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Article

Gases Emissions during Composting Process of Agri-Food Industry Waste

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Abstract: The vegetable production is an important part of agriculture sector in every country. In Poland, vegetables and fruits production covering the area of no more than 3% of agricultural land, is more than 36% of plant production and 14–15% of the whole agricultural production. The study aim was to determine the management possibilities of the selected waste from vegetable production in composting process. Laboratory tests were carried out using the bioreactor set-up with capacity of 165 dm^3, respectively, for each chamber. The composting process has been tested for the following mixtures: K1—cabbage leaves, tomato dry leaves + manure and slurry additive; K2—cabbage leaves, solid fraction from biogas plant + manure and straw additive; K3—cabbage leaves, onion husk + straw additive. In all three composts the thermophilic phase occurred which indicates that the process ran correctly. In each chamber, the temperature exceeded 70 °C and its maximum value during the experiment was 77.5 °C for K2 compost. The article discusses changes in O_2, CO_2, NH_3 and H_2S emissions during composting. The carbon dioxide concentration in the exhausted gas from analyzed composts and the ratio with oxygen they testify to the decomposition of raw materials in the composting process. The results showed that the agri-food waste can be a proper substrate for composting production. Due to legal regulations and the increase in prices of mineral fertilizers, the development of the compost market should be expected.

Keywords: agri-food waste; waste management; gases emissions; composting process; compost

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1. Introduction

Forecasts made by the United Nations predict uninterrupted population growth for the next 80 years—from 7.9 billion today to nearly 11 billion by the end of the 21st century. [1]. In this context, uninterrupted population growth is also the cause of considerable amount of waste from the agro-food industry [2]. In Poland, vegetables and fruits production covering the area of no more than 3% of agricultural land, is more than 36% of plant production and 14–15% of the whole agricultural production [3]. When harvesting and processing the vegetables large amounts of waste are formed [4]. The source of their origin are unclassified vegetables, non-commercial parts of the plants or processing waste. These wastes are frequently characterized by a considerable moisture level and high content of organic matter [5]. The use of post-production residues from the vegetable sector is a good example of a closed loop economy, which the main aims is the reduce of the carbon footprint [6].

There are many possibilities for managing waste from vegetable production. Some of them will also allow the recovery of energy that is contained in waste biomass. Those processes will allow not only to manage the wastes but moreover will be the actions protecting the environment, which already have gained importance in recent years [7,8]. Biological and chemical processes used today include anaerobic digestion, aerobic digestion, thermophilic anaerobic digestion, composting, gasification, pyrolysis, and incineration [9,10].

Increasingly often are created the installations allowing not only for waste management but also on energy recovery from the waste biomass [11].

The processes of combustion, gasification and pyrolysis are classified as thermal methods of converting matter [12]. The differences that exist between each of the aforementioned processes are primarily the different conditions under which they are carried out and the non-uniform end products [13]. Carrying out the incineration of bio-waste requires supplying significant amounts of energy along with excess air [14]. The resulting end products have no possibility of reuse. A more energy-advantageous process is gasification, which yields a combustible gas that is used in industry. Biomass pyrolysis, in contrast with the other processes, proceeds without air. The resulting products are usually bio-oils characterized by high energy density [12].

One of the biological method of organic waste disposal, which among others includes the agri-food ones is a biogas production [15]. The biogas is obtained in consequence of the methane fermentation process from the substrates placed in the fermentation chamber. It is a mixture of gases among which the methane is dominant. The biggest advantage of this process is the energy yield, both the electricity and [16,17]. The biofuels production from the waste or algae is gaining an importance in recent years, hence it is important to define the processes being the source of energy [18]. The disadvantages include the relatively large investment costs and the need for regular supply of substrates to the biogas plant, so as not to stop the fermentation process [19].

