Chapter 6

Municipal Sewage Sludge Variability: Biodegradation through Composting with Bulking Agent

David Alves Comesaña, Iria Villar Comesaña and
Salustiano Mato de la Iglesia

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.75130

Abstract

Municipal sewage sludge is a waste with high organic load generated in large quantities that can be treated by biodegradation techniques such as composting to reduce its risk to the environment. This research studies the physicochemical variability of sewage sludge from treatment plants in the south of Galicia (Spain) and determines if it is possible to establish a protocol for the use of bulking agent depending on the composition of the sludge and the development of the composting process. Therefore, physicochemical analyses of 35 sewage sludge from different municipalities and 10 samples from the same treatment plant are discussed. Three different mixtures bulking agent:sewage sludge (3:1, 2:1, 1:1, v:v) were carried out in 30 L reactors in triplicate. Finally, proportion 2:1 was replicated six times in a 600 L reactor. High inter-sludge variability was observed specially in key parameters such as moisture and C/N ratio. Intra-variability was lower, and 2:1 proportion was the most suitable mixture since extending the thermophilic phase of the composting process at a greater degree. However, repeatability of the process at a higher scale showed different responses in the temperature evolution. Variability of sewage sludge makes difficult to establish treatment protocols although minimum requirements are necessary for proper composting.

Keywords: stabilization, compost quality, bulking agent, organic matter, sanitation

1. Introduction

As a result of the usual human activities, a large amount and volume of wastes from different sources that vary in composition and toxicity are generated. An important fraction of this waste is organic biodegradable material that has different characteristics that depend, fundamentally, on its origin: agricultural, forestry, agro-industrial, or urban. In general, the uncontrolled dumping of this fraction into the soil is not advisable because its decomposition and / or the presence of hazardous pollutants can generate harmful effects that contaminate the soil, air and water. These biodegradable wastes have non-stabilized organic matter, so they present a high level of phytotoxicity and, frequently, a high load of pathogens, such as viruses, bacteria, fungi, and parasites, both for humans and for animals and plants and may become in a risk to the environment and health. In this way, the organic waste must be stabilized and conditioned reducing the possible effects previously mentioned before its disposal to the soil.

Municipal wastewater treatment plants (WWTPs) produce different solid and semisolid residues during the treatment of the wastewater. Sludge is the semisolid waste generated during the primary (physical and/or chemical), the secondary (biological), and the tertiary (additional to secondary, often nutrient removal) treatment [1]. Sludge is by far the largest waste in volume, amount to about 11 million dry tons per year in the EU, which needs suitable and environmentally accepted management before the final disposal [2]. Since these residues are a source of nutrients and organic matter, it is reasonable to return them to the soil in optimal conditions to improve fertility and continue the natural cycle of nutrients. These organic wastes can undergo biodegradation processes, that is, the breaking of the most complex components into simple compounds through the action of living organisms. Likewise, the action of organisms converts simple molecules into more complex molecules of greater stability. Composting is one of the biological treatments that can be applied for the stabilization of municipal sewage sludge.

Composting is a controlled bio-oxidative process, in which a heterogeneous organic substrate undergoes a thermophilic stage and a transient release of phytotoxins, and produces final products: carbon dioxide, water, minerals and stabilized organic matter called compost (**Figure 1**) [3]. Due to the high microbial activity during the composting process, the temperature increases and accelerates the degradation and mineralization of the organic matter. Changes in temperature throughout the process allow differentiating four phases [4]:

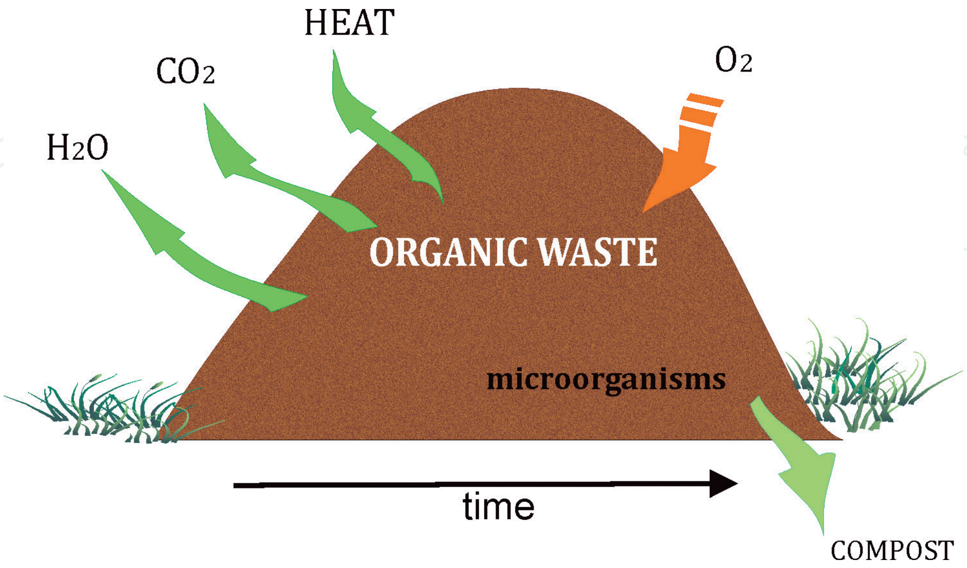

Figure 1. Simple scheme of the composting process where a pile of organic material undergoes the transformation to compost by the action of aerobic microorganisms resulting in the production of heat, carbon dioxide, and water vapor.

