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The Effect of Heat Removal during Thermophilic Phase on Energetic Aspects of Biowaste Composting Process

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Abstract: Composting is the natural, exothermic process where the huge amount of heat that is created is an issue of organic matter decomposition. However, too high temperature can reduce the microbial activity during the thermophilic composting phase. The aim of this study was to analyze the effect of heat excess removal from composted materials on the process dynamic. The experiment was performed in two parallel bioreactors. One of them was equipped with a heat removal system from the bed of the composted material. Three experiments were carried out with mixtures of different proportions: biological waste, wheat straw, and spent coffee grounds. The content of each option was determined based on a previous study of substrates to maintain the C/N ratio for the right composting process, provide adequate porosity composted material, and enable a proper degree of aeration. The study showed the possibility of receiving part of the heat from the bed of composted material during the thermophilic phase of the process without harm both to the course of composting and the quality of the final product. This shows that at a real scale, it can be possible to recover an important amount of heat from composted materials as a low-temperature heat source.

Keywords: composting; coffee grounds; heat recovery

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1. Introduction

1.1. Composting as an Exothermic Method of Biowaste Processing

Composting is one of the safest and most natural methods for managing biological waste [1]. The composting process leads to weight and volume reduction of the biological waste, as it removes pathogens, parasites, and weed seeds [2]. In addition, the end product of composting is compost rich in organic matter and humic acids, being an excellent natural fertilizer used in agriculture [3]. It is the biological process of decomposing organic materials, mainly by bacteria and fungi, which produces carbon dioxide, water vapor, and a large amount of energy in the form of heat, unlike methane fermentation, where energy is released in chemical form (in CH_4 form) [4]. Composting is one of the best, most effective, and cheapest methods of managing a wide range of organic waste materials [5]. Unlike another biological process—fermentation, the composting process can also process materials with a very high content of lignocellulosic compounds—i.e., wood and its waste [1]. In addition, compost produced from agricultural biomass has a much more positive effect on the soil characteristics compared to the usage of digestate from biogas plant, which has reduced organic matter content [6].

However, in order for the composting process to proceed correctly, several conditions must be met. First of all, the fundamental parameter of an appropriate composting process is the occurrence of the so-called thermophilic phase, i.e., a 2–4-week period with the temperature inside the compost from a given material at a level above 45 °C [7]. However, it should be emphasized that under appropriate conditions, the composted material can heat up to over 80 °C. High temperature during the thermophilic phase causes the decomposition of materials that are difficult to decompose (e.g., lignin) and affects the loss of weight due to the intense emission of water vapor and CO_2 [8]. It should be emphasized that elevated temperature also has a hygienic effect on composted waste materials and is also likely to break down chemical pollutants such as antibiotics, pesticides, hormones, and drug residues [9].

The correct course of the biological waste composting process depends on many factors, the most important of which are temperature [10], humidity [11], C/N ratio [12,13], porosity [14], and aeration [15]. A crucial initial parameter influencing the dynamics of the composting process is the C/N ratio, because the lack of nitrogen limits the intensity of the process, while the excess of N affects ammonia's intensive emission. Many researchers have underline the crucial influence of C/N ratio on the proper run of the composting process, showing negative effects of too low as well of too high values of this parameter [16].

The composting process consists of four main phases that are microbiologically different, which are identified depending on the temperature. These are the mesophilic phase, the thermophilic phase, the cooling phase, and the maturing phase [17]. The four phases may overlap partly. In the thermophilic phase, the highest activity of microorganisms and therefore the highest degree of degradation of biological material occurs between 50 and 60 °C [18]. The thermophilic phase of the composting process involves the action of microorganisms that process biological material, which generates large amounts of heat [19]. The temperatures of compost heaps with limited or zero air access can be as high as 90 °C [20]. However, temperatures above 65 °C lead to a decrease in microbial activity, which slows down composting processes and prolongs the biodegradation of waste [21].

The possibilities of receiving heat from the composting process have long been known, beginning with the systems used in China 2000 years ago. Smith et al., 2017 [22] carried out an extensive review of the structure of systems, the recovery factor, and the use of heat recovered from composting. There are three approaches to obtaining heat from composting: the direct utilization of heat from compost steam, heating by the conduction of heat exchangers inside a stack [23], and capturing latent heat using compost steam and a condenser heat exchanger [24]. Commercial applications of energy recovery from the composting process and the use of heat have been described in several articles [23,25]. In the practice found on a real-scale composting plant, researchers found that during the winter, heat recovered from working reactors is used to increase the temperature of air pumped to starting reactors in order to accelerate the process.