Biological methods such as composting are among the options for use of waste, which is significantly hydrated and high content of organic matter. In addition to high organic matter content, feedstock materials must have an optimal carbon and nitrogen ratio [20]. This process requires the presence of oxygen, however, it occurs naturally under the influence of microorganisms [21]. The compost is a fertilizer rich in organic matter and chemicals desired by plants. Another advantage is reduction of the mass and volume of the waste by water evaporation, which is caused by high temperatures during the composting [22,23]. Moreover the high temperatures will help to improve the sanitary condition of the compost mix [24]. Gaseous emissions during the composting process are a key parameter. The relationship between O_2 and CO_2 showed that the decomposition is correct. Another parameter that allows to assess the decomposition of the composted mixture are the emissions of NH_3 and H_2S.

Taking into account numerous legal and administrative barriers for biogas plants development in Poland [25], an excellent alternative seems to be the management of this type of waste throughout composting process. The main research issue raised in this paper will be the answer to the question: can the waste from the food industry be managed through the process of composting as an alternative to the methane fermentation process. In the literature, there are present the trends talking primarily about the use of this type of waste as a substrate for biogas plants [26,27]. However, in the situation of stagnation of the biogas market and a very small number of waste biogas plants, the composting may turned out to be justified under Polish conditions.

The study aims to determine the management possibilities of the selected waste from vegetable production in composting process. In order to specify the target the following indicators have been selected: temperature, gases emissions from the compost mixtures and content of organic matter in the composts. In order to accomplish this study aim the following research tasks have been taken:

- running the experiments with composting of selected organic waste under laboratory conditions,
- comparison of the composting process occurring in three chosen compost mixtures,
- defining the parameters changes of the obtained composts in comparison with initial material.

It should be emphasized that the novelty of the presented research is the combination of the analysis of the intensity of composted materials aeration with changes in their bed temperature and gaseous emissions from analyzed substrates. These are, in particular, important relationships that affect the process because inadequate (too strong or too weak) aeration is the most common cause of incorrect composting process and, consequently, strong gas emissions (methane, ammonia or nitrous oxide) and poor quality compost.

2. Materials and Methods

2.1. Time and Research Place, Experiment System

The research were carried out in the Ecotechnologies Laboratory placed at the Poznań University of Life Sciences (PULS). The composting process has been tested for the following mixtures:

K1—cabbage leaves, tomato dry leaves + manure and slurry additive;

K2—cabbage leaves, solid fraction from biogas plant + manure and straw additive;

K3—cabbage leaves, onion husk + straw additive.

The weight proportion of the substrates and initial parameters are presented in Table 1.

Table 1. Share and the properties of the composted components.

	Initial Parameters of the Substrates *					Share in the Mixtures [kg F.M.]		
	C:N	D.M. [%]	O.D.M. [%]	pH	Cond [mS·cm^{-1}]	K1	K2	K3
cabbage leaves	20.1	11.3	90.3	5.94	0.12	20	20	20
tomato dry leaves	29.2	76.8	70	6.35	11.9	10	-	-
solid fraction from biogas plant	26.7	32.5	92.9	9.07	1.29	-	20	-
onion husk	42,0	20.9	72.8	8.49	1.03	-	-	20
cattle manure	22.1	15.2	70.3	8.37	2.19	3	3	-
cattle slurry	17.4	1.7	40.7	8.5	18.22	3	-	-
straw	88.0	85.6	96.1	7.7	0.69	-	1.5	2

* D.M.—dry mass; F.M.—fresh matter; O.D.M.—organic dry matter; cond—conductivity.

Numerous scientific research confirmed the suitability of various bioreactors for laboratory tests [28]. Laboratory tests were carried out using the bioreactor set-up with capacity of 165 dm^3, respectively, for each chamber. The bioreactor chambers (with 10-cm of styrofoam layer for heat insulation) provided the proper conditions for the composting process run, and the process was conducted regardless the weather conditions, which very often have a significant impact on the composting process [29]. The design and diagram of the bioreactors are shown in Figures 1 and 2.

The total fresh weight of the mixtures intended for composting was 36 kg (K1), 44.5 (K2) and 42 kg (K3). In each of these mixtures, the base substrate was cabbage leaves (20 kg fresh weight), supplemented by other organic waste (10 kg tomato dry leaves in K1, 20 kg of solid fraction from biogas plant in K2 and 20 kg of onion husk in K3).

