Chapter 6

Wastewater Treatment Sludge Composting

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Abstract

The treatment and disposal of sewage sludges is an issue of high concern, given the role of sewage sludge in environmental pollution, risks to human health and high cost of its disposal. Under current legislation, sludge can be disposed of in agriculture after a stabilization process, such as composting. As a result of this process, organic compounds are converted into humic substances, that are more stable, concomitantly pathogens are eliminated. It is recommended to use a structuring agent to slow down process kinetics, limit GHG emissions and reduce pollutants in the sludge. The aim of this chapter is to identify innovative techniques to produce compost from sludge, with an acceptable presence of pollutants and subsequent disposal in agriculture. Particular attention is devoted to the identification of the best bulking agent and assessment of the effects of compost on the soil-plant system, also in view of the soil biodiversity preservation.

Keywords: resource recovery, bulking agent, toxicity, biochemical and chemical compost properties, fertilization

1. Introduction

In recent years, the amount of sewage sludge generated by wastewater treatment plants (WWTPs) has increased due to worldwide population growth and to efficiency of biological treatment processes [1,2]. Sludge is an important source of secondary pollution to aquatic environments and a potential risk to human health; moreover, it represents one of the most important cost items in the functioning of water treatment plants [3–5]. About 60% of the operating costs of secondary wastewater treatment plants in Europe can be associated with the treatment and disposal of products [6]. For this reason, proper sludge management becomes increasingly important, at both national and international level, and it becomes necessary to find effective measures to limit the environmental impacts and to reuse sludge as a resource, within a circular economy vision [2,7]. Current methods of utilization of sewage sludge include agricultural application, landfilling, incineration, drying, and composting and/or vermicomposting. Composting is a widely used cost-effective and socially acceptable method for treating solid or semisolid biodegradable waste [8]. In agriculture sewage sludge is used for rehabilitation of degraded soils, reclamation, or adaptation of land to specific needs [9]. The above consideration comes from several studies showing that the application of sludges to agricultural land can improve soil fertility and, therefore, crop productivity [10–12]. This field of use is also possible due to its composition; in fact, it is rich in organic matter, nitrogen, phosphorus, calcium, magnesium, sulphur, and other microelements needed by plants and living native organisms in the soil. However, sewage sludge may contain a wide range of harmful toxic substances such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins and dibenzo-p-furans, polychlorinated biphenyls, di(2-ethylhexyl) phthalate, polybrominated diphenyl ethers, detergent and drug residues, pharmaceutical and personal care products (PPCPs), endogenous hormones, synthetic steroids and pathogenic organisms [13,14], which can cause harm to the environment and humans. Due to the presence of those toxic elements, stabilization of sewage sludge is necessary to avoid any environmental risk [15]. Stabilization of sewage sludge is defined as “biological, chemical or thermal treatment, long-term storage or any other appropriate process aimed at reducing its fermentability and the health hazards arising from its use" [16]. This definition is found in Council Directive 86/278/EEC, which was issued to regulate the use of sludge in agriculture, the primary objective of which is the environment, in particular the soil, and the protection of human health. European Directive 86/278/EEC was implemented in Italy by Legislative Decree 99/1992 [17]. Both the European Directive and the Italian legislative decree can be considered obsolete, this is why the European Union is moving towards amending them to reflect the new needs of the sector and to keep up with technological innovations. Currently, there are several processes for sludge stabilization, including composting, which is one of the most widely used methods for stabilising organic matter in general, reducing the number of pathogenic microorganisms and the amount of toxic elements [18]. This is possible because during the composting process the organic compounds present in the biomass to be composted are converted into chemically recalcitrant, i.e., stabilized, humic substances, while pathogens are eliminated due to the heat generated during the process thermophilic phase [19,20]. During the composting of sludges, the addition of bulking agents is needed, as they ameliorate the composting performance by providing structural support that improves aeration and regulates moisture content and C/N ratio of composting mass [21,22]. Sludge composting, however, has to be focused on limiting some secondary causes of pollution related to the process itself, such as greenhouse gas (GHG) emissions and heavy metal contamination [23]. Indeed, in the last decades, the handling of sewage sludge with traditional methods has led to the release of an enormous amount of greenhouse gases. The choice of an appropriate bulking agent is, therefore, fundamental to limit the emission of climate-altering gases, and, at the same time, to increase the microbial activity thus improving the quality of the compost [24,25].

This chapter aims i) to give an overview of the national and international legislation on sludge management and reuse, ii) to analyse the composting process and the state of the art regarding sludge composting to understand the limitations at large-scale application and iii) to discuss the technological innovations in the field and highlight future perspectives.

2. Legislation about Sewage Sludge

The treatment and disposal of sewage sludge is a very important issue from both national and international point of view, especially in relation to the risk of secondary pollution resulting from its mismanagement [26]. Over the last 30 years, the EU has extensively regulated the management and reuse of sludge by various legislative instruments and acts, as this aspect is part of the EU sustainability vision in an environmentally safe approach, also in relation to the rapidly increasing amount of sludge produced [27]. On this basis, EU Member States have transposed European directives and applied more stringent parameters in relation to their own conditions, particularly in relation to heavy metals and pathogens [27,28]. This section of the chapter will provide an overview of the European directives and Italian legislative decrees regarding sludge management.

2.1 European Legislation

The most significant European directives related to sludge management and reuse in agriculture are Directive 86/278/EEC, called “Sewage Sludge Directive” (SSD) [16], Directive 91/271 [29], Directive 91/676/EEC [30], Directive 2008/98/EC [31], Directive 2018/851/EC [32] and Regulation (EU) 2019/1009 [33], which establish standards for making EU fertilizer products available on the market. These are complemented by the Public

Consultation [34] launched in 2020 by the EU with the aim of renewing Directive 86/278/EEC.

The Directives and the European Regulation are briefly described below (Table 1):

****Table 1****

2.1.1. Directive 86/278/CEE

The main Directive regulating the management of sewage sludge is number 86/278/EEC [16], which concerns the protection of the environment, in particular of the soil, when sewage sludge is used in agriculture. This Directive regulates the use of sewage sludge as a fertilizer in such a way as to avoid harmful effects on the environment and human health and considering the nutrient needs of plants, without compromising the quality of the soil and of surface or groundwaters. To this end, it establishes limit values for permitted concentrations in the soil for seven heavy metals that may be toxic to plants and humans, i.e., Cd, Cu, Ni, Pb, Zn, Hg, Cr.

