

Article

Heat Energy and Gas Emissions during Composting of Sewage Sludge

Grażyna Żukowska ¹, Jakub Mazurkiewicz ^{2,*}, Magdalena Myszura ¹ and Wojciech Czekala ² 

¹ Faculty of Agrobioengineering Institute of Soil Science and Environment Shaping, University of Life Sciences in Lublin, ul. St. Leszczyńskiego 7, 20-069 Lublin, Poland; grazyna.zukowska@up.lublin.pl (G.Ż.); magdalena.myszura@up.lublin.pl (M.M.)

² Institute of Biosystems Engineering, Poznan University of Life Sciences, Wojska Polskiego 50, 60-627 Poznan, Poland; wojciech.czekala@up.poznan.pl

* Correspondence: jakub.mazurkiewicz@up.poznan.pl; Tel.: +48-695-360-520

Received: 6 September 2019; Accepted: 13 December 2019; Published: 15 December 2019



Abstract: The composting of sewage sludge and maize straw mixtures was investigated in this study. The aim was to analyze the influence of different proportions of sewage sludge and maize straw in the mixtures on composting process dynamics (expressed by heat production) and gas emissions. The results showed that all examined mixtures reached a strong thermophilic phase of composting; however, the lowest dynamic of temperature growth was observed in the case of the biggest sewage sludge content (60% of sewage sludge in the composting mixture). The ammonia concentration inside bioreactor chambers was directly related to the content of sewage sludge in the composted mixture. Excessive contents of sewage sludge had a considerable effect on very low C/N ratios and high losses through ammonia emissions. Tests were carried out in reactors with a capacity of 160 dm³ under controlled conditions. All mixtures were aerated by the average air-flow of about 2.5 dm³·min^{−1}, i.e., the minimum air-flow that allows a temperature of about 70 °C to be reached and a sufficiently long thermophilic phase, which ensures proper composting.

Keywords: sewage sludge; composting; gas emissions; heat energy; C/N ratio

1. Introduction

The rapid development of urbanization and industrialization all over the world, including Europe, has significantly increased the amount of sewage [1–3]. Large amounts of sludge are generated in various biological, chemical, and physical wastewater treatment processes and its volume is constantly growing.

Data specifying the current level of wastewater production and treatment has been of global importance for the last few years, and has also been important for national decision makers, researchers, practitioners, and public institutions, in order to develop national policies and action plans for wastewater treatment and the productive use of it (in many sectors—from agriculture, to industry). Nevertheless, this information is rarely systematically monitored or reported in many countries, as described by scientists [4], with a significant shortage of data on the rural sector.

Data from the Eurostat [5] and European research analyses [6–8] showed that 27 European countries produce about 10 million Mg of sewage sludge (dry matter) per year. Per capita production in individual countries varies greatly and depends mainly on the percentage of the population with households connected to collective sewerage systems. It also determines what type of sludge is included in the calculations—raw, treated, only domestic, etc. For estimation purposes, the following solids production rates may be used: 0.2–0.3 kg·m^{−3} of treated wastewater with an average rate of 0.24 kg·m^{−3} [8].

What is important is that Germany, the United Kingdom, Spain, France, and Italy together generate almost 75% of the European sewage sludge [7]. Poland (based on data from 2015 and only from the urban sewage treatment process) also ranks very high in terms of sewage sludge production at above 568,000 Mg per year [5].

An additional stream of sludge (not shown in the official statistics) is comprised of sewage sludge generated at small wastewater treatment plants (SWWTP), usually 1–2% of treated wastewater. According to various scientists, the volume of accumulated sludge in the above-mentioned installations, per one inhabitant per year, ranges from several dozen to even several hundreds of liters. The average unit volume of sludge accumulated (after annual fermentation) in SWWTP is 173 dm³ per year [9].