- Mesophilic phase: Mesophilic microorganisms proliferate when they feed on easily assimilable organic compounds, which produce an increase in temperature from values close to the ambient until reaching approximately 45°C.
- Thermophilic phase: At temperatures above 40°C, the mesophilic activity drops, and the degradation begins a thermophilic stage reaching values of 60–70°C. This phase is crucial since temperatures of this magnitude destroy the pathogenic microorganisms and seeds of invasive plant species, so this ensures the sanitation of the compost.
- Cooling phase: Because easily degradable materials are consumed during the mesophilic phase and mainly in the thermophilic phase, there is a microbial activity decrease, and the temperature drops to environmental values returning to the mesophilic stage.
- Maturation phase: At this phase, complex secondary condensation and polymerization reactions occur, which results to the compost as the final product. It is necessary that this phase has the duration such that the material acquires the maturity and stability of an organic amendment of agricultural application.

1.1. Factors that affect the composting process

The physical, chemical, and thermodynamic characteristics of the starting material determine the composting evolution, the process efficiency, and the compost quality. Some parameters must be taken into account before sewage sludge composting such as:

1.1.1. Particle size and free air space (FAS)

The composting matrix is a mass of solid particles that must contain enough pores and interstices to enable the development of the aerobic process, so that air circulates inside the mass providing an optimum concentration of oxygen, removing carbon dioxide and excessive moisture, and limiting excessive heat accumulation [5]. Sewage sludge cannot be composted alone due to its compactness and high water content, and bulking agents must be added to provide the structural support to create interparticle voids [6]. In general, organic materials such as agroforestry waste are used as bulking agents because, in addition to providing structure, they have the capacity to absorb water and facilitate the colonization and development of microbial populations [7]. The porosity or air spaces in the composting matrix can be estimated by different methods, and one of the most used is the measurement of free air space (FAS). The minimum values of FAS to ensure biological activity are around 30%, while values of 60–70% seem to be excessive to reach thermophilic temperatures in waste with low content of biodegradable organic matter [5, 8]. The mixture of bulking agent and sewage sludge improves FAS values for composting, although these agents also affect nutrient and moisture balances. Some research has been carried out to study the bulking agent:sludge ratio, as well as the type of bulking material and its particle size, in order to determine their influence on the sewage sludge composting (**Table 1**). The optimum bulking agent:sludge proportion will depend on factors such as process conditions (composting system, volume, time, etc.), origin of the bulking agent, type of bulking (fresh or recirculated), particle size, mixture conditions (FAS, C/N ratio, moisture), etc.

Bulking agent	Proportion (bulking:sludge)	Particle size	Composting system	Reference
Wood chips	1:1, 2:1, 4:1 (v:v)	20, 10, 5 mm	4.5 L Dewar® vessels 100 L reactors	[9]
Acacia spp. trimming residues	1:0, 1:1, 1:2, 1:3 (w:w)	40 mm	35 kg reactors	[10]
Six different bulking agents	4:1 (v:v)		170 L reactors	[11]
Recycled and fresh wooden pallets	3:1 (v:v)	<20 mm and >20 mm	47 L cylindrical reactors	[12]
Sawdust	1:1, 3:1 (v:v)		3 m^3 piles	[13]

Table 1. Some research references about the bulking agent, typology, and bulking agent:sludge ratio of the composting of sewage sludge.

According to Diaz et al. [14], the particle size depends on the physical nature of the waste, and sizes of 1–5 cm are suitable for materials that do not compact easily. Haug [5] states that wood chips about 5 cm in size are the most commonly used bulking agent. However, it is logical that the greater the volume of waste under treatment, the larger the size of the bulking agent, that is, in small-capacity research vessels, the use of small particles is recommended, but when industrial reactors or piles are considered, the particle size of bulking agent increases. Thus, an industrial pile with limited turnings will require large particle sizes of bulking agent to facilitate natural aeration.

1.1.2. Moisture

Since composting is a biodegradation process, the available water content must be sufficient to the physiological requirements of the microbiota. Water not only transports the soluble substances for microbial feeding but also eliminates the waste products resulting from cellular metabolism. The optimum moisture content at the beginning is around 55–60% for sewage sludge composting [5]. Higher moisture contents can cause water to fill the micropores of the mixture and hinder the oxygenation, while lower contents cause the decrease in biological activity. Sewage sludge moisture is corrected with bulking agent that absorbs water, as long as porous and unsaturated bulking agents are used.

1.1.3. C/N ratio

The microorganisms overall use about 30 parts of carbon for each part of nitrogen for their metabolism, carbon for energy source and component of cells and nitrogen for protein and nucleic acid synthesis. It is widely known that the composting matrix is more adequate when it has an initial C/N ratio between 25 and 35. High ratio, as in agroforestry waste with high carbon content, involves a decrease in biological activity due to a lack of nitrogen for the metabolism and, therefore, a slowing down of the composting process. Low C/N values, as in municipal sewage sludge, involve an excess of nitrogen that can be lost through volatilization or leaching. Bulking agents improve this ratio by providing organic carbon to the sewage sludge mixture. Even though, the optimal C/N ratio is conditioned by the nature of the bulking agent, so if the carbon is part of compounds that are difficult to break down, such as lignin, it will only be slowly available for microorganisms [15].