On the other hand, the dry weight of individual mixtures used in the substrates was 10.46 (K1), 10.5 (K2) and 8.15 (K3), which can be calculated on the basis of Table 1.

Certain differences in the content of both fresh mass and dry mass resulted from a very prosaic reason: different bulk mass of individual mixtures and bioreactor chambers of the same volume (165 dm^3), as well as a completely different dry mass content in the main materials used for the experiment (from cabbage leaves having 11.3% of DM to tomato dry leaves with 76.8% of DM).

Figure 1. The design of two chambers bioreactor to study the composting process.

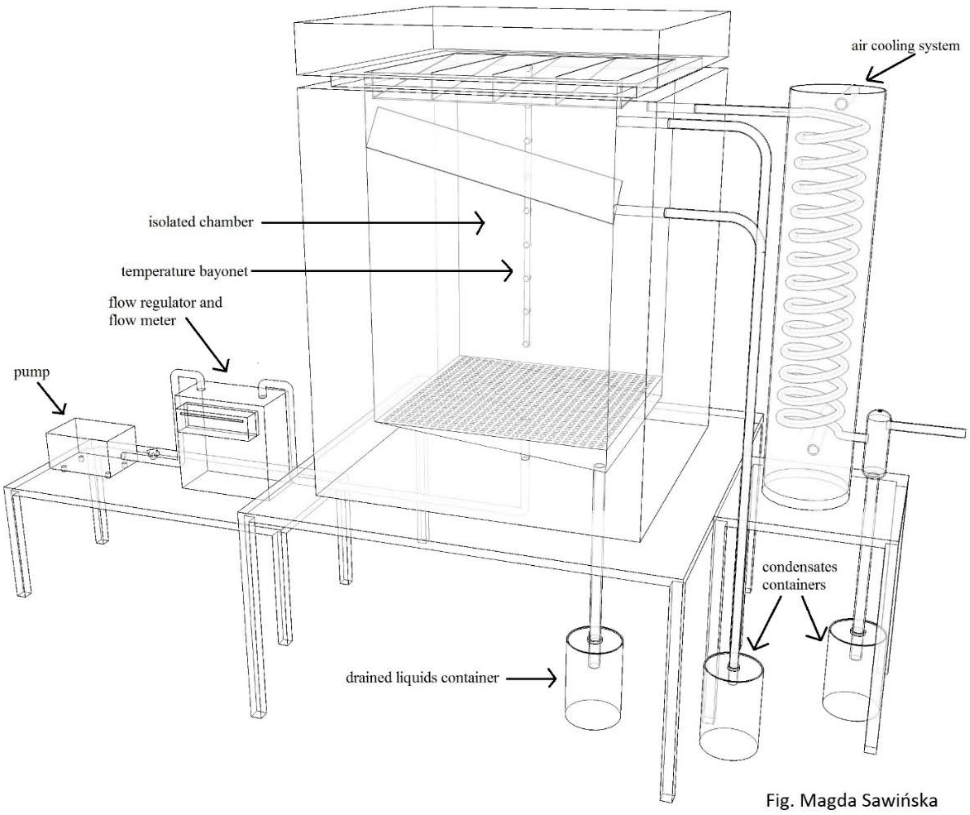

Figure 2. The scheme of the bioreactor used for studying the composting process.

2.2. Air Flow and Gases Measurements

During the experiment the air flow was regulated in the range of 2–4 dm^3/min. It has been checked at least twice a day (rotameter and flowmeter) in order to maintain the proper oxygen conditions in the air outgoing from each chamber. In case of approaching the limit value of 5% of the oxygen in the gases exhausted from the bioreactor chambers, the amount of the pumped air was increased so anaerobic conditions did not occur. The air flows in the reactors are shown in Figure 3.