Sewage sludge is a valuable source of biomass that could be used in various ways. Several methods of sewage sludge management may be mentioned, including landfill disposal, agricultural management (including composting), incineration, etc. An alternative method to standard sludge combustion is pyrolysis. According to some literature sources, it enables an over 50% reduction in waste volume, stabilization of organic matter, as well as the recovery of valuable end products [10]. The method described here consists of the thermal degradation of organic material occurring in the absence of oxidizing agents. It is relatively simple, inexpensive, robust, and may be used to convert biomass into products such as bio-oil, solid residue, and synthesis gas [10,11]. Due to its relatively high nitrogen, phosphate, and potassium contents, the use of sewage sludge in agriculture seems particularly advantageous [2,12], but it is highly dependent on its quality, primarily the content of pollutants [13,14]. The composition of sewage sludge depends primarily on the mineral and organic contents of sewage and the degree of mineralization of organic matter in the process of stabilization. Depending on the applied stabilization processes, dehydrated (dry) sludge contains, on average, 50–70% organic matter and 30–50% mineral components (including 1–4% of inorganic carbon), 3.4–4.0% nitrogen, 0.5–2.5% phosphorus, and significant amounts of other nutrients, including micronutrients [7,15,16].

A properly managed composting process is one of the most common waste management methods, provided sustainability issues are aimed at stabilizing organic waste, including sewage sludge, providing a stable and harmless end product that may be used as a fertilizer or soil conditioner that poses no threat to the environment [16–18]. Composting is a proper option for biosolid management, it is a proven method for reducing pathogens, and results in a product that is easy to handle, store, and use [19].

The selection of an appropriate composting system or technology in a wastewater treatment plant depends on several factors, such as the type and amount of sludge (primary or secondary), and this, in turn, affects economic considerations, legal aspects, location, environmental aspects, and the quality of the final product, etc. Most often it is composted in two systems: “windrow”, where the material accumulates in longitudinal rows or piles, and “in vessel”, in which the material is enclosed in the reactor [20,21]. The latter method, although much more expensive in construction and operation, does not generate any odor or leachate related problems [22]. Unlike conventional external technologies, such as windrows or piles, bioreactors have a significant advantage because they enable aeration control and have thermal insulation. These aspects enable proper oxygenation of the compost mix and its faster heating, and thus the composting time is reduced [23]. This is very important for municipal installations—shorter composting means less space needed for sludge processing. In addition, hermetic bioreactors do not allow odors to escape, which is also the case in other open systems. This results in there being no need to pay compensation for air pollution [24]. Due to the above-mentioned aspects, composting or co-composting in reactors seems more justified, especially for urban installations [22,25].

Composts from sewage sludge and microbiological products of sewage sludge conversions have a positive effect on the physical, chemical, and biological properties of soils [26]. Their natural application mitigates the problem of high costs of mineral fertilization. The macro and micro-components contained in sewage sludge are well absorbed by plants, while the quality, organic matter, accumulated in them, contributes to the improvement of the balance of humus compounds [27].

Research confirmed the positive impact of sewage sludge on the development of native soil bacteria [28]. There is a significant proportional increase in the number of studied microorganisms along with an increased dose of sewage sludge, while organic matter introduced with composts from sewage sludge has a direct impact on the growth and yield of plants and the physical, chemical, and microbiological status of the soil [29,30]. Composts from sewage sludge increased soil cation exchange capacity, whereas a high value of this indicator suggests the stronger binding of cations in the soil environment, resulting in the immobilization of nutrients and greater resistance to pollution [31]. Composts from sewage sludge improve the structure of agricultural land and are suitable for the production of industrial and energy crops, directly affecting their growth rate [32].