Sometimes, it is not possible to condition the waste in the most suitable way in industrial compost facilities. Nutrient levels, specifically the C/N ratio, may not reach the values considered optimal, so the process must be controlled to reduce nutrient losses as much as possible.

Once the parameters related to the nature of the substrate have been established and corrected, the process must be monitored and controlled within appropriate values for each phase of composting, including temperature and oxygen.

1.1.4. Temperature

Temperature is one of the key factors that define the composting process in a way that a solid mixture reaches thermophilic temperatures that, sustained over time, make it possible to obtain compost free of parasites and weed seeds. The European Commission [16] proposes that temperatures must be maintained above 55°C for 15 days in windrow composting or 60°C for 1 week in in-vessel composting to achieve sanitation in biowaste. Excess temperature above 70°C is not convenient since it can cause the death of most microorganisms, delay colonization in later phases and, as a consequence, delay the degradation of the waste. Thus, the temperature during the process must be controlled to ensure that thermophilic temperatures are reached and sustained long enough to guarantee sanitation but not exceeding 70°C.

1.1.5. Oxygen

The maintenance of oxygen levels is a key factor for the development of an aerobic biological process. Oxygen concentration in the composting mass should not be less than 5% [17], since it would cause a succession toward anaerobic microorganisms and, therefore, toward undesirable fermentation processes and the generation of odors. To keep the oxygen levels in proper values during composting, the aeration of the mass must be controlled by forced and natural ventilation or turnings. In addition to supplying the oxygen demand for organic decomposition, aeration also favors the regulation of excess water and helps maintain the temperature at suitable values [5].

1.2. Composting systems

In general, the choice of a composting system or technology in an industrial facility depends on several factors such as type and quantity of waste, economic considerations, legal aspects, location, environmental aspects and product quality, and others [17]. **Table 2** shows some of the most common systems, classified according to their relationship with the environment and the mixing or change of position.

Diaz et al. [14] established a differentiation of composting systems into two groups: “windrow,” which refers to the accumulation of the material to be composted in more or less elongated piles or rows, and “in vessel” where the material is confined within a reactor.

	Open systems	Semi-open systems	Closed systems
Statics	Piles/windrows with passive or forced aeration	Piles/windrows with aerated semipermeable cover	Containers/aerated tunnels
Dynamics	Turned piles/windrows/trenches	Turned piles/windrows/trenches in closed buildings	Dynamic tunnels drums

Table 2. Classification of the most commonly used composting systems [4, 14, 17].

From an operational point of view, it is considered that the composting process can be differentiated only in two stages. A bio-oxidative stage that corresponds mainly to the first two phases of the composting process, initial mesophilic phase and thermophilic phase, is characterized by high temperatures, elevated oxygen consumption, and the production of gaseous and liquid emissions [5]. This bio-oxidative stage is conditioned by the intensive organic matter decomposition and is usually developed with a specific technology and duration ranging from a few days to months in the industrial composting facilities. The second stage corresponds to the cooling and maturation phases. It usually lasts longer than the bio-oxidative stage although the dwell time is conditioned by the starting material characteristics and environmental and operating conditions of the facility [18]. The bio-oxidative stage is generally carried out using one of the technologies in **Table 2**, while the maturation period is carried out in piles or windrows, with more or less intervention depending on the idiosyncrasy of the facility or space available. In particular, most composting facilities that use "in-vessel" systems as technology involve the use of windrows to mature the compost [14]. A vessel system requires more investment but presents a greater control of the process: gas treatment, leachate collection system, data collection system of basic variables, watering, etc. The common dwell time in reactors or tunnels is around 14 days. Static reactors allow the monitoring of the process and, therefore, have been used in experimental research.

1.3. Research objectives

An industrial facility that periodically receives municipal sewage sludge should establish a working protocol which will optimize the composting process, ensuring the waste treatment under suitable conditions and time to obtain the highest quality compost. Obviously, it is crucial to know its initial characteristics since sewage sludge composition can be variable. For this reason, this work aims to (1) determine the inter- and intra-variability of municipal sewage sludge in physicochemical parameters, (2) establish the importance and effect of the bulking agent in the composting process of the municipal sewage sludge, and (3) check the reproducibility of the composting of sewage sludge from the same WWTP under the same conditions.

2. Sewage sludge characterization and composting

2.1. Inter-sludge variability

Municipal sewage sludge is characterized by its pasty or liquid consistency resulting from its high water content and small particle size. Physicochemical composition depends on the nature of the initial wastewater and on the technical characteristics of the treatments carried out on wastewater [19]. These treatments concentrate the compounds present in the wastewater, so sewage sludge contains a wide variety of dissolved, settled and suspended substances. It is not only a source of organic matter, nitrogen, and phosphorus but also accumulates substances with potential contamination such as heavy metals, pathogens, and organic pollutants (personal hygiene products, pharmaceutics, etc.).

This study compiles the physicochemical analysis of 35 samples of sewage sludge from different WWTPs of municipalities in southern Galicia (Spain) with populations between 1000 and 35,000 inhabitants. These facilities have secondary treatments for the wastewater with subsequent dewatering of sewage sludge produced. **Figure 2** shows the different aspect of the sampled sewage sludge.