In other words, Directive 86/278/EEC [16] prohibits the use of sewage sludge when the concentration of metals exceeds threshold values. ANNEX IA contains the limit values of heavy metals in soils, ANNEX IB regulates the maximum amount of heavy metals in sludge and ANNEX IC the maximum annual amounts of heavy metals that can be released into the soil (Table 2) [16].

****Table 2****

The main points of the Directive stipulated that sludge must undergo a stabilization process, such as composting, before being used in agriculture. However, in some EU countries farmers might be allowed to use untreated sludge if it was injected or buried in the soil.

As mentioned above, EU countries since implementing Directive 86/278/EEC [16] have introduced stricter limits for sludge use in agriculture. Of these, 18 out of 27 countries have introduced restrictions on cadmium (Cd), 14 out of 27 countries on copper (Cu), 19 out of 27 countries on mercury (Hg), 16 out of 27 countries on nickel (Ni), 14 out of 27 countries on lead (Pb), 10 out of 27 countries on zinc (Zn) [16]. In the countries that adopted more restrictions the result was a lower percentage of sludge applied in agriculture [13]. In addition, several countries introduced limit values for other elements, e.g., for chromium whose limits were introduced in 23 countries (up to 1500 mg kg^{-1} sludge dw), 7 countries introduced limits for arsenic (up to 75 mg kg^{-1} dw), Romania and Hungary for molybdenum (50 mg kg^{-1} dw), and Hungary also added limits for cobalt and selenium (20 and 100 mg kg^{-1} dw, respectively). Finally, Hungary have introduced limits for Cr VI (hexavalent chromium) [13,35], 1 mg per kg of dry matter

Directive 86/278/EEC [16] does not include limit values or special requirements for organic micropollutants and pathogen content in biosolids, but the different States have added limit values in national regulations. The organic compounds most controlled by the different States are PCBs (polychlorinated biphenyls), AOXs (absorbable organic halogens), and PAHs (polycyclic aromatic hydrocarbons). Regarding the content of pathogens, the national legislation of most countries controls the presence of Salmonella spp. (except for Lithuania, Luxembourg, and Slovakia) [10].

2.1.2. Revisions of Directive 86/278/EEC

From 16th June to 25th June 2020, the European Union created an initiative with the aim of encouraging citizens, stakeholders, and plant operators at European level to give their opinion on the roadmap created for the reformulation and modification of the Sewage Sludge Directive [16]. Subsequently, from 20th November 2020 to 5th March 2021 a "Public Consultation” was launched with the aim of collecting opinions from stakeholders, operators, and experts in the field at European level. These initiatives arise from the need to update

Directive 86/278 EEC, which has been in force for over 30 years and no longer meets the needs and requirements of the industry, also in the light of scientific and technological evolutions, and today's needs, such as an adequate regulation of pollutants in sludge, especially "emerging contaminants", e.g., organic chemicals like pharmaceuticals, PAHs and perfluoroalkylates, cosmetics and microplastics [34].

This initiative will evaluate the effectiveness of the Directive and analyse the risks and opportunities associated with managing sewage sludge in agriculture [34][16].

2.1.3. Regulation (EU) 2019/1009

Regulation (EU) 2019/1009 [33], which will come into force on 16th July 2022, establishes rules regarding the making available on the market of EU fertilizer products. It covers seven categories of fertilizer products: fertilizers, soil conditioners, lime and/or magnesium correctives, growing media, inhibitors, plant biostimulants and physical mixtures of fertilizer products. The aim of the Regulation is the creation of a single market for fertilizer products that are currently not regulated by standards, thus creating common safety, quality, and labelling standards [33]. With this regulation, for the first time, limit values for organic contaminants are introduced, allowing for a high level of soil protection and a reduction in risks to human health and the environment [33].

It is divided into 11 CMCs (Categories of Constituent Materials) and 7 PFCs (Functional Categories of Products). Sewage sludge is treated in CMC 3 and CMC 5, which state that it is no longer possible to produce a fertilizer by aerobic composting (CMC 3) or by anaerobic digestion (CMC 5) from sewage sludge, industrial sludge or dredging sludge [33].

2.2 Italian Legislation

In Italy, the most important Legislative Decree on this issue is the number 92/99 [17], which is the implementation in Italy of the Sewage Sludge Directive [16]. Other decrees that regulate sludge management are the Legislative Decree number 152/2006 [36] amended by the Legislative Decree 205/2010 [37] which deals with the activity of recovery of sludge to produce soil improvers, the Legislative Decree 75/2010 [38] on fertilizers and art. 41 of the Legislative Decree No. 109/2018, called "Decreto Genova", on the subject of "Urgent provisions on the management of sewage sludge" [39].

The Legislative Decrees are briefly described in Table 3.

****Table 3****

2.2.1. Legislative Decree 99/92

The Legislative Decree no. 99 of the 27th of January 1992 [17] is the implementation of Directive no. 86/278/EEC [16] and aims to regulate the use of sewage sludge in agriculture to avoid harmful effects on soil, vegetation, animals and humans, while encouraging its proper use. The Legislative Decree 99/92 [17] requires that sludge be subjected to treatment (biological, chemical, or thermal treatment, long-term storage, or other appropriate process) suitable to produce a fertilizing and/or soil amendment and corrective effect, and not containing toxic and harmful and/or persistent and/or biodegradable substances in concentrations harmful to the soil, crops, animals, humans and the environment in general [17]. It confirms the limit values for heavy metals in both soil and sludge set by ANNEX I A and ANNEX I B of the Directive 86/278/EEC [16]. However, it adds a restriction not foreseen in the European Directive, namely the obligation to subject sewage sludge to chemical, physical or biological treatment with the aim of stabilizing the sludge by reducing the amount of pathogenic organisms present [17].