Sewage sludge—mainly due to its excessive moisture content and low C/N ratio—cannot be composted as a monosubstrate [33]. The high moisture content (above 80%), low C/N ratio, plastic structure susceptible to compaction, high bulk density (above 800 kg·m^{−3}), and low air-filled porosity (max 30%) of sewage sludge do not allow it to meet the requirements for composting [34,35]. Literature sources provide information that composting of sewage sludge alone failed to raise the temperature to the thermophilic values typical of composting [36]—e.g., the highest recorded temperature was around 33 °C [35]. For this reason, the composting of sewage sludge requires the addition of supplementary substrates that provide an appropriate structure in the composting pile. Sewage sludge is characterized by a low C/N ratio, which contributes to the release of ammonia and the intensity of diseases caused by *Fusarium* spp. [37]. According to Dach [38], because of the effect of C/N levels on ammonia emissions, it may be difficult to obtain the appropriate C/N ratio in composted sewage sludge, as sewage sludge is characterized by a high nitrogen content (4–5% TS), which has a significant effect on the organic carbon to nitrogen ratio, amounting to less than 10. Therefore, sewage sludge typically requires preparation before the composting process [39,40], for example, by adding materials containing straw, woodchips, or biochar [41]. This type of bulking agent addition to high moisture compost mixes can provide optimal humidity and sufficient porosity for proper airflow. In addition, if the low carbon biochar used could improve the C/N ratio, it would have a positive effect on composting dynamics. The addition of 5% and 10% biochar reduced ammonia gas emissions by 30% and 44%, respectively, in the gaseous and liquid phases during the composting of poultry manure with wheat straw [41]. In these studies maize straw was used as a supplementary substrate to provide an appropriate structure in the composting mixture.

It is not only the quality of the compost itself that is important, but also the size and type of gas emissions. During the composting process, various gases are released: Carbon dioxide (CO₂), methane (CH₄), oxides of nitrogen (NO_x), nitrous oxide (N₂O), volatile organic compounds (VOC), ammonia (NH₃), hydrogen sulfide (H₂S), water vapor (H₂O), and others in smaller quantities [42–44]. The first five of these gases cause the greenhouse effect. Compared to carbon dioxide, CH₄, N₂O, VOCs, and NO_x have greater atmosphere-warming potentials, being as much as 20–25, 290–310 and even 2000-fold higher, respectively [44,45]. The process also releases smaller amounts of other gases such as NH₃, CO₂, CH₄, N₂O, H₂S, NO_x, and volatile organic compounds (VOC), each of which has a different effect on air quality [44].

The aim of this study was to analyze the influence of different proportions of sewage sludge and maize straw mixtures on composting process dynamics, heat energy, and gas emissions. These parameters are important not only in respect of technology optimization, but also in designing devices for energy recovery from composting processes [46] and the reduction of gas emissions (greenhouse gas—CO₂ and odorogenic—NH₃). While there are numerous publications on obtaining good quality compost and several process optimization studies have already been undertaken [47], there is still a need for research studies concerning the environmental impact of composting, especially regarding gases [44]. Therefore, in order to increase economic efficiency, maize straw was selected as a structural material, because it is a commonly available and cheap material (in Poland, it is about 12 Euro·Mg^{−1}), while a relatively low air-flow, at about 2 dm³·min^{−1}, was applied while nonetheless ensuring the correct course of composting processes. Tests carried out on several dozen kilogram

samples regarding composting under controlled conditions at low airflows were carried out in very few works [48].

2. Materials and Methods

2.1. Characteristics of Substrates

Anaerobically stabilized, dewatered sewage sludge (SS) was collected from a municipal wastewater treatment (near Poznań, Poland). Maize straw (MS) was sampled from an experimental university farm (near Poznań, Poland) and supplied to the laboratory for physical and chemical analyses. Basic parameters were determined, such as moisture (MC) and organic matter (OM) contents, total organic carbon (C_{org}), total nitrogen (N_{tot}) and bulk density (BD), fresh mass (FM), and total solids (TS).

Sewage sludge was mixed with maize straw in different proportions (Table 1), with the substrate weight and the percentage ratios expressed in terms of FM and TS, respectively. The composition of all mixtures composted in bioreactor chambers (Ch) is shown in Table 1.

Table 1. Proportions of composting mixtures, calculated in fresh (FM) and dry matter (TS).