All the parameters reflected those found in the literature for sewage sludge with similar characteristics (**Table 3**) [1, 20]. Moisture contents were lower than that observed by these authors; however, the values were homogenous despite being sampled from different WWTPs and seasonal periods. Sewage sludge composting requires moisture contents around 55–60% [5, 15] so the addition of bulking agents with low moisture allows not only reaching more adequate values of this parameter but also maintaining the structure and porosity of the mixture.

The content of organic matter is similar to the established ranges for untreated sludge despite they are sludge digested secondarily [1, 20]. Their high amount of organic substrates together with their high microbial load (inherent to their origin and the treatment with activated sludge) discourages direct disposal into the soil. Sewage sludge not enough stabilized incorporates pathogens and can cause rapid and uncontrolled biodegradation with the release of toxic substances. However, the high organic content makes these wastes suitable for treatment by biological techniques.

These sewage sludge had a pH close to neutrality that was not incompatible with microbial development, although acidic pH affects the availability of heavy metals because heavy metal cations are generally most mobile under acid conditions [19]. The electrical conductivity presented an important variability, but harmful values for the microbial development were not reached.

Total carbon correlated positively with the content of organic matter ($r = 0.76$, $p > 0.0001$), but this parameter presented greater variability with high values in some of the samples indicating

Figure 2. Municipal sewage sludge from two WWTPs in the south of Galicia (Spain).

	Mean	Median	Percentile 5–95%
Moisture (%)	84.0	85.3	76.8–87.4
Organic matter (%)	71.7	73.6	55.7–81.5
pH	6.8	6.8	5.9–7.9
Electrical conductivity (mS cm^{-1})	0.63	0.59	0.09–1.41
Total carbon (% dw)	35.8	36.1	28.1–40.1
Total nitrogen (% dw)	5.23	5.5	3.3–6.7
C/N ratio	7.2	6.5	5.7–12.2
P_2O_5 (% dw)	3.5	3.6	1.6–5.1
N-NH_4^+ (g kg^{-1} dw)	7.3	6.0	0.7–19.5

Table 3. Physicochemical composition of 35 sewage sludge samples in Galicia, Spain.

an insufficient digestion. Since the ideal ratio for composting is around 20–30 parts of carbon per part of nitrogen, the addition of a carbonated material is necessary to avoid excessive loss of nitrogen. The addition of crushed wood is widely used in industrial facilities for sewage sludge improvement in several aspects: increase C/N ratio, increase in porosity, and moisture control, and with this, the distribution of the oxygen is necessary for the development of the aerobic microorganisms inherent to the composting process. However, the excessive use of bulking materials or co-substrates is not desirable in a treatment facility as the treatment of a larger volume of waste is prioritized in order to optimize costs and resources.

It is well known the harmful nature of sewage sludge when certain compounds, such as heavy metals, reach concentrations above a specific threshold. The most important toxic heavy metals include chromium (Cr), cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), nickel (Ni), and mercury (Hg). Concentrations of heavy metals in sewage sludge may vary widely, depending on the sludge origins. The content of heavy metals in wastewater, especially those originated in industrial zones and large metropolitan areas, can impose a serious problem since the sludge tends to accumulate heavy metals that exist in wastewater [21]. The mobility of trace metals, their bioavailability, and related eco-toxicity to plants depend strongly on their specific chemical forms or ways of binding [1]. There is a general consensus in the scientific literature that aerobic composting processes increase the complexation of heavy metals in organic waste residuals and that metals are strongly bound to the compost matrix and organic matter, limiting their solubility and potential bioavailability in soil [22]. All heavy metals analyzed (**Figure 3**) showed a wide variability with values, without considering the outliers, of 18 times in copper, 20 times in lead, and 15 times in mercury, for example. However, these values are typical in sewage sludge [1].

The content of heavy metals in sewage sludge is frequently related to industrial density as a consequence of discharges to public sanitation. However, diffuse sources such as urban runoff and small household operations can contribute to contaminated discharges from an imposed residential area [23]. Also, high population agglomerations usually cause higher contents of

