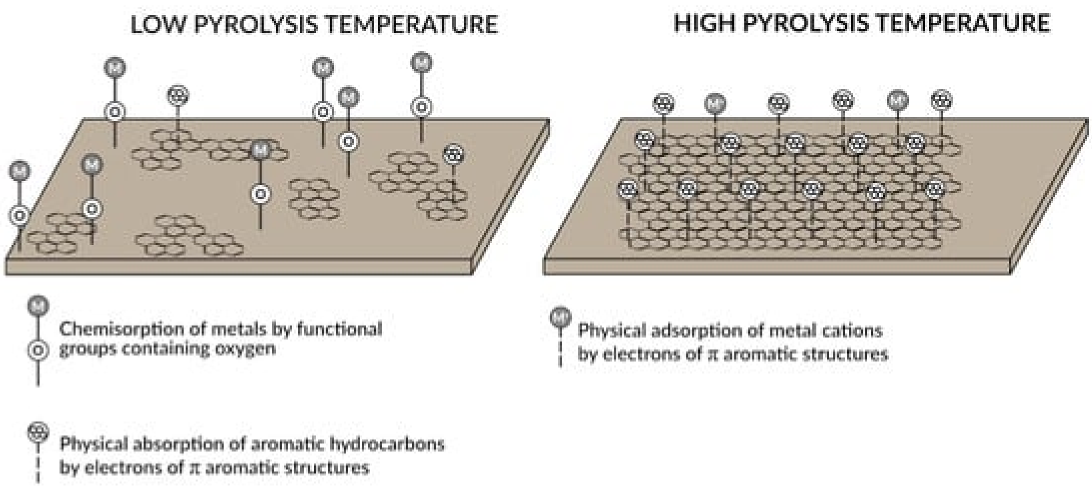

Figure 5. A schematic diagram showing the mechanisms of sorption of organic and inorganic pollutants on biocarbons produced at high and low temperatures [34], modified.

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.

2. 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. [35] 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. The study of Soria et al. [36] 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. [37] 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 [37][38]. 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 [39]. 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) [40]. Other studies have indicated the effectiveness of organic matter addition on increase surface roughness resulting in a large decline in soil erosion rates [41]. 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 [42]. Several advantages of using of biochar on degraded land identified IPCC special report [43]: (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.

2.1. 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. [44] 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 [45]. 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 [46]. Ngo et al. [47] 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 [48]. 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.

2.2. 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 [49]. 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 [50]. **Figure 4** shows the good agricultural practices described in the literature that influence the SOM content of soils.

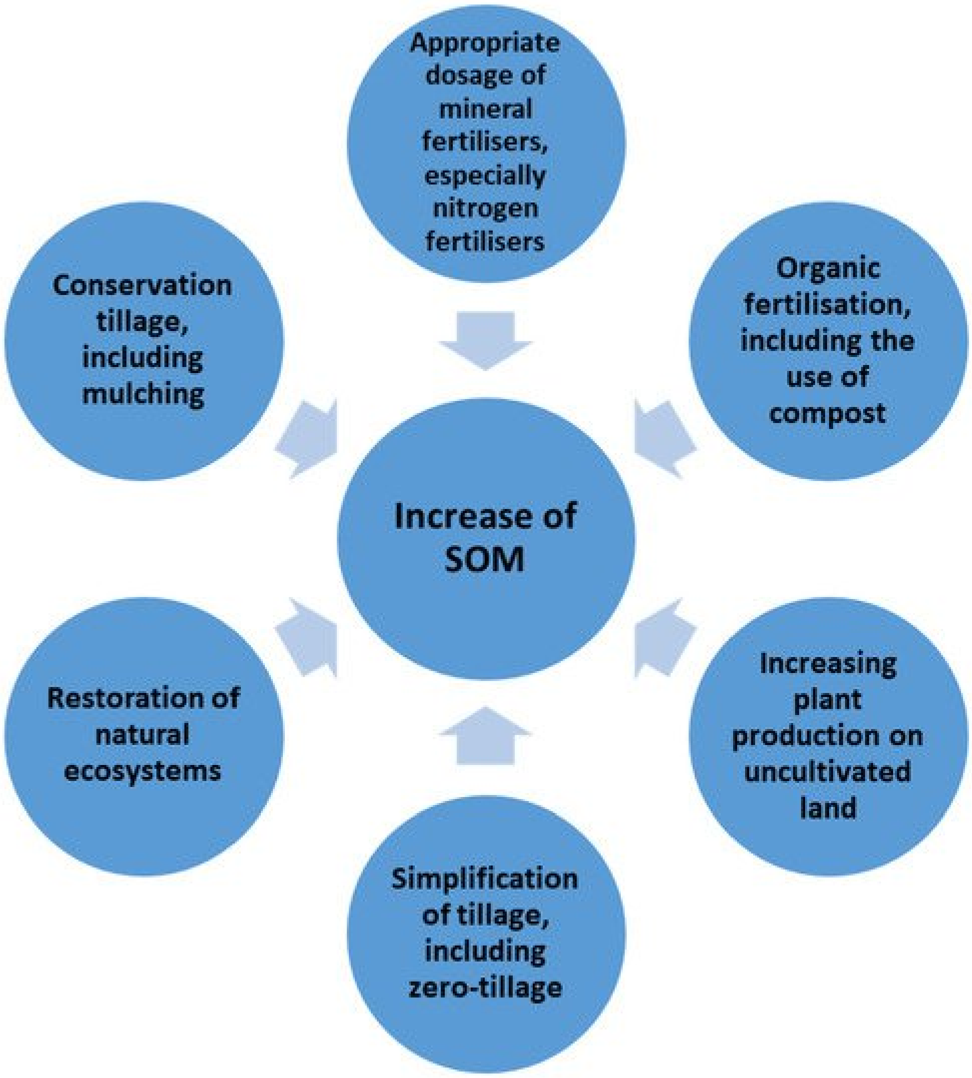

Figure 4. Methods of increasing carbon deposit in the soil [51][52].

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 [53]. 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 [49]. Earlier investigations on impact of biosolids on soil organic carbon buildup in calcareous strip-mined land in soil was done in Illinois [54]. 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)):

$y = 0.064\ x - 0.11$

(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. [55] 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.

2.3. 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 [56][57]. 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 [58].

2.4. 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 [59]. 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. [60] 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 5**). 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 [61]. 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.) [61]. 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 [62].

. 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. [63].

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