1.2. Materials for Composting

Composting is a process that allows the processing of a very wide range of different types of biological materials [26]. This process is particularly dedicated to processing various types of more or less burdensome organic waste into a stabilized and environmentally friendly compost [27]. It is worth emphasizing that composting is a very stable process, and microorganisms are resistant to various contamination types in organic waste [28]. Therefore, this process is dedicated to processing such waste materials as municipal sewage sludge, kitchen waste, expired and spoiled food, animal excrement, and even carcass (outside the EU, where the disposal of the carcass in the composting process is not prohibited) [29,30]. Many examples from economic practice show that the management of nuisance waste in the composting process can bring companies many financial benefits—on the one hand, thanks to the fees for taking the waste, and on the other hand, thanks to the revenues for selling the compost [31,32]. However, it should be noted that the price of compost is related to accessible nutrients and organic matter content [33].

In practice, the right solution is to compost materials with different parameters, i.e., substrates with high and low nitrogen content (such as poultry manure and wood chips), moist and dry (such as stillage and onion husk with the addition of maize straw), or also with high and low bulk density (e.g., sewage sludge and straw) [34,35].

The physicochemical properties of composted biological waste necessitate the use of various natural additives to improve the composting process [36]. Different organic compositions, such as biochar, wood bark, straw, leaves, spent coffee grounds, and inorganic materials, such as zeolites, lime, and minerals, are added to the compost as bulking agents [37–39].

Coffee is one of the most popular beverages in the world and the second most traded commodity after crude oil [40]. In 2018/19 (crop year), global coffee production exceeded 10.26 million tons [41]. One kilogram of coffee beans generates 0.91–1.2 kg of spent grounds, depending on the brewing method [42]. Such a large quantity of coffee waste generates significant environmental consequences on a global scale [43]. Coffee is brewed with the use of various methods in households and catering outlets, and pure grounds are rarely produced. In most cases, spent coffee grounds are mixed with other biological wastes from restaurants and households, which makes them a suitable material for composting.

The composition of the coffee grounds is as follows (as reference value [g/100 g dry matter (DM)]): total carbon—47.8–58.9 [44,45]; total nitrogen—1.9–2.7 [46,47]; cellulose—8.6–12.4 [46,48]; hemicellulose—39.1 [46]; lignin—23.9–33.6 [46,49]; fat—2.29 [46]; ash—1.3–1.43 [46,49] and protein (g protein/100 g)—6.7–17.44 [46,50].

Coffee grounds are abundant in organic compounds, which makes them suitable material for a variety of applications, including:

- Composting [12,51,52],
- Biodiesel production [53,54],
- Pellets and briquettes production [55–57],
- Source of sugar [58],
- Production of activated carbon [59],
- Sorbent for removing metal ions [60,61],
- Ethanol production [62,63], and
- Mushroom growing medium [64,65].

Spent coffee grounds constitute organic waste whose decomposition requires significant quantities of oxygen, thus posing a considerable burden on the natural environment. Coffee grounds can be partially toxic due to the presence of polyphenols, caffeine, and tannins. Composted coffee grounds undergo fermentation due to their high moisture content, which increases the risk of spontaneous ignition [66]. Coffee grounds should be processed to prevent environmental hazards. The addition of non-composted spent coffee grounds may adversely affect the activity of microorganisms in the soil [67].

Heat is partially accumulated in waste, and it increases the temperature of composted material. A drop in the warmth of composted matter by several to more than ten degrees (while maintaining the lowest temperature threshold for the thermophilic phase at 55 °C) does not inhibit the composting process. It supports partial heat recovery [68]. Maintaining the temperature value has a positive effect on the speed of the composting process. Receiving too much heat can cool the compost pile and slow down the degradation of biological material [69].

The aim of this study is to analyze the effect of heat removal during the thermophilic phase on the energetic aspects of the biowaste composting process. The basic tested materials were cabbage leaves with wheat straw, and this mixture was supplemented by different additions of spent coffee grounds. Knowing that composting is a strongly exothermic process, we can assume that in the real-scale installation, it could be possible to recover the significant amount of ecologic heat, which actually is practically never used.

2. Materials and Methods

The experiment was performed in two parallel bioreactors. Adiabatic sealed bioreactors with a working volume of 30 dm^3 each, equipped with a controlled aeration system, were used in the experiment. The bioreactors were provided with a sensor system for controlling temperature distribution in the analyzed compost heap and measuring the moisture content of emitted gases. The content of oxygen, carbon dioxide, methane, sulfur compounds, and nitrogen compounds were measured with a portable gas analyzer (GA5000, Geotech), and the results were automatically recorded in a computerized data acquisition system. One of the bioreactors was equipped with a dedicated heat removal system where the heat exchanger was designed to evenly receive heat from composting material during the thermophilic phase of the process (Figure 1). It has to be underline that this heat removal system was the key element for the realization of the planned experiment in order to reach the aim of the study.