Composting Mixture Numbers	Composting Mixture			
	Weight, FM		Mixture's Proportion (Calculated in TS)	
	SS, kg	MS, kg	SS, %	MS, %
Ch1	20.0	16.0	30	70
Ch2	33.0	14.5	44	56
Ch3	26.3	7.5	55	45
Ch4	40.0	9.1	60	40

Sewage sludge demonstrated typical properties for this type of material. Moisture content (MC) (84%), organic matter (68%, TS), and total nitrogen (6%, TS) levels were high, and thus the C/N ratio of SS was approx 6.2. The reported physicochemical and physical parameters showed that sewage sludge could not be composted alone. Maize straw substrate showed a high content of organic matter, but it contained a relatively low content of nitrogen (0.6%). Due to the high content of organic carbon (48%), MS showed a high C/N ratio. The investigated sewage sludge and maize straw substrates were analyzed for physicochemical and physical properties which are presented in Table 2.

Table 2. Characteristics of investigated substrates.

Substrates	Parameters				
	TS %	OM % TS	Corg %	Ntot %	C/N
Sewage sludge	15.9	68.3	38.5	6.3	6.2
Maize straw	45.8	94.0	48.5	0.6	80.9

2.2. Characteristics of Composting Mixtures

Changes in initial moisture content, bulk density, and the C/N ratio of the investigated mixtures, as well as total solids (TS) content and average air-flow (AAF), were calculated in terms of TS and is shown in the table below (Table 3).

With a decreasing ratio of the maize straw substrate in the mixtures, their moisture content increased from ca. 71% to 79%, while that of organic matter decreased from ca. 86% to 78%. A decrease in the C/N ratio was also observed.

Table 3. Selected parameters of investigated composting mixtures.

Parameters	Composting Mixture Numbers			
	Ch1	Ch2	Ch3	Ch4
MC, %	70.81	74.97	77.47	78.56
OM, % TS	86.22	82.66	79.89	78.48
C/N	19.7	14.3	11.6	10.6
TS, kg	10.51	11.89	7.62	10.53
AAF, dm ³ min ⁻¹ ·kg ⁻¹	0.24	0.21	0.33	0.24
BD, kg·m ⁻³	257	350	349	362

2.3. Description of the Experiments

The composting process was carried out in specially designed bioreactors [49]. The use of thermal insulation in bioreactors eliminated the external influence of environmental factors. The bioreactor used for these experiments was designed and built in the shape of a cuboid with a side length of 0.5 m, height of 0.7 m, and capacity of 165 dm³ [50]. The walls of the chambers were made of plastic and were additionally reinforced with metal elements.

Aeration of bioreactors was provided by means of a special air-pumping pump. The amount of air injected into the chambers was controlled and the pressurized air was evenly distributed, thanks to the metal grate installed at the bottom of the chamber.

At the initial stage, the minimum air-flow was selected to obtain a temperature of about 70 °C and a sufficiently long thermophilic phase that ensured proper composting. The minimum air-flow was about 2.0 dm³·min⁻¹, at an average air-flow of 2.5 dm³·min⁻¹, which corresponded to a flow in the range of 0.17 dm³·min⁻¹·kg⁻¹ TS to 0.26 dm³·min⁻¹·kg⁻¹ FM.

The air-flow through the chambers was adjusted manually using a rotameter (flow readability of 0.05 dm³·min⁻¹), whereas constant control was facilitated by electronic flow sensors, connected to the data register. Moreover, the amount of air-flow was also measured with analog counters.

The bioreactor was additionally equipped with a drainage system to eliminate effluents that arose during the composting process of the mixture. The tanks, located below the chamber in a gravitational manner, were discharged by means of a connector placed inside the chamber. The specific design of the chamber cover facilitated condensate drainage.

The bioreactor chambers were installed with a set of measuring sensors designed, among other things, to control the temperature, content, and concentration of selected gases. The temperature variation was registered by means of temperature sensors connected to a 16-channel recorder and were read manually during the gas measurements.

The C/N ratio of the investigated mixtures was calculated from the contents of organic matter, total organic carbon, and total Kjeldahl nitrogen in each of the substrates. Moisture content was determined by oven drying at 105 °C (24 h); organic matter was determined by the loss on ignition at 550 °C in a muffle furnace until the weight was held constant (ca. 3 h).

