ORIGINAL ARTICLE

Biostabilization process of undersized fraction of municipal solid waste with biochar addition

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Abstract

The main goal of this work was to analyze the impact of biochar addition and changes in air-flow rates on the intensive phase of aerobic biostabilization of undersized fraction of municipal solid waste (UFMSW). The novelty of this paper stems from the use of biochar to shorten the process and generate "well-stabilized waste". The following six different input mixtures were tested (without biochar and with the addition of biochar at: 1.5%, 3%, 5%, 10% and 20%), at three different air-flow rates: 0.1, 0.2 and 0.4 $m^3 \cdot d^{-1} \cdot (kg\ org\ DM)^{-1}$. It was found that the biochar addition of more than 3 wt% causes water accumulation in the treated waste, but does not allow for reducing organic matter (OM) content below 35% DM, nor OM_{loss} values below 40% (the exception is the 5 wt% addition of biochar at the air-flow rate of 0.2 $m^3 \cdot d^{-1} \cdot (kg\ org\ DM)^{-1}$). Moreover, 10 wt% and 20 wt% biochar additions to UFMSW intensify the increase in microbial abundance, which may result in higher oxygen demand or development of anaerobic zones. The most favorable biochar doses in terms of final UFMSW sanitization are 3 wt% and 5 wt%.

Keywords Municipal solid waste treatment · Biostabilization · Biochar · Respiration activity · Microorganisms

Introduction

Aerobic biostabilization of undersized fraction of municipal solid waste (UFMSW) is a type of aerobic decomposition process often used in mechanical–biological treatment (MBT) plants [1]. This process is widely applied and is still being improved, especially in developing countries of Central and Eastern Europe [2]. In MBT plants mixed municipal solid waste (MSW) is subjected to screening, and next the oversized fraction of MSW is usually processed further for energy use, whereas the UFMSW, containing mainly the biodegradable waste, is transferred to dedicated bioreactors for biological treatment processes, e.g. methane (anaerobic) digestion, biodrying and/or biostabilization [3, 4]. Biological processing of the UFMSW is mainly conducted using anaerobic [5–7] and aerobic biostabilization [8–10] resulting in limited sanitation (decreased microbial activity) as well as reduction of waste mass and volume and organic matter (OM) content.

The process of aerobic biostabilization does not fit into the idea of the circular economy because after the process the main stream of waste is directed to landfills [11], which results in the release of carbon dioxide (CO_2) and many deleterious gases to the atmosphere [12]. On the other hand, this process is the only chance to reduce the mass of landfilled waste in regions, where recycling systems are still inadequate [1]. The biostabilization process is usually carried out in an MBT installation in closed bioreactors, with active aeration systems. The air flow rate is regulated and depends on the temperature of the processed waste. The process air exiting the bioreactors is typically treated in special biofilters to prevent emission of potential contaminants to the atmosphere [13, 14]. This operation lasts in bioreactors for 2 to 3 weeks and is called the intensive phase [15, 16]. Next, after unloading the bioreactors, the process is continued in open windows (maturation phase) [6, 9, 15]. This is the longest part of the process. It may last even several weeks and ends only after the required stability of the waste is reached [14, 17]. A detailed description of the UFMSW biostabilization process is presented in publications by Vaverková et al. [16], Yuan et al. [18] and Połomka and Jedrczak [19].

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The essential goal of conducting this process is to generate the "well-stabilized waste" that meets the criteria given by, among others, Vaverková et al. [16] and Połomka and Jedrczak [19] as follows: (1) organic matter (OM) defined by the loss of ignition (LOI) of the stabilized waste should be less than 35% related to dry mass (DM), and total organic carbon (TOC) should be less than 20% DM, (2) based on comparing the UFMSW before and after the biological treatment process, OM_{loss} should be greater than 40%, (3) respiration activity (AT4) should be less than 20 mgO$_2$·g DM^{-1} after the 2-week intensive phase and less than 10 mgO$_2$·g DM^{-1} prior to stabilized waste landfilling. Achieving the aforementioned reduction rates (OM content below 35% DM, OM_{loss} below 40%, and AT4 below 10 or 20 mgO$_2$·g DM^{-1}) are crucial to conclude about reaching the satisfactory effects of the analyzed process.