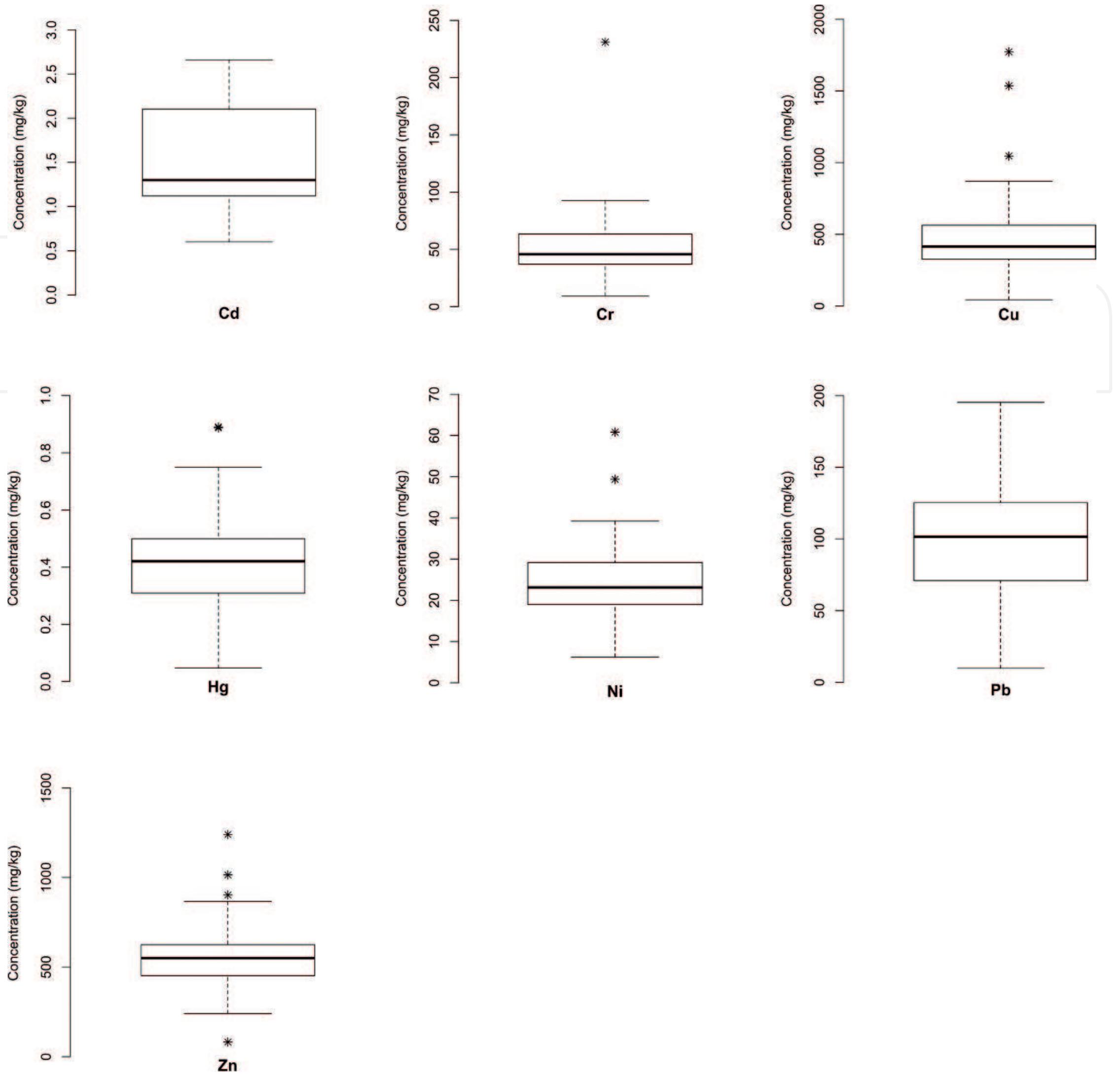

Figure 3. Distribution of heavy metals in sludge samples as revealed in the box plot diagram.

heavy metals in the wastewater. Sewage sludge samples analyzed in this study came from municipalities with different populations, from 1000 to 35,000 inhabitants, although no correlation was found between the population and the contents of heavy metals. The atypical values observed in Cr, Cu, Hg, Ni, and Zn can be attributed to point pollution, and it is considered that the sewage sludge do not present a high pollutant load. However, organic pollutants that are common in wastewater (antibiotics, hydrocarbons, detergents, etc.) have not been analyzed in this study. Aerobic composting has been extensively documented to reduce the concentrations of organic compounds via biological degradation [24–26].

2.2. Intra-sludge variability

To determine the variability of the physicochemical composition of the same sewage sludge, ten samples from the same WWTP were analyzed in a period of 5 years (**Table 4**). Although variability was observed in the parameters analyzed, this was lower than the inter-sludge

	Mean	Percentile 5–95%		Mean	Percentile 5–95%
Moisture (%)	85.5	84–87	Cd (mg kg^{-1} dw)	1.3	1.0–2.1
Organic matter (%)	75.0	71–79	Cr (mg kg^{-1} dw)	40.6	27.1–48.8
pH	6.8	6.2–7.4	Cu (mg kg^{-1} dw)	330	244–402
Electrical conductivity (mS cm^{-1})	0.55	0.1–1.1	Ni (mg kg^{-1} dw)	20.9	14.9–27.7
Total carbon (% dw)	36.3	33–40	Pb (mg kg^{-1} dw)	89.8	65–122
Total nitrogen (% dw)	5.75	5.2–6.6	Zn (mg kg^{-1} dw)	502	443–590
C/N ratio	6.3	5.8–6.8	Hg (mg kg^{-1} dw)	0.48	0.3–0.8
P_2O_5 (% dw)	4.6	3.9–5.3			
N-NH_4^+ (g kg^{-1} dw)	5.5	0.4–13			

Table 4. Analysis of physicochemical parameters of 10 sludge samples from the same WWTP for 5 years.

variability. It is important to highlight the greater homogeneity in the C/N ratio and moisture, while organic matter, total carbon, ammonium, and electrical conductivity had important oscillations. As the WWTP did not have operational alterations in the treatment process over the sampling time, it is assumed that the variability is a consequence of the input wastewater. Heavy rainfall can dilute wastewater, while water consumption in municipalities tends to decrease in the rainy season. However, no appreciable seasonal differences were found in the parameters studied, with more sampling being necessary to corroborate this observation.