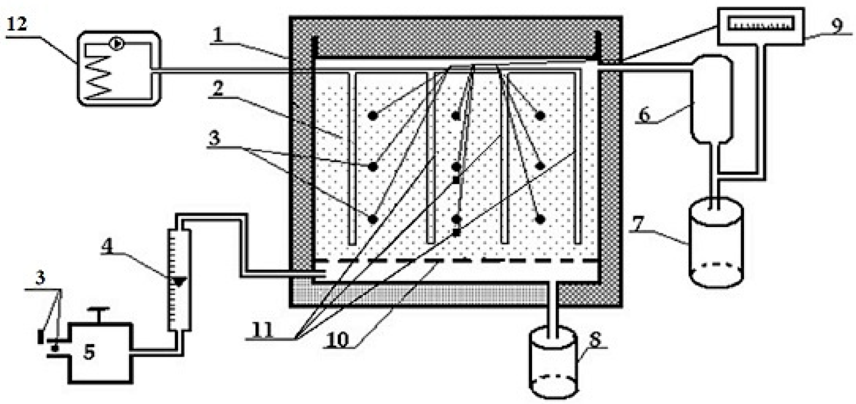

Figure 1. Schematic diagram of the system for laboratory composting with heat collection capability. 1—bioreactor, 2—compostable materials, 3—temperature sensors, 4—flow meter, 5—air pump with flow regulator, 6—air cooler, 7 and 8—condensate and leachate collectors, 9—gas analyzer, 10—perforated plate, 11—heat exchanger, 12—system of circulation and measurement of collected heat.

The heat removal system consists of a heat exchanger placed inside the composted material in the form of properly shaped tubes. Water with a variable flow rate is pumped through the heat exchanger. The flow rate depends on the temperature inside the bed of the composted material. We measured the temperature difference (with accuracy ±0.5°) of water at the outlet and at the inlet of the heat exchanger. The temperature difference and the amount of water flowing made it possible to calculate the amount of heat received.

Data from the literature [70,71] were used to set the optimal temperature at which heat can be received without compromising the composting process or the quality of the produced humus. The amount of received heat was computed by the metering system. Błaszczyk and Fit [71] and Neugebauer et al. [72] processed the results of several studies investigating the rate of carbon dioxide production, oxygen consumption, and biomass loss during composting at different temperatures. The microbial activity was highest at a temperature of 55–65 °C. Błaszczyk and Fit [71] indicate that this is the optimal temperature range for most thermophilic microorganisms.

The materials used in the described research were analyzed before the experiment within the following methods (always in three repetitions): Total Solids—TS, within the Polish Norm PN-75 C-04616/01 (drying in 105 °C by 24 h), organic matter (Volatile Solids, VS) content was analyzed within the norm PN-Z-15011-3 by combustion in 525 °C by 3 h and pH within the norm PN-90 C-04540/01. Total carbon (C) and total nitrogen (N), which are indispensable for C/N ratio calculation, were determined using a Perkin Elmer Series II 2400 autoanalyzer with a thermal conductivity detector (TCD). The basic characteristics of the materials used in the composting experiments are presented in Table 1.

Table 1. Characteristics of materials used in composting experiments.

	TS (% FM)	VS (%TS)	Nitrogen (g/kg TS)	pH	C/N Ratio (-)
Cabbage leaves	9.11	90.3	21.0	5.91	20
Wheat straw	95.3	88.9	3.4	6.96	125
Coffee grounds	49.3	48.4	27.3	6.20	21

Three experiments were conducted simultaneously with three batches of mixed biological waste composed of cabbage leaves, wheat straw, and coffee grounds. Identical biomass mixtures (MIX1, MIX2, and MIX3) were composted simultaneously in two bioreactors (bioreactor one, without heat removal system and bioreactor two, with heat removal system). The composition of each mixture presented in Table 2.

Table 2. Composition of composted biological material.