2.2.2. Art. 41 of the Legislative Decree No. 109/2018

The Legislative Decree of the 28th of September 2018 No. 109 [39], also known as the "Decreto Genova" is a Decree-Law concerning urgent provisions for the city of Genova and the safety of the national network of infrastructure and transport following the seismic events of 2016 and 2017, but also other emergencies [39]. Art. 41 of the aforementioned legislative decree contains a reference to the use of sewage sludge, pending a systematic and long-awaited revision of the legislation currently in force, with the introduction of new limits on C10-C40 hydrocarbons (whose limit value has been raised from 50 mg kg^{-1} SS to 1000 mg kg^{-1} SS) and on heavy metals (Toluene $\leq$100 mg kg^{-1} SS, Selenium $\leq$10 mg kg^{-1} SS, Beryllium $\leq$2 mg kg^{-1} SS, Arsenic <20 mg kg^{-1} SS, Total Chromium <200 mg kg^{-1} SS, Chromium IV <2 mg kg^{-1} SS), which allowed a gradual resumption of the withdrawal of sludge suitable for spreading in agriculture [39].

2.2.3. Upcoming regulatory developments for sludge in agriculture

In view of the amendment of Legislative Decree 99/92 [17], some hypotheses have been put forward in the draft of the new decree of 11th February 2020. In particular, the new legislation will focus on the updating of the limit values of the substances already included the integration of the list of admissibility of harmful substances, the establishment of a register with mandatory registration of producers of sludge for agriculture and a strengthening of control mechanisms on spreading.

2.3 Sewage Sludge legislation in other countries

In the United States, sewage sludge management is regulated by the "40 CFR Part 503 rule" which represent the "Standards for the Use or Disposal of Sewage Sludge" issued in 1993. This rule identifies a set of parameters for chemical pollutants in sewage sludge, their treatment and use, and pathogen reduction. It also includes a set of standards and controls to promote specific management and disposal technologies. Japan’s laws governing sludge management are the Fertiliser Regulation Act enacted in (2000) and the Soil Contamination Countermeasures Law (2001). The first one includes criteria for the concentration of heavy metals in sewage sludge used as fertiliser, the second one defines limits for contaminants such as toxic elements in leachate and the use of sewage sludge in various aggregates and cement products. Australian sewage sludge legislation has focused mainly on the land application of biosolids. These regulations have been structured along the lines of the Environment Protection Authority (EPA) Rule 503, and set limit values for many organic contaminants, as well as stricter limits for heavy metals and pathogen content. In China, currently, two laws, two administrative regulations and thirty-two standards are in use for sludge management. Regarding the laws, the CPGPRC, 2005a is the Environmental Protection Law of the People's Republic of China and provides the basis for sludge pollution prevention. In addition, the Solid Waste Environmental Pollution Prevention and Control Law includes preventing solid waste (including sludge) pollution, protecting human health, safeguarding ecological safety, and promoting sustainable eco-society development through CPGPRC, 2005b. As for administrative regulations, with the MEP, 1996 there are the interim provisions on environmental protection and waste import management and its supplementary provisions prohibit the illegal transfer of waste (including sludge) to China. As for standards, they can be grouped into three categories: national standard, ministerial standard, technical regulation, and guideline.

3. Sewage Sludge Composting

3.1 Composting

Composting is an aerobic process intended to sanitize sewage sludge to decrease or eliminate toxic compounds and pathogenic microorganisms, with the goal of limiting harm to animals, environment, and humans [40]. Different technologies can be applied to composting sewage sludge affecting aeration, GHGs emission, odours emissions, and other characteristics (Table 4). An additional positive aspect of composting is the stabilization of sludge and the production of compost that can be stored and used far away in time and space from the place of its production [41,42]. Being a biological process, microorganisms play a crucial role in the composting process [43,44].

****Table 4****

Many parameters of the composting mass have to be controlled during the composting to achieve good compost quality and early maturation. These parameters include porosity, temperature, oxygen content, C/N ratio, moisture content, pH, electrical conductivity, and cation exchange capacity [45]. The optimal value of each of these parameters is reported in table 5.

****Table 5****

During composting, the sludge goes through three distinct phases that have been identified based on temperature changes and microorganisms' succession [46] (Fig. 6.1). The first phase is the mesophilic one, during which an exponential growth of mesophilic and some thermophilic microorganisms occurs, with a rapid consumption of easily assimilable substrates, such as monosaccharides and amino acids, and continuous increase of the temperature that starts to kill some microorganisms [47]. The temperature of the compost usually increases rapidly up to 55-65°C within 24-72 hours after the formation of the pile, and it is maintained for several weeks ("thermophilic" phase). During it there is a dominance of thermophilic microorganisms from all three main microbial groups (bacteria, fungi, actinomycetes), although some mesophilic organisms may survive in this phase [48,49]. Once the temperature approaches 70 °C, the compost is sanitized because pathogens (affecting both plants and humans) are killed, weed seeds are inactivated and phytotoxic compounds (organic compounds toxic to plants) are broken down [47,49]. Common pathogens killed during this phase are *Escherichia coli*, *Staphylococcus aureus*, *Bacillus subtiliss*, and *Clostridium* *botulinum* [50]. During the thermophilic phase, oxygen must be replenished through passive or forced aeration, or by turning the compost pile for a successful composting [51]. A well-ventilated compost pile has an oxygen content of at least 5% during the active phase of composting (ideally closer to 10%). As microbial activity increases in the compost pile, even more oxygen is consumed. If the oxygen supply is not replenished, the compost pile can switch to anaerobic decomposition, slowing down the composting process and producing bad odours. Finally, as the nutrient resources are strongly depleted and converted by microorganisms, the process begins to slow down and the temperature drops. At this point, the mesophilic microorganisms recolonize the pile, and the compost enters the maturation phase during which temperature gradually decrease towards about 38°C [47,52]. Progressively, the rate of oxygen consumption decreases to the point where the compost can be piled without turning. During maturation, organic materials continue to decompose and are converted to biologically stable humic substances - the mature or finished compost. Maturation is a critical and often overlooked phase of composting. A long maturation phase is necessary if the pile has received too little oxygen or too little or too much moisture [52].

****Figure 6.1.HERE****

It is important to understand how to evaluate the maturity or stability of compost because stability will affect many of the chemical and biological properties of the compost and, ultimately, how it can be used. "Stability indices" and maturity/stability tests are available from compost research and education organizations [53].