Qualitative and quantitative analyses of the gases produced (H₂, CO₂, NH₃, O₂, and H₂S) were carried out daily using a Geotech GA5000 gas analyzer. This analyzer performance was verified weekly using calibration gases (100 ppm NH₃, 500 ppm H₂S, 35% CO₂, 65% CH₄, and O₂ in technical air) supplied by Mettler (Poland). Gas analysis consisted of measuring the flowing gas through the analyzer, located at the outlet of the chambers.

The investigated sewage sludge and maize straw were analyzed (each time in three repetitions) for physicochemical and physical properties, which are presented in Table 2. The analyses (dry matter, organic dry matter, pH, Corg, Ntot, and N-NH₄) were made at university laboratories, applying standard procedures [51].

3. Results and Discussion

While the initial temperature of composted mixtures was low (because of the low temperature of sewage sludge collected from an open storage facility during wintertime), all the materials had passed by with very fast growth temperatures (Figure 1). In all the chambers, the temperature reached or exceeded 70 °C. High temperature (over 60 °C) for at least two days will annihilate most pathogens [52]. It should be noted, however, that the highest temperatures were only attained after several days. Typically, the highest temperatures are reached after 2–3 days [22,53]. Extending the time to reach the maximum temperature was associated with a fairly low air-flow of about 2 dm³·min^{−1}, which resulted in a small amount of oxygen available to microorganisms. The concentration and amount of oxygen is directly related to the self-heating properties of compost, as well as the emission of other gases. An adequate content of this gas (over 10%) facilitates organic matter decomposition without the fermentation process [53].

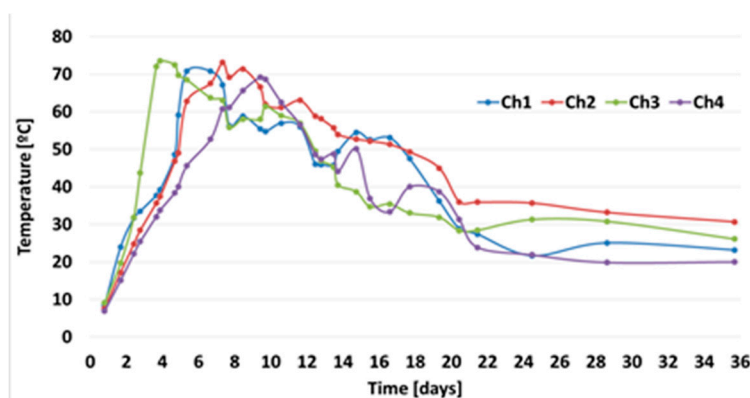


Figure 1. Changes in temperature during the composting experiment.

The highest temperatures were first reached for samples Ch3 and then Ch1 (Figure 1)—which is closely related to bulk density (both mixtures had the lowest values). The other samples had higher bulk density, and at low air-flows, the microorganisms did not receive enough oxygen to start the thermophilic process—as is the typical case. From the second day of the experiment, the temperature increased (similar to the amount of carbon dioxide, which will be shown later in this paper) due to the presence of a thermophilic phase in the composts.

A high temperature period was observed for almost three-weeks of composting. Then, temperatures were reduced to 30–35 °C and slowly decreased until the end of the experiment. All composted materials passed through an intensive thermophilic phase; however, some differences in temperature growth were observed. A similar course—with the characteristic four phases of composting temperatures—was reported in many other studies [50,54].

The mixture in Ch1, despite the better C/N ratio, however, reaches a slightly lower temperature than Ch2 and Ch3 (Figure 1). The addition of a co-substrate with a much better C/N ratio than sewage sludge was beneficial for microbial growth. The addition of such a bulking agent to the compost mix provides an additional higher porosity and air permeability, thus oxygen concentration in the compost mix can be adequate in all locations. However, this has economic consequences, however, it takes up space and increases processing costs [24,55]. However, an excessively high porosity ratio (low bulk density) results in a very high level of air filling. The higher the permeability, the greater the ventilation, thus an excessive heat loss of the compost mix increases as well [56]. In extreme cases, this may prevent the sludge mixture from reaching the thermophilic temperatures required for sanitary purposes [57]. More information on the subject may be found in References [58–60].