The distribution of heavy metals corresponds with the lower quartile (values lower than the median) of inter-sludge heavy metal analysis, so it is a waste with low degree of contamination. Although the WWTP treats the wastewater of 25,000 inhabitants, the level of industrialization of the municipality is low, and the services sector dedicated to tourism is predominant, so the presence of heavy metals in the wastewater corresponds to domestic and residential operations with low inorganic pollution.

In industrial composting facilities, the sewage sludge is subjected to preconditioning which generally consists of mixing with bulking agents and other co-substrates and which must be based on the composition of the input waste. As observed, this composition is variable, and therefore it is necessary to know if this variability influences the development of the process in a significant way.

2.3. Bulking agent proportion

Using crushed wood it is possible to improve both the physical and chemical parameters of sewage sludge, so that the distribution of oxygen and macronutrients are more suitable for aerobic microbial growth necessary for the process. For the determination of the balance between bulking agent and sewage sludge, mathematical formulas or proportional rules can be used trying to reach the desired humidity, FAS, or C/N ratio [5, 17, 27]. The objective of this experience was to determine the proportion of bulking agent most suitable for the development of sewage sludge composting, taking as reference to the self-heating capacity of the waste and the capacity to maintain the thermophilic conditions. As sewage sludge is obtained after secondary treatment, some of the more readily available compounds have already been consumed, so the biodegradation process may be weakened or slowed down. Composting must guarantee maximum sanitization reaching high temperatures and presenting an extended thermophilic phase. In this way, organic matter is stabilized, and the content of pathogens inherent in wastewater is reduced or eliminated.

Therefore, a composting test was carried out on 12 static reactors of 30 L each one with aeration control using three different proportions in volume 3:1, 2:1, and 1:1 and bulking:sludge in triplicate (**Figure 4**). Sewage sludge characterized in **Table 4** was used. As a bulking agent, crushed wood with a size between 0 and 10 mm was used. This particle size has been the ideal one for a pasty residue and for the volume and characteristics of the reactors according to previous experiences. The main characteristics of this bulking material were moisture 32% and organic matter 90%. Composting in reactors facilitates the control of temperature (maximum 60°C), oxygen levels (minimum 5%) and the time and aeration regime (continuous and depending on the tracking parameters). Likewise, this system allows exhaust gases to be directed to a biofilter for odor control and the collection of leachates.

From an empirical point of view, the sludge and bulking mixture were done with difficulty due to the pasty character of this waste which tended to form clumps. In particular, the 1:1 ratio was the most complex mixture to make because some areas were not structured enough and converted the mixture into a dense mass that affected the compaction inside the reactor and produced possible anoxic areas. In contrast, the 3:1 ratio had a porous and looser structure, and most of the sludge was surrounded by wood particles. Oxygen levels remained over 8% in all proportions. **Figure 5** shows how the microbial activity and therefore the temperature responded to the conditions of the experiment. The municipal sewage sludge presented the adequate nutritional conditions for microbial growth according to what was observed in the evolution of temperature. This evolution was significantly different depending on the proportion of bulking agent ($p < 0.0001$). Although the lowest proportions experienced quick

Figure 4. System of 12 composting reactors of 30 L, each one inside a wooden box for the maintenance of adiabatic conditions (left) and mixture of bulking agent with sewage sludge in 3:1 proportion in volume (right).

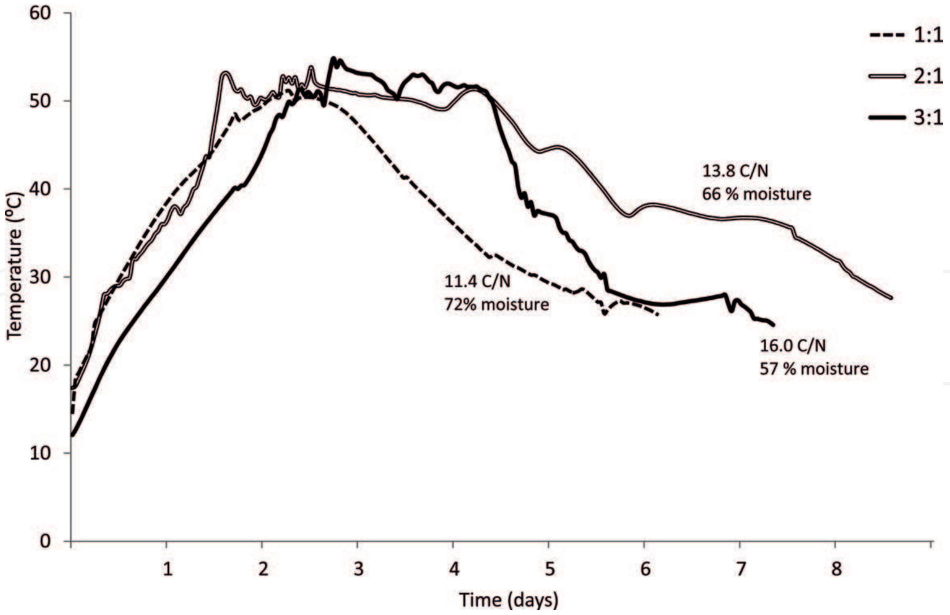

Figure 5. Evolution of the average temperature of the three proportions bulking agent:sludge inside the 30 L composting reactors.