Numerous studies have been conducted to optimize sewage sludge composting methods and processes and to evaluate their effect on the removal of organic and inorganic pollutants, such as heavy metals, PAHs, PPCPs, and pathogens. Fuentes et al. [54] investigated the mobility of zinc (Zn), copper (Cu), nickel (Ni), cadmium (Cd), lead (Pb), mercury (Hg) and chromium

(Cr) in different types of sludges (aerobic, anaerobic, unstabilised and sludge from a waste stabilisation pond) to evaluate their use for agricultural purposes. They concluded that all sludge types could be used for soil amendment due to their high content of organic matter and nutrients (N, P and K). However, on the basis of heavy metals content, they excluded for agriculture purposes, the anaerobically digested sludge because of its high Cr content. The waste stabilisation pond sludge showed a higher degree of mineralisation and stabilisation than the other sludge types and a lower metal availability index. The lower availability of heavy metals, according to the authors, relies on the fact that heavy metals were complexed with the oxidisable polymeric organic fractions which are the less mobile [54]. Of the different treatments analysed, the not stabilized sludge contained the highest accumulations of heavy metals in the most readily assimilable (soluble) fractions, i.e., exchangeable and reducible [54]. Also, Cai et al. [55] investigated the concentrations of four heavy metals, cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn), in compost obtained from five different sewage sludge composting processes (continuously aerated composting, intermittently aerated composting, manual-rotated composting, inoculated manual-turned composting and, manual-turned composting), to evaluate their suitability for land application and to observe speciation of the heavy metals. The different processes consisted of the use rice straw as a bulking agent at 10% w/w compared to the mass to be composted, with a low C/N ratio (13:1), and applying an inoculation mixture consisting of microorganisms, enzymes, and growth-promoting agents. Continuously aerated composting treatment exhibited better compost quality and lower potential toxicity of heavy metals, while the inoculation of microorganisms and of enzymes during composting had no obvious benefit on the humification of the organic matter and on the reduction of mobility and bioavailability of heavy metals. However, after 56 days of composting of sewage sludge with rice straw, Cai et al. [55] found that the total concentration of Cd increased between 12 and 60%, Cu between 8 and 17%, Pb between 15 and 43% and Zn between 14 and 44%, compared to those in the initial sewage sludge, probably due to the mineralisation of the organic matter of the sludge during composting. In addition to the concentration, the speciation of heavy metals was also influenced by the properties of the sludge, the composting process and thus the physico-chemical properties of the final compost, such as organic C, humic content, and pH. Such results were in contrast with those obtained by Fuentes et al. [54], thus highlighting the need of forward investigation to assess the accumulation of heavy metals in the compost obtained from sewage sludge. Zheng et al. [56] conducted a study to investigate the influences of different aeration treatments on the biodegradation effects of triclosan and changes of the microbial community during the composting process [56]. Triclosan is a broad-spectrum antibacterial agent widely used in pharmaceuticals and personal care products [56]. Aerobic composting was found to be an effective way to degrade triclosan in sewage sludge, as it effectively degraded and inactivated triclosan during the thermophilic phase, thus ensuring the stability and safety of the composting products. Triclosan degradation increased by increasing oxygen content in the composting mass from 7.3%, 7.5% and 8.2% to 10.4%, 13.9% and 15.7%, respectively. The high ventilation increased triclosan degradation by 23%. Such an increase was ascribed to the increase of the relative abundance of triclosan-degrading microorganisms and of their microbial activity. The Authors concluded that future research on functional microorganisms related to triclosan degradation is needed [56]. Guo et al. [57] focused on the biodegradation of polycyclic aromatic hydrocarbons (PAHs) during the sludge composting process. Their study was conducted on a production scale using sewage sludge and green forest waste with a mass ratio of 3:1, 3:2, and 3:3, respectively [57]. The treatment with a sewage sludge/bulking agent ratio of 3:2 was the most suitable for PAHs degradation, with a removal efficiency of 75% and a residual PAH concentration of 1.8 mg kg^{-1} after 50 days of composting. The increased degradation of PAHs, as well as of cellulose, was linked to the ability of microorganisms belonging to the genera Bacillus, Pseudomonas and Methylotenera to use PAHs and cellulose as a source of carbon and energy [57]. In all treatments, the residual concentration of PAHs met the permitted limit; their degradation rates were 0.0280, 0.0281 and 0.0218 mg day^{-1} and their removal efficiencies 71%, 75% and 62% in 3:1, 3:2, 3:3 sewage sludge/bulking agent ratio treatments, respectively [57]. Lasaridi et al. [58] conducted a study investigating the four main hazards of sludge, namely heavy metals, instability, pathogenic potential and antibiotic resistance. Their study was carried out at laboratory scale using two mixtures of sludge and green waste as bulking agent at ratios 1:1 and 1:2 w/w, respectively. Higher amount of bulking agent facilitated the composting process, led to nitrogen retention and compost stability. A good level of sanitisation was achieved for both mixtures, despite the relatively low temperatures during the thermophilic phase (~ 45°C) registered in the laboratory during the experiment; this was possible because the total mesophilic population remained unchanged during composting [58].

Tarpani et al. [59] disagreed with the benefits of sludge composting and considered composting as one of the least recommended methods for sludge management. Such consideration relies on the life cycle environmental impacts of five sludge treatments (agricultural application of anaerobically digested sludge, agricultural application of composted sludge, incineration, pyrolysis, and wet air oxidation) evaluated on the basis of 18 parameters (climate change, fossil depletion, metal depletion, water depletion, ozone depletion, freshwater eutrophication, marine eutrophication, terrestrial acidification, ionizing radiation, freshwater ecotoxicity, terrestrial ecotoxicity, human toxicity, natural land transformation, urban land occupation, agricultural land occupation, particulate matter formation, photochemical oxidant formation). They showed that anaerobic digestion has the lowest environmental impact and allows nutrient and electricity recovery. Indeed, anaerobic digestion could allow to achieve net-negative GHG emissions of -174 kg CO_2 eq. 1000 kg^{-1}

DM, whereas all other alternatives have net positive GHG emissions, even assuming full resource recovery [59]. The only two categories for which anaerobic digestion could have the worst impacts are marine eutrophication and photochemical oxidant formation. In contrast, when evaluating resource recovery, composting is the worst alternative, followed by pyrolysis with lower recovery rates [59]. Agricultural application of anaerobically digested sludge causes the highest freshwater ecotoxicity due to heavy metals. Therefore, stricter control of heavy metals in sludge is necessary. In contrast, PPCPs have a negligible contribution to freshwater ecotoxicity compared to heavy metals in anaerobically digested sludge. Since thermal processes are currently attracting attention because of their potential benefits, the results of the study by Tarpani et al. [59] suggest that their adoption is only environmentally beneficial if high resource recovery rates can be achieved.