Results on slightly different mixes (sewage sludge, cattle manure, and sawdust) with, e.g., C/N ratio 15 : 20 and higher, showed a definitively lower level of maximum temperatures—about 55 °C. This could be due to the lack of thermal insulation of the reactors and the lack of condensate drainage

(which in large part go back into the mixture and reduce its temperature and must be evaporated again) [22].

In order to compare the intensity of the composting process, the cumulative temperatures were calculated for each chamber (Figure 2).

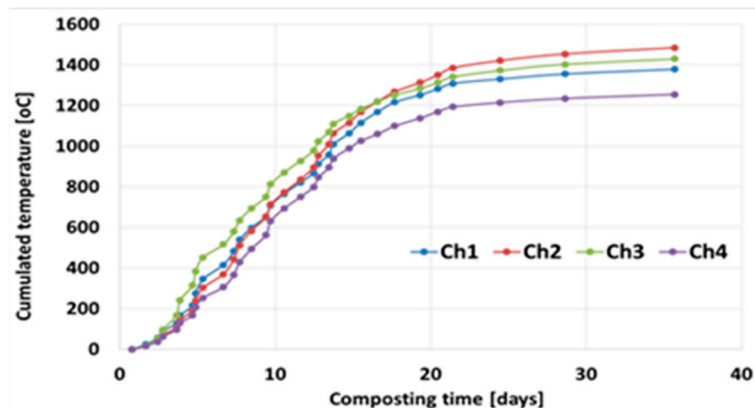


Figure 2. Changes in cumulative temperature during the composting experiment.

The highest cumulative temperature was obtained in Ch2, while it was the lowest in Ch4. Ch4 contained the mixture with the lowest TS content (21.4%), which was related to the highest content of sewage sludge. It has to be underlined that sewage sludge usually mostly contained water and it was also the case in the sludge used in this experiment (only 15.9% of TS). The presented results are similar to those obtained by other scientists, stating that, to a certain simplification, the moisture content in the mixture of around 75% is close to the optimal conditions [54], which were found in sample Ch2. Thanks to such moisture content of the sample, the maximum temperature and cumulated temperature values were obtained, while the final composting product with good physicochemical properties, as well as higher degradation of organic matter and higher gas production, were provided.

The emission range of ammonia (from 0 up to 1100 ppm) is an important parameter, related to the fact that agriculture is an important producer of this gas, which, when released to the atmosphere, deteriorates its quality. The emission volume of the inorganic nitrogen compound is closely related to the content of sewage sludge in the compost mixture. The high sewage sludge content in a compost mixture had a considerable effect on ammonia emissions from the mixture, as presented in Figure 3.

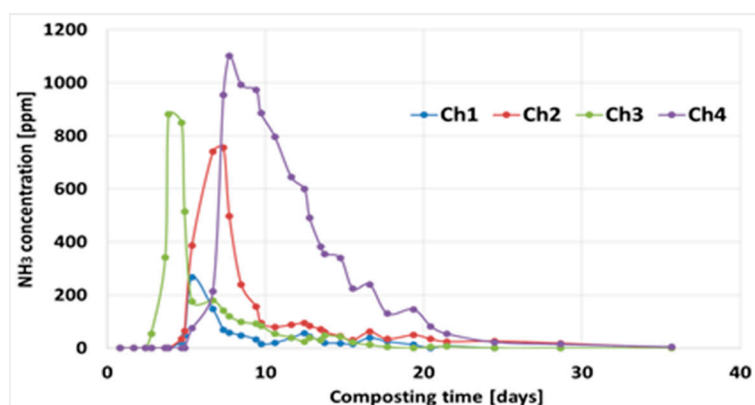


Figure 3. Changes in ammonia concentration inside bioreactor chambers.

The highest ammonia concentration (over 1100 ppm) was obtained in the Ch4 mixture, which contained the highest sewage sludge content (60% TS) and the lowest C/N ratio (10.6). The Ch1

mixture with only 30% of sewage sludge and a C/N ratio of 19.7 reached the highest NH_3 concentration at 267 ppm and this ammonia content was completely depleted within the first 20 days of composting.