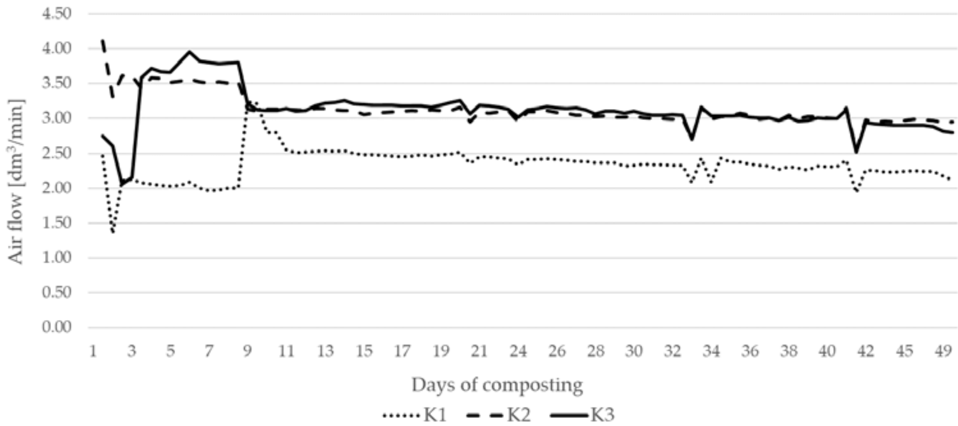

Figure 3. The air flow entering the bioreactors.

During the composting the composition of the air escaping from the composting chamber has been studied. The measurements were accomplished using a gas analyzer GA5000 Geotech company. This device allowed the analysis of the five gases at concentrations: CH_4 0–100%, CO_2 0–100%, O_2 0–25%, NH_3 0–1000 ppm, H_2S 0–10,000 ppm. Once a week, with use of calibration gases it has been checked the accuracy of the measurements using calibration gases from the Air Products company. If necessary, the device was calibrated using the same gases.

2.3. The Measurement and Analysis of the Other Process Parameters

- Temperature measurements in the composted material

Temperature measurements were made automatically using a specially-designed tool. It was so-called temperature bayonet—the rod with nine sensors (PT-100) spaced apart by 5 cm. This arrangement allowed to test the temperature in the whole layer and not only in one of its points. So designed bayonet was placed in the middle of the bioreactor. The measurements were recorded on a computer at intervals of 8 h.

- Sampling and analysis

The compost samples were taken in order to investigate the changes in physic-chemical parameters at the beginning of the experiment, at the end, and during aerations. In order to obtain the representative results the material was taken from different places of the reactor chamber. All tests were performed at the Department of Biosystems Engineering (Poznań University of Life Sciences).

- pH and conductivity measurements

In order to measure the pH and conductivity every time 20 g of substrate was weight into the beaker and then refilled up to 200 g with distilled water. After 15 min there was a measurement using previously calibrated multifunction device CX-401 from Elmetron company, Zabrze, Poland.

- Defining the content of dry mass and dry organic mass

The measurement of the dry mass was performed using a dryer–drying in the temperature of 105 °C for 24 h. Dry organic mass was determined while the muffle furnace (temperature 520 °C). The measurement was performed in three replications.

- Mass and bulk density measurements

At the beginning of the experiment, at the end and during the aeration the measurement was performed using the scale. This allowed to determine the mass loss during the experiment. On the basis of mass changes and changes of the compost piles height, inside the reactors was measured bulk density of the compost.

3. Results and Discussion

3.1. Temperature Changes

The basic and one of the most important parameters indicative of the proper composting process run are temperatures changes during its course [24,30]. The temperature proves the changes occurring in the substrate mixtures. If composting process ran correctly there must occur the thermophilic phase with temperature exceeding 60 °C for a minimum of 48 h. This will allow the rapid decomposition of organic matter, and also will kill a significant amount of pathogens in the composted material [31].

In the conducted experiment the temperature above the discussed earlier limit occurred in all tested mixtures. High temperatures remained the longest in the chamber K2 which took about 4 days. The highest temperature of all analyzed was 77.5 °C and also was characteristic for K2 chamber (Figure 4). The high temperature results were typical for composting process, which has been described in many studies by other authors Luo et al. [32], Miyatake and Iwabuchi [33] and Macias-Corral et al. [34].