	Cabbage Leaves (kg)	Wheat Straw (kg)	Coffee Grounds (kg)	C/N Ratio (-)
MIX1	10.0	1.0	0.0	35
MIX2	10.0	1.0	1.0	29
MIX3	10.0	1.0	2.0	27

Before composting, biological wastes were ground and mixed to increase their porosity and promote aeration. Moisture content was determined using a moisture analyzer RADWAG MAC 50/NH. The moisture content of the composted batches ranged from 62% to 68%. The composted material had a C/N ratio of 27 to 35 (Table 2). The heat recovery system installed in one of the bioreactors was automatically activated when the temperature inside the compost heap exceeded 55 °C. The coolant flow rate increased with temperature. The heat recovery system was automatically shut down when the temperature dropped below 55 °C. The level of aeration was determined based on the literature [39,72]. All batches were supplied with air at the rate of 0.15 $m^3 \cdot h^{-1}$, and external temperature was determined at 20 °C.

It has to be underlined that at the real industrial scale, the high costs of biowaste treatment by the composting process can be reduced if the heat generated during the thermophilic phase of the process can be recovered and used as a low-temperature heat source.

3. Results

3.1. Temperature

Microorganisms decomposing organic matter produce significant quantities of carbon dioxide and heat. The temperatures in each bioreactor filled with various types of biological wastes are presented in Figures 2–4. The temperature in the bioreactor without heat recovery is denoted as Series1, and the temperature in the bioreactor with heat recovery is denoted as Series2. In bioreactors without heat recovery, temperatures similar to those presented in the literature were reported [72,73]. In each case, a significant influence of coffee grounds addition on the composting process was observed, especially on the dynamics of temperature increase in the initial phase of the composting process. In the case of the MIX2, the temperature of 55 °C was recorded as early as on the sixth day of the experiment, when for MIX3, it was on the eighth day, and for MIX1, respectively, it was on the ninth day of research (Figures 2–4). There were also significant differences in the maximum temperatures that were noted in the bioreactors without a heat collection system: MIX2—80 °C, MIX3—75 °C, MIX1—64 °C. The results of the experiment indicate that the addition of coffee grounds to biological material can stimulate the composting process. In the case of the MIX2, the addition of 1 kg of ground coffee increased the maximum temperature during the thermophilic phase by 23 °C compared to the maximum temperature for MIX1. For MIX3, the maximum temperature during the thermophilic phase was only 10 °C higher than for MIX1, suggesting that the addition of 2 kg of ground coffee was excessive, resulting in a less favorable C/N ratio than in MIX2.

In all three mixtures, the thermophilic phase of the composted material was prolonged when the composted mixture was cooled and maintained at a temperature of 55–65 °C: one day for MIX1 and MIX3, and two days for MIX2.

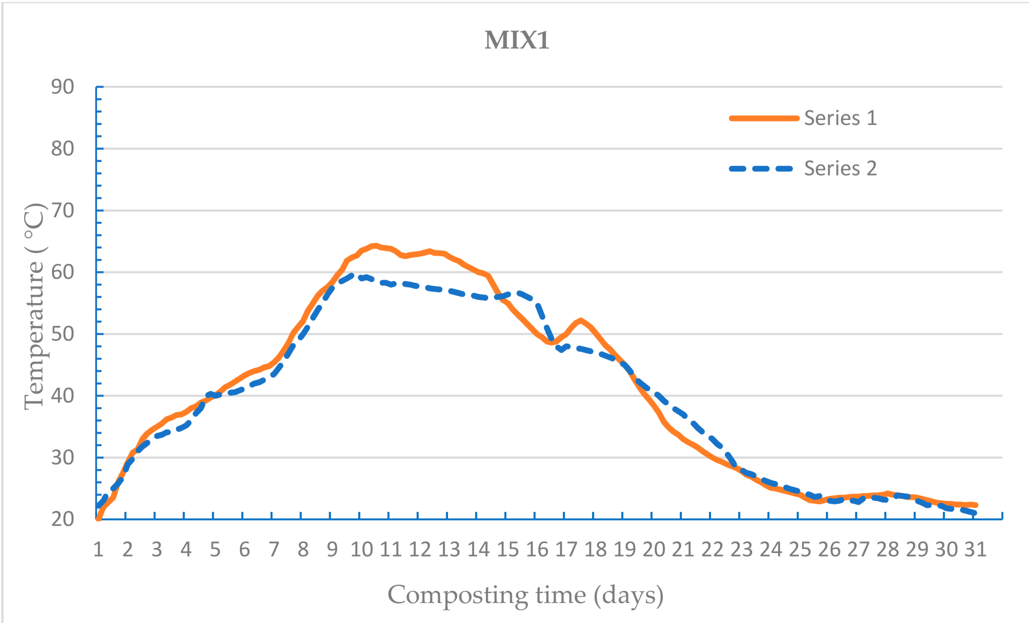

Figure 2. Changes in temperature during the composting of MIX1.