Overall, based on the results of the studies discussed above, stabilization of sludge is still a challenge and future studies are needed to better understand the mechanisms concerning the mobility and speciation of heavy metals in land-applied sewage sludge, the potential to reduce or eliminate antibiotics and other PPCPs, and the control of other organic contaminants such as PAHs. In addition, it is also important to assess pollution and risks derived from biological contaminants such as pathogenic microorganisms.

3.2 Bulking Agents

Due to the high moisture content and bulk wet density, sewage sludge commonly has dense and plastic structure and, therefore, susceptible to compaction [8]. Compaction makes the composting process of sludge not efficient and, for this reason, the addition of a bulking agent to the mass to be composted is needed [60]. Beside to decrease the wet bulk density thus favouring aeration, the bulking agent controls many other important parameters (Fig. 6.2) [25,59]. Several studies have investigated the effect of different bulking agents on composting process and compost properties. The most common used bulking agents are wood shavings, sawdust, hay and grass clippings, wheat straw, maize stalks, manure, biochar, agricultural waste, zeolite [15,61–63]. In view of the environmental sustainability and circular economy, the selection of an appropriate bulking agent should take into account, besides its effect on composting process and compost properties (Fig. 6.2), also its origin, availability and proximity to the composting area. For example, waste biomasses are the best candidate to be used as bulking agents in view of a circular economy perspective, whereas their proximity to the composting area contributes to reduce the transport costs and decrease the carbon footprint of the composting process.

This section reports the main findings on how the bulking agents increases the biodegradation of the biomass to be composted, controls the composting parameters, and reduces GHG emissions and the presence of pollutants.

****Fig. 6.2.HERE****

Uçaroğlu et al. [15] investigated, at laboratory scale, the compostability of wastewater treatment sludge with different bulking agents to individuate the most suitable one. The bulking agents used were wheat straw, plantain leaf, corncob, and sunflower stalk, in a mixture of 60% sludge and 40% bulking agent. The mixture sludge-straw and sludge-sunflower showed the highest degradation of organic matter, 38% and 33% respectively, the highest dry matter loss, 30% and 26% respectively, and the highest temperatures, i.e., 64°C and 57°C [15]. On the other hand, the mixture of wheat straw and plantain leaf as bulking agents was not efficient when considering the increase of temperature and the organic matter mineralization. Therefore, the Authors [15] also tested the mixture of both corncob and sunflower stalk, which proved to be very successful bulking agents, producing a stabilized compost that could be used in agriculture as a soil additive and nutrient source. Uçaroğlu et al. [15] ascribed such results to the higher amount of organic acids in compost obtained with corncob and sunflower stalk, which reduced the pH from 6.8 to 6.3 and from 7.5 to 6.6, respectively. Such results were in line with those obtained also by Guo et al. [57]. Also, Wu et al. [64] assessed the effects of bulking agent on the sewage sludge composting process. They tested reused pumice and pumice decorated with sucrose as bulking agents. Their results [64] showed that the reused pumice, since largely increased the growth of mesophilic microorganisms, could be used as inoculant to promote the degradation of organic matter and to reduce the NH_3 emission. On the other hand, sucrose-decorated pumice reduced ammonia loss by 43%, probably because of the ability of microorganisms to assimilate ammonia into glutamate thus converting ammonia into glutamine. Moreover, the addition of pumice reused or decorated with sucrose in the sludge composting mass regulated the moisture content due to its water adsorption capacity and improved the degradation of organic matter. The reduction of nitrogen losses was also reported by Doublet et al. [65] that analysed seven mixtures composted over a period of 12 weeks in 170 L reactors. They mixed sludge with green waste screening, grass clippings, a mixture of crushed hardwood materials mixed with ground dry leaves, crushed wood pallets, bark, and corn stalks. The authors observed that the availability of nitrogen in the final compost increased as a consequence of the reduction of the NH_3 volatilisation, probably caused by i) higher ligno-cellulosic characteristics of the bulking agent, ii) careful control of aeration, iii) initial C/N ratio (between 13.5 and 25.7, in the different treatments) and iv) presence of rather biodegradable carbonaceous materials [65]. Besides to be affected by the type of bulking agent, the composting process and thus the final characteristics of the compost may be affected by the ratio of bulking agent to the mass to be composted. Lu et al. [21] conducted a pilot scale study by using wood chips, ceramsite and vegetable ash as bulking agents at a ratio of 3:1 or 4:1 (w/w) between the composting mass and bulking agents, respectively. Their results indicated wood chips as an efficient bulking agent to improve composting performance, while the addition of ceramsite failed to initiate composting, and plant ash facilitated the decrease of moisture content during composting but slightly hindered heat release [21]. The best sludge/bulking agent ratio was the lowest because of leading to an increase of the temperature after two days since the composting started (from 13 to 67°C). Furthermore, all monitored heavy metal concentrations were below limit levels, probably due to their immobilization by organic acids and subsequent leaking in the leachate. Similar results are reported by Yañez et al. [66] who, using a ratio of 2:1 and 3:1: between sewage sludge and bulking agent (wood chips of Acacia dealbata), respectively, found lower sludge/bulking agent ratio allowing to achieve rapidly temperatures for a good composting process. On the other hand, the ability of the bulking agent to reduce the mobility of heavy metals was also demonstrated by Saffari et al. [67] that investigated the effect of mixture of sewage sludge and three bulking agents (tree leaves, wheat straw, and pistachio hull wastes) in the composting process on total concentration and chemical forms of As, Cu, Pb, and Cr in produced compost from sewage sludge. They found that the bulking agents increased the stability and decreased the mobility factor of the studied metals compared to produced compost without BAs. Oleszczuk et al. [68] focused their study on the role of the bulking agent in affecting the availability of PAHs, whose content represents a limitation for the application of composted sludge to agricultural land. They assessed the influence of fly ash and sawdust on 16 PAHs. Composting was carried out in containers with only sewage sludge (100%), sewage sludge added with fly ash (20 or 30% w/w) or sawdust (30% w/w). Composting was carried out for 353 days, after which the compost was stored for further 300 days. Results showed that after composting total PAHs decreased from 83% to 88% in all the treatments. However, a significant lowering of the total concentration of PAHs after the storage period was noticed in the treatment with 20% fly ash as bulking agent. This was probably due to the ability of fly ash to absorb organic contaminants. Based on such finding, the authors point out that there are still circumstances able to affect the content and qualitative composition of the PAHs after the appropriate composting period. Such an aspect has to be considered when assessing the toxicity and availability of PAHs in compost and soil [68]. Awasthi et al. [25] analysed another aspect closely linked to sludge composting, which is the emission of climate-altering gases and how the choice of a suitable bulking agent can reduce the GHG produced. The aim of their study was to mitigate greenhouse gas (GHG) emissions during composting of freshly dewatered sewage sludge using biochar (B) combined with zeolite (Z) and low dose of lime (L). Biochar (12%) was mixed with 10%, 15% and 30% of zeolite and 1% of lime. Overall, their results showed that the addition of 12%B+10%Z during composting of freshly dewatered sewage sludge facilitate the degradation of organic matter and reduce the maximum emission of greenhouse gases and ammonia. Such results could be due to the zeolite ability to increase the porosity of the substrate that in turn enhance the activity of aerobic bacteria and their enzymatic activities, thus speeding up the mineralization of organic nitrogen and reducing ammonia and N_2O emissions [29].