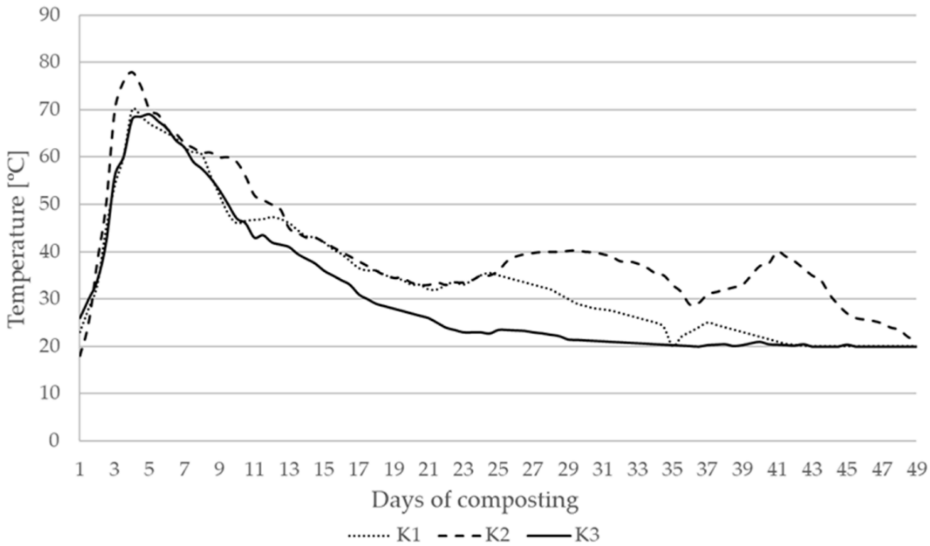

Figure 4. Temperature changes in analyzed composts.

The course of changes in the concentration of O_2 and CO_2 in the K1 chamber differs significantly between the 7th and 11th day of the process from the other chambers. The K1 chamber of the bioreactor was loaded with the smallest amount of substrates (the total mass is 36 kg compared to 44.5 kg in K2 and 42 kg in K3). Hence, in the first 7 days after the start of composting, the air flow set for the K1 chamber at the level of approx. 2 dm^3/min was sufficient to ensure both an intensive increase in temperature (Figure 4) and the oxygen concentration inside the bioreactor chamber at a level well above 10% (Figure 5). However, on the 7th day of composting, the sharp decrease in the oxygen content in the gases leaving the reactor chamber K1 was observed, and at the same time an equally rapid increase in carbon dioxide was noticed. This can be related to the rapid decomposition of tomato dry leaves taking place at that time (observed visually during the periodic opening of the chambers to collect samples), which took several days to enter the stage of intense decomposition. The decrease in the oxygen level in the chamber below 5% (Figure 5) made it necessary to increase the amount of flowing air (Figure 3).

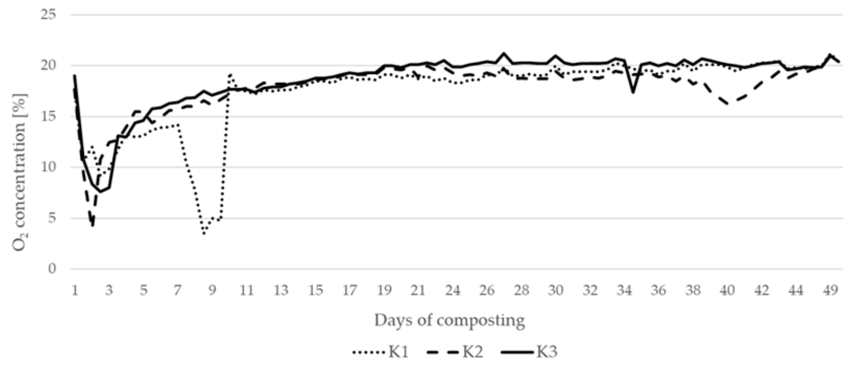

Figure 5. Concentration of the oxygen in the exhausted gas in analyzed composts.