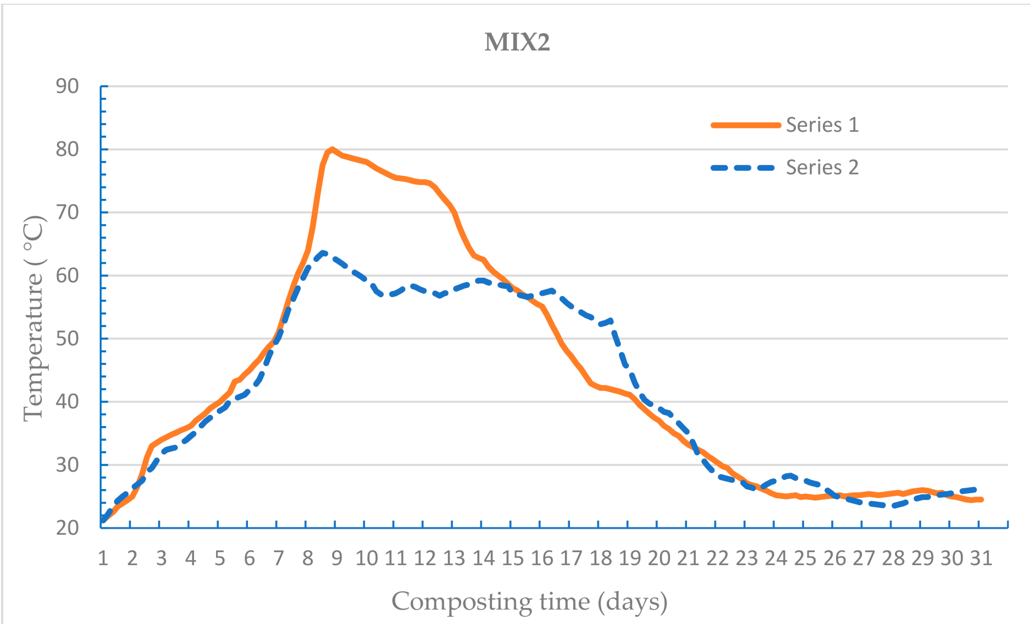

Figure 3. Changes in temperature during the composting of MIX2.

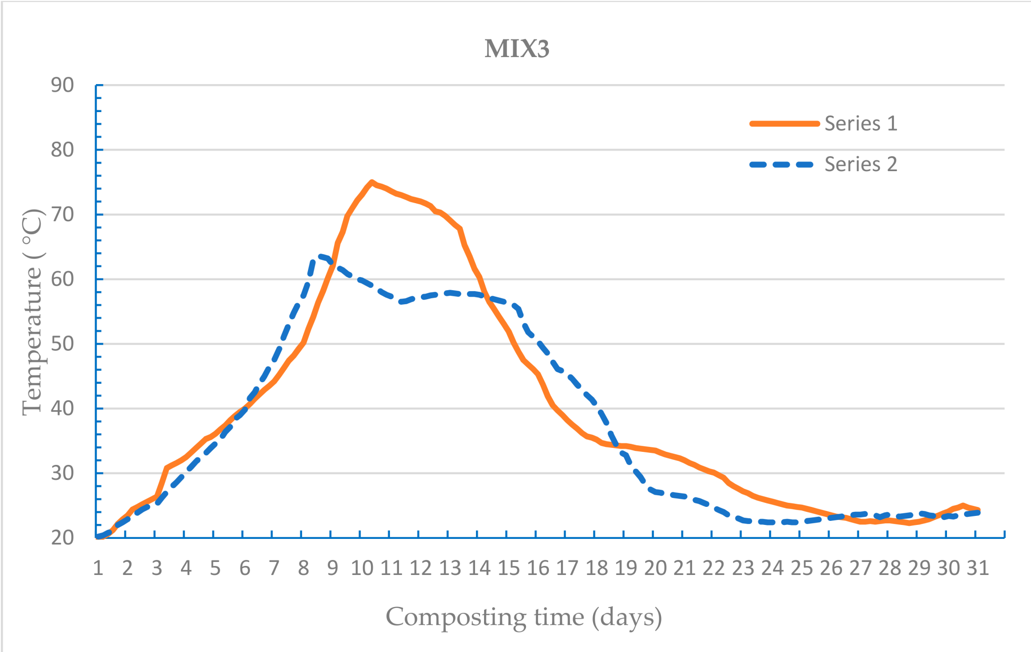

Figure 4. Changes in temperature during the composting of MIX3.