self-heating, the 3:1 ratio was possibly slowed down as a result of the higher content of more recalcitrant carbonated substances that were difficult to break down. The maintenance period of thermophilic temperatures was higher in the 2:1 ratio (4 days), followed by 3:1 (3 days), and finally the 1:1 ratio (1.5 days). It is logical that the higher the content of sewage sludge in the mixture, the greater the content of substances that are easier to break down and the greater the amount of treated sewage sludge per unit volume. However, the 1:1 ratio maintained lower microbial activity that, in line with what was observed during mixing, can be a consequence of its greater compaction and the presence of preferential aeration channels in the mass that prevent a correct distribution of air. After reaching temperatures lower than 35°C, the process was completed, and a high colonization of fungi was observed in some reactors (**Figure 6**). The mass balance after 9 days of the process showed organic matter losses of 10% (2:1), 4.5% (3:1), and 1.6% (1:1). Although 3:1 ratio reached the maximum temperature, there

Figure 6. Development of fungi in reactors with a 2:1 ratio (left) and emptying of a reactor with a 3:1 ratio (right).

was a quick thermal decline after the thermophilic phase which, added to the slight loss of organic matter, indicates that the more porous structure of the mass caused a rapid cooling that prevented the support of temperature and biodegradation at an intensive level.

The bulking:sludge ratio more suitable from the point of view of temperature, in the short term considered in this experiment, was the ratio 2:1, although its initial moisture content was not considered optimal and its C/N ratio could facilitate the loss of nitrogen. This proportion allows greater treatment of sewage sludge per unit volume than the 3:1 ratio in an industrial treatment facility.

2.4. Composting reproducibility

The following experiment consists of the comparison of composting experiences on a larger scale that have a purpose to verify the reproducibility of the sewage sludge process with a 2:1 ratio (bulking:sludge). In this way, the same sewage sludge as in sections 2.2. and 2.3. (**Table 4**) was sampled six times. Crushed wood was used as a bulking agent, but the particle size was adapted to reach a 30% FAS in the mixture [5] and to the highest reactor volume (600 L), considering wood particles between 0 and 30 mm as optimal. Each mixture bulking:sludge was introduced into the reactor (**Figure 7**), the temperature and oxygen levels were controlled by forced aeration, and processes were finished when the temperature dropped to environmental values after the thermophilic phase.

Compared with the previous experience, the initial C/N varied remarkably (8–16), especially due to the wide fluctuations of the initial carbon. Also, moisture contents were higher than in the previous experiment. Regarding the development of the process (**Figure 8**), the evolution of the temperature was significantly different ($p < 0.001$), and two groups can be differentiated: a group of reduced thermophilic phase constituted of sewage sludge reactors 1, 2, and 3 (SS1, SS2, and SS3) and a group of prolonged thermophilic phase constituted of sewage sludge reactors 4, 5, and 6 (SS4, SS5, and SS6). Notable differences were observed in terms of high-temperature conditions: from 3 days under thermophilic conditions in SS1 to 18 days in SS6. Thus, it was observed that the higher the C/N ratio, the greater the capacity to maintain the thermophilic conditions (SS5 and SS6), while the influence of this

Figure 7. Composting reactor of 600 L equipped with a fan, recorder, and control of process parameters and biofilter (left) and colonized mixture of bulking agent with sewage sludge in 2:1 proportion in volume after process time (right).

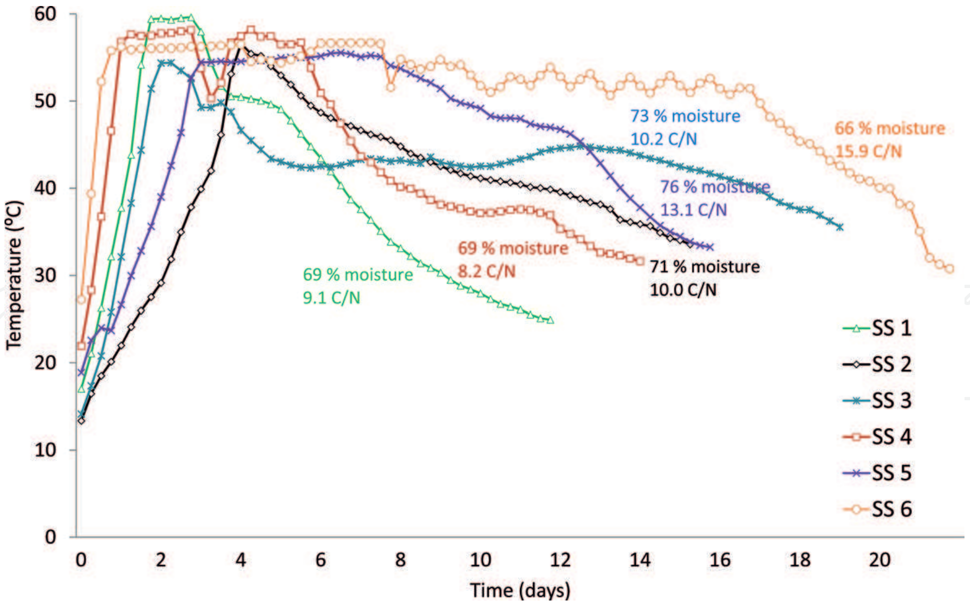

Figure 8. Evolution of temperature during the reactor phase of sewage sludge from the same WWTP at different sampling periods mixed with bulking agent.

parameter on the initial self-heating capacity was not observed. However, the time to reach thermophilic values slowed down with high moisture contents (> 70% moisture), contrary to the experience in 30 L reactors.