The additional aeration (mixing of whole material) was carried out in the 35th day of the experiment, when the temperature in each of three tested mixtures has fallen below 30 °C. This process aimed to improve the structure of the mixture and deliver a significant amount of oxygen. It is expected that after aeration, the temperature should rise again above that which prevails in the environment. If such an increase will not occur, it can be stated that composting process is over and there will be no further intensive decomposition of organic substrates. In the analyzed experiments, the desired effects of additional aeration/mixing were only in the chamber K2. After 5 days since the aeration the temperature exceeded 40 °C and remained at this level for two consecutive days. In the first chamber the temperature rose slightly settling peak at 26.4 °C. In chamber no. 3 there was no significant increase noted after the aeration (Figure 4).

3.2. Changes of Gases Emissions

Gaseous emissions from the composting piles are equally important parameter informing about the proper course of composting process as the temperature changes [35]. Among the gases in the reactor chamber the most important are oxygen and carbon dioxide. It is the presence of the first one in excess of 10% that influences the process correctness. When its concentration falls below 5% can develop anaerobic conditions that cause rotting of the compost [36]. The evidence of this is mainly the appearance of the methane at the level of 0.1% and the hydrogen sulfide in concentration from about 200 ppm and higher. In the analyzed compost mixtures no methane emissions were measured, and the oxygen flow was maintained at the level of 10%. In the second chamber (K2), wherein the process run most rapidly the oxygen concentration fell below 5% on the second day.

This proved a very rapid decomposition of organic materials by the microorganisms. After a decline below 5% the flow of the air entering the chamber increased from 2 dm^3/min do 3.5 dm^3/min so to avoid rotting (Figure 3). The similar situation took place in the first chamber (K1), however it occurred much later (7th and 8th day) than in the second and third chambers. This proves that the thermophilic phase also run clearly however after a long time than it was in the other reactors. The lowest concentration of oxygen in the third chamber took place on the second day and amounted 7.6%. Those changes are shown in Figure 5. The oxygen concentrations in mixtures are dependent mainly on substrates which are the composition of the feedstock for composting. In studies Luo et al. [32] for example, concentrations below 15% occurred over a longer period of time. Similar results in the oxygen content have been demonstrated in research of Xu et al., [37] where the substrate was the cattle manure.

The emission of carbon dioxide is an important parameter of biological changes [38]. Its level is closely correlated with the oxygen values. This is due to the fact that the sum of the concentrations of those gases should be close to their sum in the atmospheric air. After intensive phase involving heat release and significant emission of carbon dioxide the levels of CO_2 started to decrease. First it was in the chambers 2 and 3 and after day 7th also in the first reactor (Figure 6). The 40th day of composting was noticeable relatively large peak for the curve of the second reactor. It shows an increased decomposition of organic matter, which was caused by additional aeration by mixing of whole material in 35th day of the experiment.

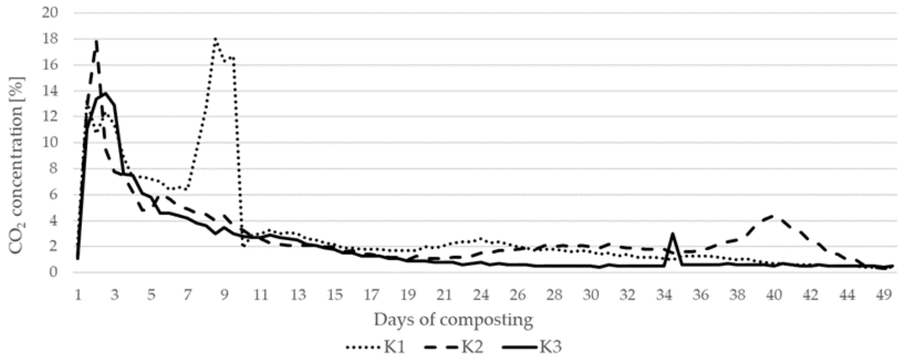

Figure 6. The carbon dioxide concentration in the exhausted gas from analyzed composts.