The highest ammonia emissions were recorded both during and immediately after the thermophilic phase, regardless of the initial mixture. Other groups of researchers measured similar ammonium concentrations during composting, e.g., a maximum of 1476 ppm when also composting the mix with 60% sewage sludge [53]. The exact composition of the mixture was slightly different than in these studies—in addition to 35% sawdust, there was still 5% straw, but also a 45% higher total weight and air-flow that was over 20% greater (which had a detrimental effect on the release of ammonia). Other studies have also shown high ammonia emissions during high temperatures, while the peak of NH_3 emissions coincided with the maximum temperature and oxygen uptake rate [48,61–63].

However, for a better comparison of ammonia losses, it was decided that we would calculate NH_3 emission from 1 kg of sewage sludge that was initially used for composting (ammonia emission from straw was negligible). The results are presented in Figure 4. A similar increase in ammonia emissions in the first phase of composting and a sudden reduction after reaching the maximum temperature can be found in other field studies [42].

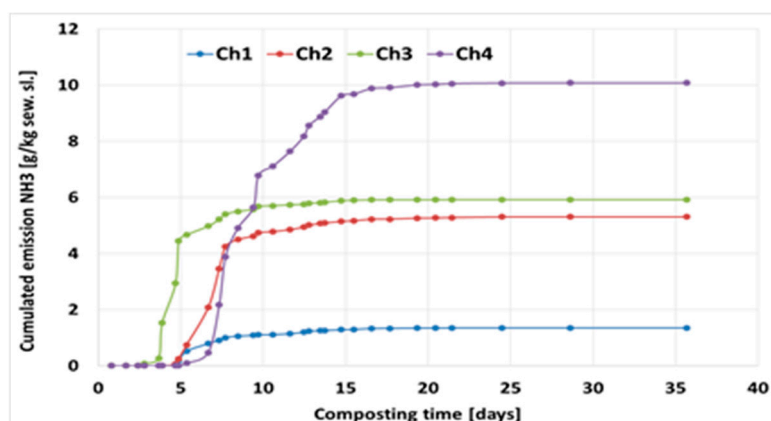


Figure 4. Cumulated ammonia emission from 1 kg of TS of sewage sludge.

Other researchers, observed a slightly higher level of ammonia emissions when composting sewage sludge, straw, and sawdust, where ammonia was at the level of 1500–1000 ppm. This was due to the low C/N ratio, between 9–17, and the slightly higher maximum temperatures [64].

The results clearly show the relationship of sewage sludge and straw proportions. The cumulated ammonia losses increase with an increase in sewage sludge content (and a decrease of C/N ratio) from Ch1 to Ch4.

In order to reduce such high ammonia emissions from a compost mixture with high nitrogen content, appropriate additives, e.g., biochar, could be successfully used. This material has special properties—recalcitrance and sorption properties—which facilitates its application as a bulking agent and/or amendment [41].

The first two weeks of composting showed intensive CO_2 emissions (Figure 5), which is characteristic of the intensive decomposition of organic matter [65,66]. The greatest changes can be seen for the thermophilic composting phase (from four to nine days, depending on the mix).

Contrary to ammonia emissions, the highest carbon dioxide emission was recorded from the Ch1 mixture (Figure 5). This proves the highest dynamics of composting process, because the total amount of carbon emitted from 1 kg of the Ch1 mixture was 98.7 g (361.9 g CO_2). In contrast, the Ch4 mixture only emitted 50.1 g of carbon (183.9 CO_2) from 1 kg of mixture that was initially used for composting, which is almost a 2-fold lower result.

The occurrence of maximum temperatures from all compost mixtures led to a significant reduction in carbon dioxide emissions being observed, which is consistent with other studies [22,53,65,66].