As a result of the research, it can be extrapolated that a ratio of 2:1 (bulking:sludge) does not reach the ideal moisture for the composting process, but if the C/N ratio exceeds 10 and the moisture is below 70%, the maintenance of the thermophilic conditions seems to be prolonged. In an industrial compost facility, it is very complicated to establish an ideal mixing protocol for a specific sewage sludge since the variability of the input material causes important variations in the development of the composting process.

2.5. Compost analysis

After emptying the reactors from the reproducibility test, the pre-composted materials were turned and kept in piles for 90 days to mature, and next, compost analyses were performed (**Table 5**). Variability can be observed in the general characteristics established by the legislation on fertilizer products [28] and other important parameters of stability and maturation of compost [29, 30].

It is important to note that organic matter is high in some samples as a consequence of the short periods under thermophilic conditions and that the finest fraction of the bulking agent becomes part of the compost after sieving, increasing this parameter. However, the organic matter is reasonably stabilized with low respiratory activities (less than mg O_2 g^{-1}SV h^{-1}) and poor self-heating of the compost with maximum rating for this test (classes IV and V). Likewise, the germination indexes were high (> 80%) which allows the use of compost without harming the plant growth. The pathogens were within the values for the use of compost, and all experiences allowed sanitation although the group of reduced thermophilic phase (SS1, SS2, and SS3) presented the highest values of *Escherichia coli*.

	Range	**Spanish Fertilizers Law [28]**		
Moisture (%)	51–66	< 40		
Organic matter (%)	66–75	> 35		
pH	5.4–6.2	—		
Electrical conductivity (mS cm^{-1})	0.9–1.2	—		
Total carbon (% dw)	33–38	—		
Total nitrogen (% dw)	2.9–3.4	—		
C/N ratio	10–14	< 20		
P_2O_5 (% dw)	3.3–3.5	—		
Basal respiration (mg kg SV h^{-1})	100–330	—		
Self-heating test	IV–V	—		
Germination index (%)	96–108	—		
Salmonella spp. (in 25 g)	Absence	Absence		
Escherichia coli (ufc/g)	<10–800	<1000		
		Class A	***Class B***	***Class C***
Cd (mg kg^{-1} dw)	0.8–1.6	0.7	2	3
Cr (mg kg^{-1} dw)	38–52	70	250	300
Cu (mg kg^{-1} dw)	240–300	70	300	400
Ni (mg kg^{-1} dw)	21–26	25	90	100
Pb (mg kg^{-1} dw)	54–84	45	150	200
Zn (mg kg^{-1} dw)	300–480	200	500	1000
Hg (mg kg^{-1} dw)	0.3–0.4	0.4	1.5	2.5

Maximum values allowed in the Spanish fertilizers law for compost are included

Table 5. Maturity and stability parameters in sewage sludge composts from the same WWTP sampled in different times and composted in 2:1 ratio bulking:sludge in static reactor and followed by pile maturation.

The Spanish legislation on compost, Royal Decree 506/2013 of 28 June on fertilizers [28], classifies compost into three categories according to the heavy metal content: classes A, B, and C. The content of Cd, Ni, Pb, Zn, and Cu assumes that all composts are classified as class B. So, low inorganic pollution in input sewage sludge allows meeting the quality criteria for the use of compost as an organic amendment. Although the sewage sludge evolved differently inside the reactor, maturation in a pile for 90 days seems to assimilate the composition of the composts.

3. Conclusions

The development of cities and the centralization of sanitation services mean that the sewage sludge produced in wastewater treatment plants has a growing presence in our society.

Composting is a viable alternative for sludge management, but initial characteristics of the waste must be determined for process optimization. The municipal sewage sludge presents high inter- and intra-variability in key parameters for the evolution of the composting process such as moisture and the C/N ratio. The levels of heavy metals in specific samples of sewage sludge are not useful information if there are no periodical analyses to detect point pollution or seasonal changes. The addition of bulking agent is necessary for the development of the composting process, but its size and proportion must be adapted to the waste composition, the composting system used, and the volume of treatment. The variability in sewage sludge composition makes it difficult to establish treatment protocols in industrial composting facilities, although the establishment of minimum process conditions is necessary, for which the use of a minimum proportion of bulking agent:sludge 2:1 in volume is recommended. Despite the different evolution of the composting process, if the initial sewage sludge presents average composition, the compost achieves adequate quality parameters.

Acknowledgements

The authors thank the research support services of the University of Vigo (CACTI) for the carbon, nitrogen, and heavy metal analysis.

Author details

David Alves Comesaña, Iria Villar Comesaña* and Salustiano Mato de la Iglesia

*Address all correspondence to: iriavillar@uvigo.es

Department of Ecology and Animal Biology, University of Vigo, Vigo, Spain

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