3.2. Carbon Dioxide Emissions

The amount of carbon dioxide in gas emitted from composted waste is an indicator of the activity of thermophilic microorganisms, which metabolize biomass by consuming oxygen and producing carbon dioxide. The content of carbon dioxide in the exhaust gas produced by each bioreactor for each type of composted waste is shown in Figures 5–7. Series1 represents the content of carbon dioxide in exhaust gas produced by the bioreactor without heat recovery, and Series2 denotes the amount of carbon dioxide in exhaust gas from the bioreactor with heat recovery.

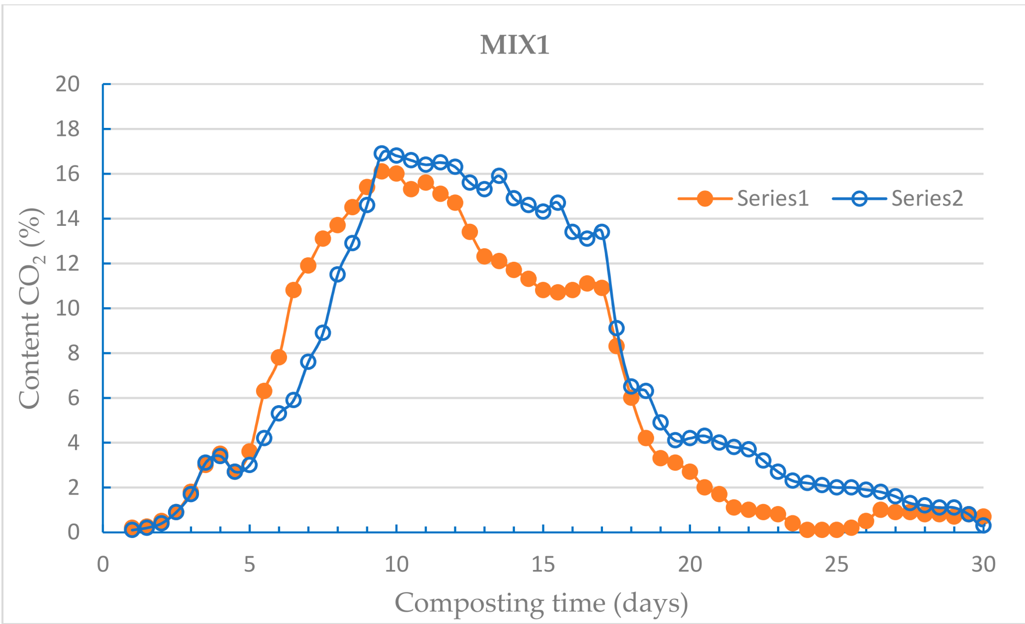

Figure 5. Changes in content CO_2 during the composting of MIX1.

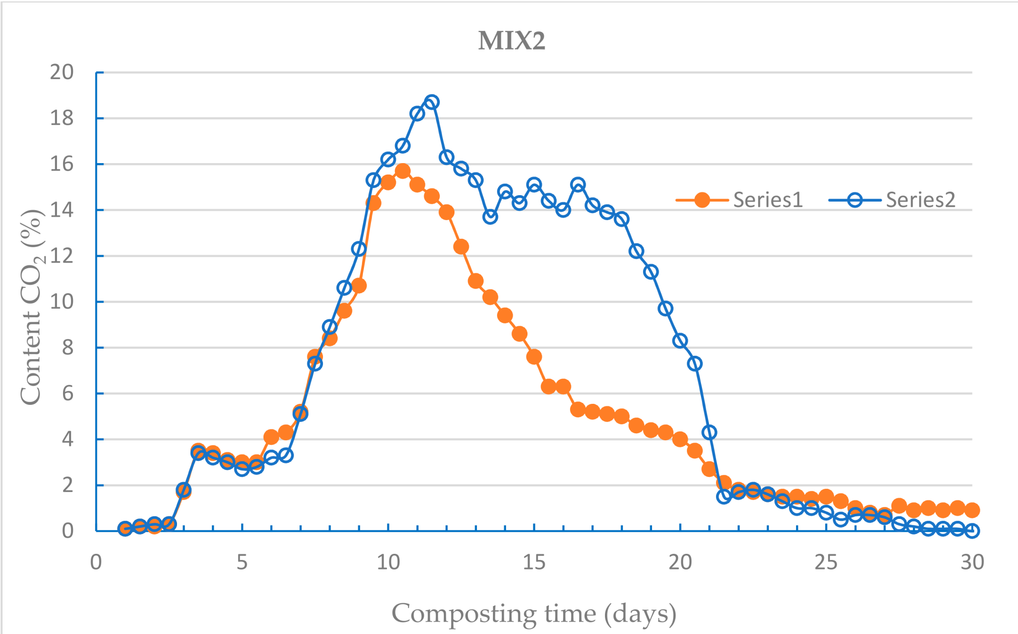

Figure 6. Changes in content CO_2 during the composting of MIX2.