A specific gas produced mainly by the decomposition of the proteins (including the amino acids) is ammonia. As it is well known, the use of natural fertilizers such as slurry or manure is related to the emissions of this gas into the environment. There is no difference in the case of organic fertilizer that is compost. Thus, the fertilizers management can be a real threat to the functioning of ecosystems and the biosphere [39,40]. This concerns not only fertilizers but also other types of biomass from agriculture or agri-food industry [41].

The detection limit for the discussed gas is within the range of 15–25 ppm. Above 400 ppm are visible symptoms such as irritation of the eyes and respiratory tract [42]. Hence, it is important to control this gas both in reactor composting and in piles. In the reactors this gas can be captured and purified which should not be carried out in piles in the open air. As it is shown in Figure 7 the ammonia emissions in composted vegetable waste were significantly high during the first week of composting. For the first chamber the maximum emission was 295 ppm (4th day), and for the second reactor 332 ppm in the third day. In the third chamber the maximum emission was 146 ppm. The values of ammonia in all studied cases were relatively high and, if longer exposure could be harmful to humans. In case of composting in reactors it is necessary to purify the gases prior to the air introduction to the atmosphere.

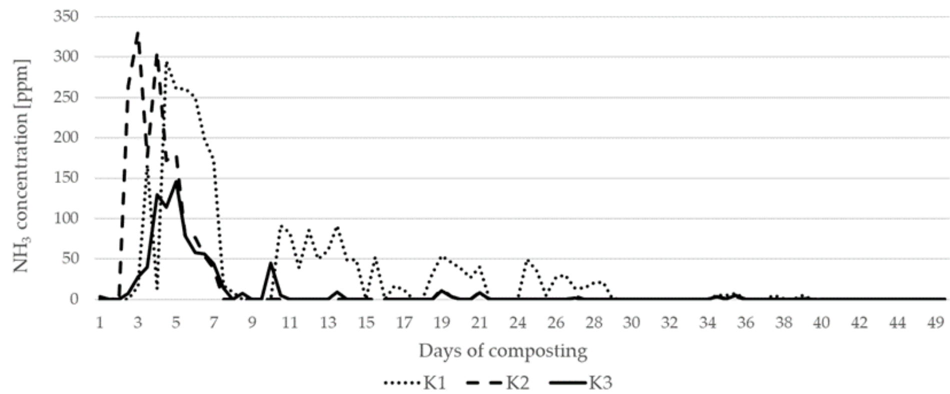

Figure 7. The ammonia concentration in the exhausted gas in the analyzed composts.

It should be noted that the lowest level of ammonia concentration in the bioreactor chambers was recorded for the K3 mix. It is a mixture consisting largely of high carbon materials (onion husk and straw), having at the start of the experiment by far the highest level of C:N (46.6) compared to K1 (26.5) and K2 (33.0). So if C:N increases, the level of ammonia emitted decreases. Therefore, in the case of industrial composting, it is beneficial to add substrates with an increased carbon content.

The last of the analyzed gas was the hydrogen sulfide. It is a chemical non-organic compound, resulting from the decomposition of organic matter rich in sulfur-containing compounds (such as cystine and cysteine). The detection threshold of this gas is as low as less than 1 ppm. Already at a concentration of about 100 ppm may be eyes irritation and loss of smell, and concentration of 1 mg/m^3 issues directly death after seconds. Hence it is so important to control the amount of the fold-up substrates. This gas is undesirable not only because of the harmful effects on humans but also because of the environmental conditions for bacteria decomposing the substrates. In the composted waste the hydrogen sulfide emissions were not very strong (maximum 57 ppm in 2nd chamber) and happened practically only in the first five days for all of the analyzed compost mixtures (Figure 8). Other issues were purely individual and showing no trends.