Finally, another important issue about the bulking agent is its effect on the metabolic activity and bacterial community composition. With regard such aspect, Du et al. [69] conducted a pilot scale study using 400 L bioreactor systems and mixtures of sewage sludge and sawdust modified with rice straw biochar at different dosages (5, 10 and 20% of the fresh weight of the mixture). They observed that the addition of biochar at dosages of 10% and 20% weakened the correlation between temperature and bacterial community composition but strengthened the relationship between enzyme activity (dehydrogenase, arylsulphatase, protease, cellulase, β-glucosidase, and peroxidase) and bacterial community. The Authors [69] ascribed such results to the porosity of biochar that, providing empty space for microorganisms, further stimulated the activity of heterotrophic microorganisms.

Table 6

3.3 Reuse of Composted Sewage sludge

Composting sewage sludges largely overcomes the problems associated with land application of sludges. The high temperature reached during the thermophilic composting phase (Fig. 6.1) destroys pathogenic organisms. The compost produced is a humus-like material, free of bad odours, and useful to supply organic matter and nutrients to soils [70]. Unlike sludge, it can be conveniently stored, easily handled, and uniformly spread on land. Thus, sludge compost can be used advantageously in agriculture and for reclamation of degraded soils. Moreover, from an environmental and circular economy point of view, their application to soil contributes to store CO_2 and allows to close the nutrient cycles [71]. Khaliq et al. [72] applied 22 kg of composted sludge and 0.5 kg of inorganic fertilisers to study the effects of applying composted sewage sludge and inorganic fertilisers on soil quality and performance of radish (*Raphanus sativus*) and bean (*Phaseolus vulgaris*). Composted sludge, compared to inorganic fertilisers, supported higher crop yields due to the increase of available nutrients for plants, particularly the % of total nitrogen. Furthermore, chemical analyses of the soil and of the two crops showed no risk of heavy metal accumulation. Considering that the experiment was of short duration, the authors recommend long-term studies (at least 5 years) to improve the understanding of the effects of sewage sludge compost on soil fertility and crop yields,thus contributing to the development of sustainable agricultural. Moreover, the beneficial effect of compost obtained by sewage sludge on soil quality and plant growth is related to the amount of compost supplied to soil. Cheng et al. [73] evaluated the effects of a variable amount (5 to 100% in relation to the amount of soil) of composted sludge, used as a soil conditioner for turfgrass production, on physical and chemical properties of soils following the application. They showed that soils amended with ≤20% sludge did not significantly influence seedling emergence, while the chlorophyll, nitrogen, phosphorus, and potassium content of perennial ryegrass grown in such soils were significantly improved. Bulk density, water retention and soil nutrient content were also improved with the addition of composted sludge, but application of compost in large quantities introduced excessive amounts of heavy metals and soluble salts, which increased the potential for soil pollution and had an inhibiting effect on turfgrass growth. The detrimental effects on seedling emergence and turf growth observed on substrates with high (≥40%) composted sludge content was mainly attributed to the presence of high concentrations of soluble salts. Following this study, the authors suggested that the addition of composted sludge at levels of 10-20% can significantly improve the supply of soil nutrients for turfgrass growth, without significantly affecting the heavy metal and soluble salt content of the soil. Besides to affect the total amount of nutrients, composted sewage sludge may affect their chemical forms. Elsalam et al. [74] focused on changes of nitrogen forms, besides of organic matter content, in soils treated with composted sewage sludge, as well as on maize and bean growth. The amount of total nitrogen within maize and bean leaves increased significantly in plants grown on sludge-treated soils. Furthermore, the amount of soil NO_3^- increased as the amount of sewage sludge applied increased (higher with an application of 160 t acre^{-1} than with 80 t acre^{-1}). In contrast, the amount of NH_4^+ was not affected. These results, according to the authors, could be due to the alkaline nature of the soil pH (>7.0) that could be more favourable for nitrifying bacteria than ammonifying ones.

The addition of composted sewage sludge to soils can cause chemical and biological contamination, if inadequately managed. Indeed, long-term spreading of composted sludge can lead to the accumulation of contaminants (i.e., heavy metals) in agricultural soils and affect the entire ecosystems [75]. Several studies have focused on assessing the benefits and limitations of repeated application of composted sludge to soil and its effect on crops [74,76–78].