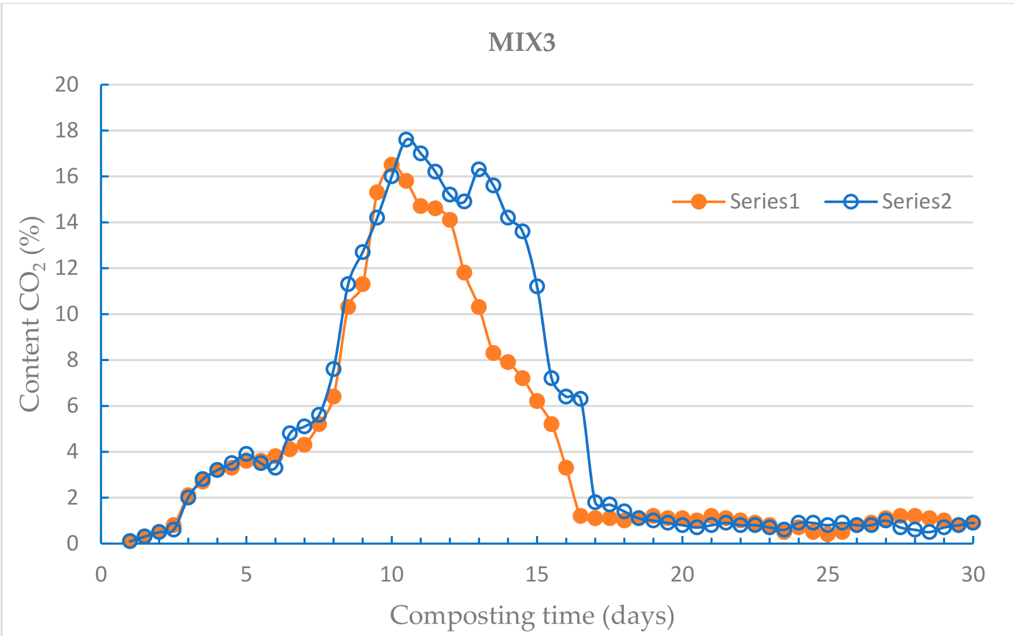

Figure 7. Changes in content CO_2 during the composting of MIX3.

The data shown in Figures 5–7 indicate that the content of carbon dioxide in exhaust gas was highly correlated with temperature in all bioreactors. Lower temperatures during the thermophilic phase in bioreactors with heat recovery did not decrease the amount of carbon dioxide in the exhaust gas, but in contrary, CO_2 emission was higher and more intensive. The above phenomena indicate that thermophilic microorganisms remained highly active when the composted material was cooled and maintained at a temperature of 55–65 °C. In Figure 6 (MIX2), carbon dioxide concentrations in exhaust gas are higher than in the remaining cases, which indicates that MIX2 was characterized by the most satisfactory C/N ratio and the decomposition process during the thermophilic phase was run in the optimum temperature (55–65 °C) (Figure 3).

3.3. Heat Recovery

In each case of composted mixtures, the heat recovery system worked properly. In the case of MIX1, the heat recovery system operated for 173 h; for MIX2, it operated for 236 h; and for MIX3, it operated for 188 h (Figures 2–4). The calculated amount of heat obtained per kilogram of the dry mass of the composted material was respectively for the mixture 1—855 $kJ \cdot kg^{-1}$, mixture 2—1950 $kJ \cdot kg^{-1}$, mixture 3—1455 $kJ \cdot kg^{-1}$. It should be noted that the highest heat production (in case of mixture II) was obtained in the case of 1 kg of spent coffee ground addition, which was 10% of the initial mass prepared for composting. No addition as well as a higher addition (20%, 2 kg) of coffee spent grounds led to obtaining a lower amount of heat generated during the thermophilic composting phase.

Comparing the obtained results, we can observe the relation of the recovered heat with CO_2 emission, which is related to the high activity of thermophilic microorganisms decomposing organic matter.