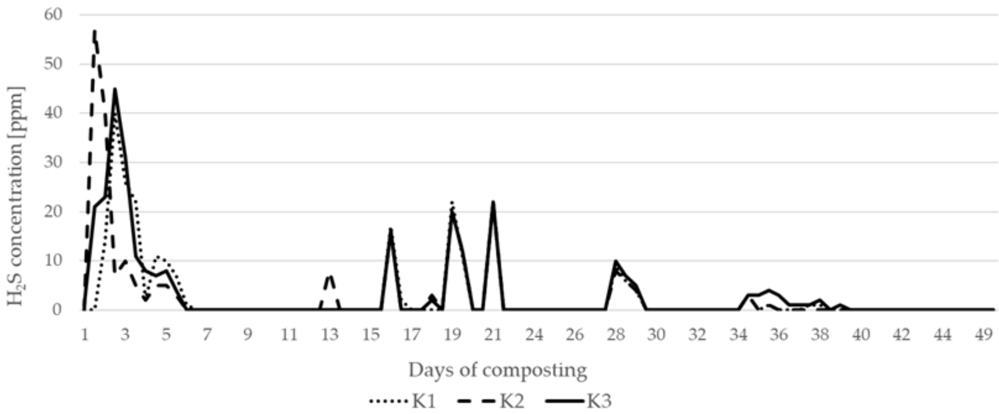

Figure 8. The concentration of hydrogen sulfide in the analyzed composts.

3.3. Changes of the Other Parameters

Temperature changes, including in particular the occurrence of thermophilic phase are certainly the most important criterion determining the course of the composting process [43]. In addition, the important parameters are relations in the concentrations of oxygen and carbon dioxide in the air issuing from the pile [44]. It is worth to remember that there are other indicators and their changes also provide us with valuable information about the process [45]. One of them are the changes of the substrate fresh mass, dry mass and dry organic matter [46].

In the composting process over the time the mass of the composted material should reduce. The reason for this is primarily the water loss due to the high temperature, and mass loss due to the decomposition of organic matter [47,48]. In all three chambers, such changes were observed. The highest mass loss of about 40% was observed in the third chamber where the main substrate beside the cabbage leaf was a husk onion. For the chambers 1 and 2 loss was at a similar level and amounted, respectively, 38.3% and 39.3%.

In the samples collected from all of the reactors was also observed a decrease of organic matter, and the growth of mineral matter. This indicates that the substrates have been partially degraded [49,50]. The largest change of this parameter occurred in the third compost where the difference at the beginning and end of the experiment was 28.82% (Table 2).

Table 2. Parameters changes during composting process.

Reactor	Time	F.M. [kg]	D.M. [%]	O.D.M. [%]	ρ * [kg·m^{-3}]	pH [-]	Cond [mS·cm^{-1}]
K1	Start	35	29.8	74.81	275	6.63	5.16
	Aeration **	23	26.44	55.25	484	8.36	6.77
	End	21.6	26.6	52.86	515	8.02	7.14
K2	Start	44.5	23.6	92.41	349	8.36	0.53
	Aeration	31.2	17.75	81.17	444	9.08	9.39
	End	27	17.78	78.93	483	8.74	1.68
K3	Start	42	19.4	82.29	336	7.75	0.65
	Aeration	28.8	17.57	56.22	720	9.07	1.03
	End	25.1	18.87	53.47	743	9.42	1.52

* ρ—apparent density; ** Additional aeration made by mixing of whole material at 35th day.

4. Conclusions

In all three analyzed mixtures where the major substrates were waste from the agri-food industry the composting process run correctly. This is evidenced by the temperature changes and relations between oxygen concentrations and carbon dioxide in the air flowing out from the bioreactor chambers.

The confirmation of the previous conclusion are also changes of other parameters such as weight loss or increase of the content of mineral matter in the compost analyzed at the end of the experiment.

Analyzing the results obtained in the composting process it can be stated that selected organic waste from the vegetables production can be managed by composting process.

This will certainly be a good alternative to the problems in the development of the biogas market in Poland. However, taking into account the high water content in this type of waste it should be remembered to provide the proper conditions for the process by the addition of substrates such as straw and manure.

Poland (similar to many EU countries with developed vegetable cultivation) is a producer of a large amount of vegetable waste. As a result of the described research, it was shown that it is possible to produce compost from various vegetable mixtures–provided that the appropriate starting parameters for composting are maintained and the process is maintained in aerobic conditions. The compost produced in this way can be a valuable material for fertilizing, in particular in the current increase in the prices of mineral fertilizers in the EU and the general tendency to increase the use of organic fertilizers.

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