****Fig. 6.3.HERE****

Alvarenga et al. [78] assessed the potential risk, such as pathogens and heavy metals, of using dewatered and composted sludge as a soil conditioner for the cultivation of sorghum and Sudan grass. They conducted a pot experiment comparing sewage sludge from two different wastewater treatment plants with a compost produced from sludge and agricultural waste. Their results showed that the sludge composted with agricultural waste met the legal requirements for land application, whereas the non-composted sludge had a high pathogens content, which compromised its use [78]. Both treatments had a marked beneficial effect on plant growth and soil nutritional characteristics, without a significant increase in total and available heavy metal concentrations in soils. Bioaccumulation factors for heavy metals in plants were low, and their concentrations in above-ground plant material were below the maximum tolerable level for livestock, used as an indicator of risk of heavy metals entering the human food chain. Despite the results obtained, the authors stressed that their study was a pot experiment aimed at a preliminary assessment of the risks/benefits of using these organic materials in agricultural soils, and consequently needs to be complemented by field trials, also assessing repeated application over time. In addition, other applications of composted sludge have been evaluated in recent years, such as its spreading in forest soils where no crops are cultivated for consumption [73,79]. Zhao et al. [79] investigated the effects of composted sludge to forest soils. This is considered a promising method for sewage sludge disposal because it can improve soil fertility and productivity without posing any risk concerning food contamination. However, unlike agricultural land, forest soils are covered with litter, which could influence the effects of sewage sludge on the soil bacterial community and hence on the nutrient cycling. Zhao et al. [79] focused on the effects of applying sewage sludge (30 t ha^{-1}) on the bacterial community of the topsoil (0-10 cm depth) in three forest plantations (*Eucalyptus urophylla*, *Pinus elliottii* and *Schima superba*).

Treatments included addition of composted sewage sludge, addition of sewage sludge after removal of litter and a control. The application of sewage sludge altered the composition but not the α-diversity of bacterial communities in the soils of three forest plantations. The shift in key bacterial groups also indicated the adaptation of the soil bacterial community to the application of sewage sludge. As a new application of composted sludge, the authors suggested that future studies should focus on potential functional changes in soil bacterial communities caused by the application of sewage sludge in forests [79].

4. Conclusions and perspectives

The composting of sewage sludge is a valid method for its reuse, allowing a waste product, whose disposal is becoming difficult to manage, to be seen as a resource. This possibility of reuse is part of a "Circular Economy" vision and goes along with the new policies supported by the EU. As pointed out, a first step to allow a greater diffusion of this method of sludge management is the formulation of a new European Directive to replace the Directive 86/278/EU and meet the technological developments that have taken place in the last thirty years. Another aspect that should not be underestimated in a future perspective of this application is the need to create a composting process that limits the emission of GHG, the mobilisation of heavy metals and PPCPs, the pathogenic organisms present in the sludge; all of this is possible through the choice of a suitable bulking agent and the right sludge/bulking agent ratio, but further studies are needed, especially conducted on a field scale. Although the studies analysed did not show any contamination from the application of composted sludge to the soil, it is still necessary to identify a careful final reuse of this composted sludge that is sustainable and does not negatively affect the environment by polluting the soil and aquatic environments, as a result of the leaching of harmful elements from the sludge. For this reason, it is crucial to weigh the pros and cons of the use of this bioresource, and further research is needed to enable the study of local food crop production, bio-energy potential and amendment needs.

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Caption for Tables

Table 1: European Directives and Regulations concerning the management and disposal of sludge.

Table 2: Limit values given in ANNEX IA, ANNEX IB, and ANNEX IC of Directive 86/278/EEC [16]

Table 3: Summary table of Italian Legislative Decree concerning the management and disposal of sludge in Italy

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Table 5: Optimal parameters during the composting process

Table 6: Results of the effects of bulking agent on the composting process

Tables

Table 1 - European Directives and Regulations concerning the management and disposal of sludge.

Directives or Regulations	**Objective**
Directive 86/278/EEC [16]	Concerning the protection of the environment, in particular of the soil, in the use of sewage sludge in agriculture.
Directive 91/271/EEC [29]	On urban wastewater treatment. The aim of this Directive is the protection of the EU environment from the negative consequences of pollution caused by urban wastewater, such as eutrophication.
Directive 91/676/EEC [30]	Concerning the protection of waters against pollution caused by nitrates from agricultural sources.
Directive 2008/98/EC [31]	Waste Framework Directive. Concerning the waste management and abrogating some previous directives.
Directive 2018/851/EC [32]	Repeals Directive 2008/98/EC, making significant changes.
Regulation 2019/1009 [33]	Laying down rules on placement on the market of EU fertilising products, amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003

Table 2 – Limit values given in ANNEX IA, ANNEX IB, and ANNEX IC of Directive 86/278/EEC [16]

Parameters	**Limit values – ANNEX IA (mg/kg)**	**Limit values – ANNEX IB (mg/kg of dry matter)**	**Limit values – ANNEX IC (kg/ha/y)**
Cadmium (Cd)	1 to 3	20 to 40	0.15
Copper (Cu)	50 to 140	1000 to 1750	12
Nickel (Ni)	30 to 75	300 to 400	3
Lead (Pb)	50 to 300	750 to 1200	15
Zinc (Zn)	150 to 300	2500 to 4000	30
Mercury (Hg)	1 to 1.5	16 to 25	0.1
Chromium	-	-	-

Table 3 - Summary table of Italian Legislative Decree concerning the management and disposal of sludge in Italy.

Legislative Decree	**Objective**
Legislative Decree 99/1992 [17]	Implementation of Directive no. 86/278/ EEC concerning the protection of the environment, in particular of the soil, in the use of sewage sludge in agriculture.
Legislative Decree 152/2006 [36]	This Legislative Decree is called the "Testo Unico Ambientale", which contains the main rules that regulate the environmental discipline.
Legislative Decree 75/2010 [38]	Provisions on the reorganization and revision of regulations on fertilizers.
Legislative Decree 205/2010 [37]	Provisions implementing Directive 2008/98/EC of the European Parliament and Council on wastes and repealing certain Directives.
Art. 41 of the Legislative Decree No. 109/2018 [39]	Urgent provisions on the management of sewage sludge.

Table 4: Characteristics of different composting technologies and their effect on compost quality and environment (after Lim et al. [80]).