4. Discussion

Talking about the reliability of the obtained results, it has to be underlined that the volume of used bioreactors (30 dm^3 of working space) is bigger than those mostly found in the literature (5–15 dm^3) [74,75]. Additionally, the thermal insulation of the bioreactor chambers has guaranteed the reduction of heat losses by walls. The bioreactors design is quite similar to the construction of large-scale industrial bioreactors for biowaste composting. Thus, we assume that the obtained results can be applied in the commercial-scale plants in order to recover the heat generated during the thermophilic phase of composting. This can change the composting plant into the very modern and energy-efficient factories, which are characteristic for the coming Industry 4.0 [76]. The better energy efficiency of industrial plants and agriculture is one of the European Green Deal (EGD) policy elements currently being implemented in the EU [77]. This research, indicating the possibility of improving the composting process's efficiency by managing some of the heat generated (previously lost to the atmosphere), fits in with the recommendations of the new EGD policy.

Due to the highly diversified structure, chemical composition, and humidity, additives must be used to compost most biological waste. These additives impact improving the C/N ratio, porosity, or moisture of the composted biological material [78,79]. It is necessary to use additives while composting wastes with high humidity and low carbon content [80]. In the case of composting sewage sludge, additives can be, for example, barley straw [81], maize straw [82], or wood chips and sawdust [83]. The above-used additives improve the composted material's porosity, which facilitates the access of oxygen necessary for the metabolism of thermophilic microorganisms that degrade biological waste [84]. An equally important reason for the use of composting additives is to reduce ammonia emissions. Many publications show very high ammonia emissions when composting materials with a low C/N ratio [85,86]. One way to reduce this emission is to use various types of additives: materials rich in organic carbon, substances with high absorption capacity (e.g., wood bark), or biochar [30]. Many studies have shown that various materials added to composted waste can significantly reduce NH_3 emissions [87,88].

The crucial role of C/N in the composting process can be also noticed when the described research studies are compared with quite similar experiments done by Santos et al. [51]. The optimal initial C/N ratio is often fixed as between 25:1 and 30:1. In the described experiments, the MIX1 with the highest C/N ratio (35:1) has reached the lowest maximum temperature (65 °C), whereas MIX2 and MIX3 (C/N close to optimal—29 and 27:1) have reached the temperatures of 80 and 75 °C. This means that in MIX1, the lack of nitrogen can become a limitation factor for the strong dynamic of microbes growth. However, in the experiments with coffee grounds described by Santos et al. [51], the mixtures had an initial C/N ratio between 18.7:1 and 22.2:1, which seemed too low for initial composting. As a consequence, the maximum temperature during the thermophilic phase never reached even 60 °C. This can result in a limited availability of organic carbon compounds, which are indispensable for reaching the dynamic thermophilic phase and strong CO_2 emission.

On the other hand, in the described research, the influence of the addition of coffee grounds on the heating intensity of the composted mixture (vegetable waste and straw) was investigated, as well as the influence of heat recovery during the process on the most intensive heating of the compost, the length of the thermophilic phase, and CO_2 emission. It should be emphasized that the composting process generates significant amounts of heat, especially as a result of metabolic processes of thermophilic microorganisms [89]. In the case of composting systems with bed aeration, in most cases, the heat is removed with the outgoing air, and it is not used anywhere [90]. Single systems that use the air heat from the aeration of compost piles are created in closed bio-waste treatment systems [25]. There are also systems using the heat of composting as the lower source of an absorption heat pump in large systems of biological waste utilization by the composting method [91], or heat collection systems using thermoelectric generators converting the low-temperature heat of the bioreactor housing and converting it into electricity [92]. It should be noted that uncontrolled heat consumption may slow down and sometimes stop the composting process (especially in the range over 80 °C). In this case, heat collection systems should be used that ensure the maintenance of the optimal composting temperature in the thermophilic range of the 5–65 °C process.

5. Conclusions

Based on the described experiment results, we can formulate following conclusions:

1. The addition of spent coffee grounds (10%) for the composting of green bio-waste materials (cabbage leaves with straw addition) increases the effectiveness of the composting process.
2. In each of all the investigated cases, the discharge of heat excess by the refrigeration system caused a prolongation of the thermophilic phase. Presumably, this shows that temperatures in the range 55–65 °C create the best thermal comfort for the growth of the microorganisms and decomposition of organic material, which was also confirmed by the increased emission of carbon dioxide from the cooled composts with added coffee grounds (MIX2 and MIX3).
3. Heat recovery during the most intense part of the thermophilic phase has provided thermal comfort for the microorganisms by keeping the temperature in the range of 55–65 °C. The effect was the higher CO_2 emission from cooled materials, which is an effect of higher microbial activity.
4. The amount of heat recovered, even in the case of MIX2 (1950 $kJ \cdot kg^{-1}$ dry matter), is not high, but for large installations for biological waste composting, it can be used, for example, to heat the batch in the following bioreactors in winter conditions or for other similar purposes.

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