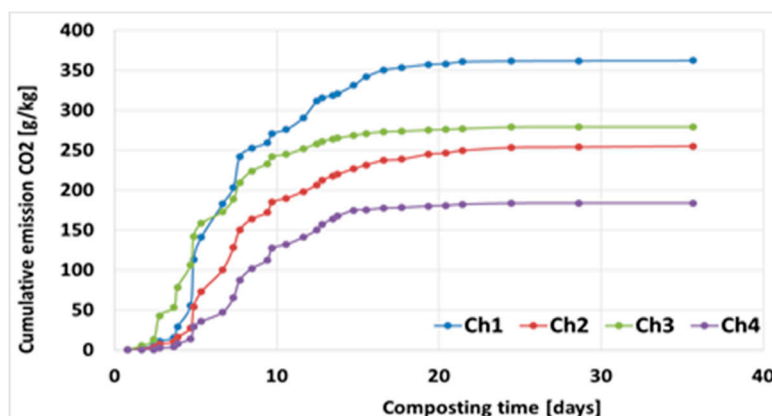


Figure 5. Cumulated CO₂ emission from 1 kg of TS composted mixtures.

When analyzing Figures 4 and 5, it can be seen that the higher the cumulative carbon dioxide emission, the lower the ammonia level. This is especially visible for mixtures of Ch1 and Ch4. This type of dependence was also presented in other studies. For example, as stated in the aforementioned publication, the higher the C/N ratio, the greater the CO₂ emissions from various mixtures with sewage sludge [22]. On the one hand, sewage sludge usually has a high moisture content and a low C/N ratio, providing favorable conditions for ammonia emissions, especially if the C/N ratio is <15 [65]. On the other hand, after the addition of compounds rich in carbon (maize straw) they were transformed into carbon dioxide by microorganisms and were used to immobilize nitrogen, which is important for reducing the loss of ammonia [65,67–69].

4. Conclusions

Based on the obtained results, the following conclusions were formed:

1. Maize straw as a carbon-rich substrate improves the C/N ratio and thus enables appropriate composting of sewage sludge.
2. Maize straw as a bulking agent increased the porosity of the compost mix accordingly. The free spaces in the mixture promoted the correct flow of oxygen, thus ensuring the occurrence of a thermophilic phase.
3. All the examined mixtures reached a strong thermophilic phase of composting; however, the lowest dynamics of temperature growth were observed in the highest sewage sludge content (Ch4, 60% of sewage sludge).
4. The mixture designated as Ch1 was characterized by a high C/N ratio at almost 20, with a high OM content over 86%, but in terms of CO₂ and NH₃ gas emissions (intermediate values between the tested samples) and in terms of economic considerations, the highest cumulative temperature was found and a relatively moderate demand for the carbon source (C/N = 11.6), and so the Ch3 mixture seems to be the most advantageous.
5. An excessively high content of sewage sludge strongly influenced the C/N ratio and losses through ammonia emissions.
6. The concentration of ammonia in the bioreactor chambers was directly related to the content of sewage sludge in the composted mixture. A two-fold increase in the content of sewage sludge in the composted mixture from 30% to 60% resulted in more than a six-times lower ammonia concentration.
7. Cumulative emissions of CO₂ showed the greatest dynamics of substrate mixture decomposition with the highest content of organic matter and C/N ratio. However, its value decreased along with the increase in the content of sewage sludge in the mixture (the mixture with the lowest sewage sludge content).

8. The results of the analyzed parameters showed that the composting process worked properly and that composting maize straw may be a cheap solution in sewage sludge management.
9. It was found that, even with very low air-flow (average air-flow of $2.5 \text{ dm}^3 \cdot \text{min}^{-1}$), but with a regular bottom-up aeration system (by not very high bulk density), ongoing monitoring of exhaust gas concentrations enabled the proper composting of all mix variants.

Author Contributions: Conceptualization, J.M., M.M., W.C.; methodology; validation, J.M., G.Ž., W.C.; formal analysis, J.M., M.M.; investigation, W.C., M.M., J.M.; resources, J.M., W.C.; data curation, J.M., G.Ž., W.C.; writing—original draft preparation, J.M., M.M., W.C., G.Ž.; writing—review and editing, J.M.; supervision, G.Ž.; project administration, G.Ž., W.C.; funding acquisition, G.Ž. All authors have read and agreed to the published version of the manuscript. please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

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