Composting technologies **Compost characteristics**	**Aerated Windrow Composting**	**Aerated Static Pile Composting**	**In-Vessel Composting**
Usable waste	All type of wastes; preferable for those with low emission of odours such as the plant-based wastes.	Preferable for wastes with high homogeneity and consistency; bulking agent is required.	All type of wastes; preferable for easily degradable wastes such as food wastes.
Land area requirement	It requires large tracts of land and continuous supply of labor to maintain and operate the facility and turning frequencies.	It requires less land than the windrow method, because the controlled supply of air allows construction of large piles.	It requires less land and manual labor than windrow composting. But this method is expensive.
Technologies required	It is a large-scale operation and, for this reason, is subject to regulatory enforcement, zoning, and siting requirements.	It may require significant cost and technical assistance to purchase, install, and maintain equipment.	It may require a technical expertise to operate it properly.
Environmental impact	High production of leachate and bad odours. High GHG emission.	High production of leachate and bad odours. Lower GHG emission compared to windrow.	Very little odour or leachate is produced. High GHG emission.
Compost quality	The compost obtained is of medium to good quality.	The compost obtained is of medium to good quality.	The compost obtained is of good quality.

Table 5 - Optimal parameters during the composting process

Parameters	**Optimal value**
pH	6-8 [60,81]
Moisture	55-65% [61,82]
O_2	5-7% [83]
Bulk Density	150-950 kg m^{-3} [84]
C/N ratio	30-40 [60]

Table 6: Results of the effects of bulking agent on the composting process

Reference	**Bulking Agent**	**Effects**
Uçaroğlu et al. [15]	Straw, plantain leaf, corncob, and sunflower stalk	pH reduction Organic matter degradation
Wu et al. [64]	Pumice and pumice decorated	NH_3 emission reduction Moisture content regulation Organic matter degradation
Doublet et al. [65]	Green waste screening, grass clippings, a mixture of crushed hardwood materials and ground dry leaves, crushed wood pallets, bark and corn stalks	NH_3 emission reduction Control of aeration
Lu et al. [21]	Wood chips, ceramsite and vegetable ash	Control of Heavy metals Moisture content regulation
Yañez et al. [66]	Woodchips of Acacia dealbata	Fast attainment of the initial composting temperature Control of Heavy metals Moisture content regulation
Saffari et al. [67]	Tree leaves, wheat straw, and pistachio hull wastes	Stability and reduction of heavy metals mobility factor
Oleszczuk et al. [68]	Fly ash and sawdust	PAHs reduction
Awasthi et al. [25]	Zeolite, biochar and lime	GHGs reduction

Caption for Figures

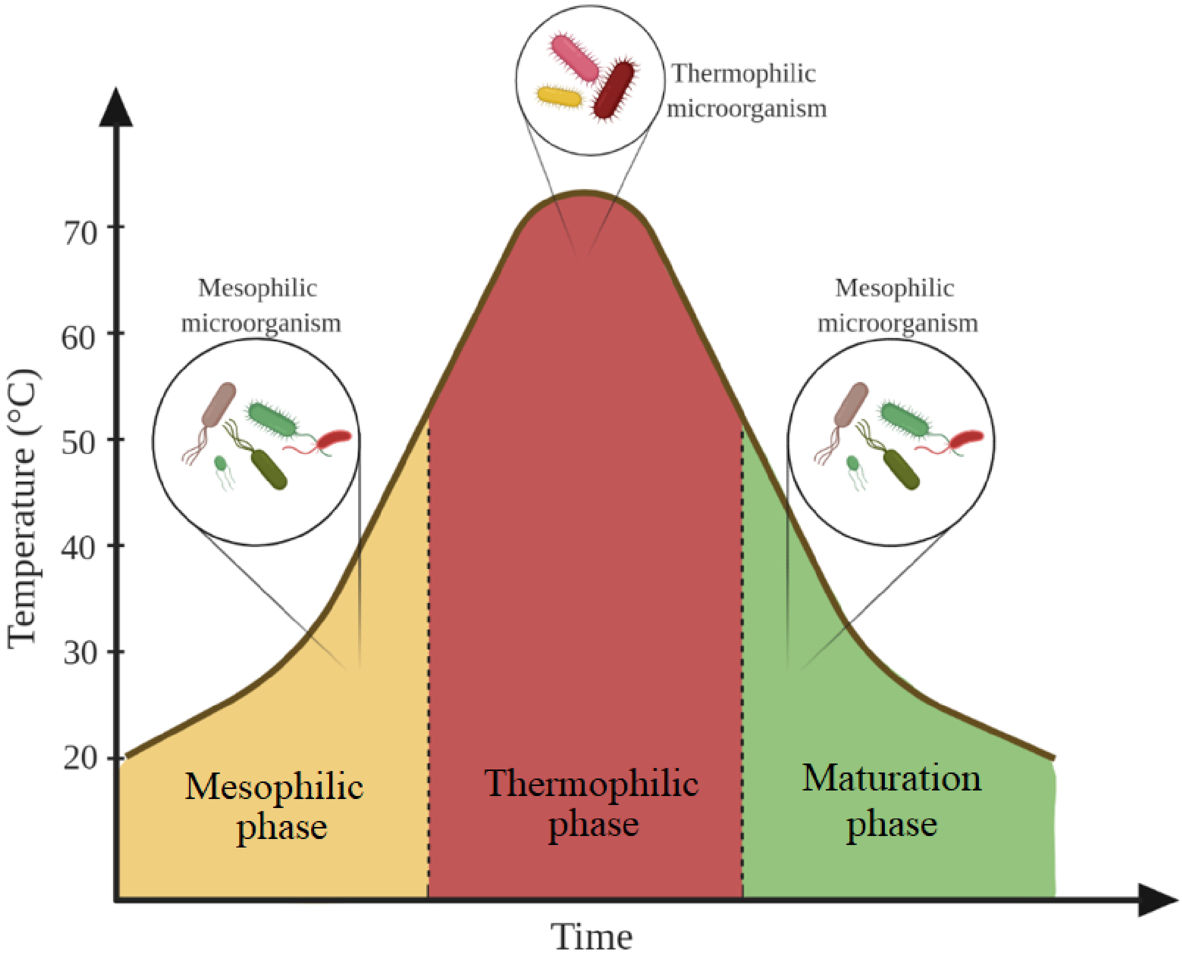
Fig. 6.1.jpg – Time course of the composting process.

Fig. 6.2.jpg - Parameters and pollutants controlled by the bulking agent during composting.

Fig. 6.3.jpg - Benefits of applying sewage sludge to degraded soils.

Figures

Fig. 6.1.jpg – Time course of the composting process.



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