Aerobic biostabilization is characterized by a very negative effect on the environment due to odor emissions, leachate generation and final waste landfilling [20]. This indicates a pressing need to deal with this problem. Currently, new methods for biostabilization of UFMSW are being sought in many countries to minimize the negative environmental impact of this process [21]. To this end, changes have been introduced in aeration methods [22], bioreactor designs [3], as well as the waste treatment technologies [18]. Currently, the aerobic biostabilization process is aided by ozonation [23], addition of other substances, such as CaO [24] and even dedicated microorganisms [25]. Religa et al. [26] demonstrated that under real-world conditions in very large-volume bioreactors, leachate recirculation during UFMSW biostabilization leads to a decrease in the proportion of organic matter, total carbon content and respiration activity (AT4) in the waste due to the persistence of high water content. The properties characterizing the stabilized waste were obtained after 15 ± 2 days of the process conducted under real (technical) conditions. Thus, maintaining a high water content in the waste seems to be crucial for UFMSW biostabilization.

Czekała et al. [27], Vandecasteele et al. [28] and Malinowski et al. [29] observed that the use of biochar in small doses (both at the laboratory condition and technical scale) can change the biological treatment process of organic waste (or food waste). The effects of using biochar on the temperature of the composting process, accumulation of water in the composted waste and nitrogen in the produced fertilizer, reduction of CO$_2$ and NH$_3$ emissions [30], as well as reduction of the time required for the decomposition of the biodegradable fraction of waste during the intensive phase have been very well recognized [31, 32]. Godlewska et al. [33] report that the positive effect of biochar addition on biological waste treatment is related to its specific surface area and carbonaceous functional groups. Mierzwa—Hersztek et al. [34] assessed phytotoxicity of biochar ashes

indicating that the ash extracts have a positive effect on the growth of *Lepidium sativum* L. compared to the control.

The physicochemical properties of biochar, which is most often produced from woodchips in pyrolysis process, were described, among others, by Khan et al. [35], Vandecasteele et al. [28] and Akdeniz [36]. Keerio et al. [37], Villabona-Ortiz et al. [38], Alayont et al. [39], Durak and Aysu [40] and Yücedağ and Durak [41] described the effect of pyrolysis temperature and catalyst on production of bio-oil and bio-char from different plants.

Liu et al. [42] found that the addition of 5 wt% biochar resulted in a higher temperature in the waste windrow during sludge composting (66 °C), which may cause the number of pathogenic microorganisms to decrease. Awasthi et al. [43, 44] indicate a significant effect of biochar activities on abundance of selected microbial groups during composting. Hao et al. [45] found that biochar-amended (10%) composting significantly reduced heavy metals (HM) bioavailability by enhancing the correlation between bacterial bands and HM fractions. Malinowski et al. [29] found that even at low doses of biochar (less than 5%) a positive impact on reducing the time necessary to reach maturity of compost (under real conditions) and reducing its phytotoxicity is observed. However, the literature does not report the effect of biochar addition on the course of aerobic biostabilization of UFMSW, nor its effect on changes in physicochemical properties of treated waste, the number of microorganisms present and respiration activity (AT4). Furthermore, the impact of biochar additives on the phytotoxicity of the UFMSW is unknown.

I hypothesized that the addition of different doses of biochar (obtained from woodchips) to the process of aerobic biostabilization of UFMSW would positively influence the physicochemical properties of the treated waste (reducing the time to achieve the required parameters), as well as contribute to decrease in the number of microorganisms, phytotoxicity and biological activity of the waste. Nevertheless, this effect would be modified by the share of biochar applied and various air-flow rates. The novelty of this research lies in describing the impact of biochar addition and air-flow rate on the biostabilization process (3-week intensive phase) of UFMSW separated from MSW.

The main goal of this work was to analyze whether the biochar application at different doses affects the quality of waste during the process and allows for obtained the "well-stabilized waste". The scope of analyses included microbiocenosis, phytotoxicity and selected physicochemical properties of the waste. The duration of each trial was 3 weeks. Changes in temperature and oxygen concentration in waste and process gases are described by Malinowski [14]. Additionally, an indirect aim of the paper was to answer the question whether the application of biochar in MBT plants can be useful to their operators. The results were expected to

provide insights into understanding the impact of applying biochar in the biostabilization process of UFMSW.

Material and methods

Material and experiment

The UFMSW samples used in research were obtained from the process of mechanical treatment of MSW on 80 mm rotary (trommel) screen in an MBT plant (MIKI Recykling Ltd.) in Kraków (Poland). Waste samples for testing were taken using the quartering method. Biochar was obtained from woodchips as a result of pyrolysis process (at 550 °C by 30 min) conducting in the Thermolization Energy Recovery Module [14, 29]. The size of biochar particles used in the study was < 10 mm. Six different doses of biochar were applied and mixed with UFMSW in the process as follows: B1.5%, B3%, B5%, B10%, B20% and B0% without the addition of biochar as a control sample (% are expressed as wet weight).

The experiments were carried out for 3 weeks using "BKB 100" (thermal insulated) laboratory bioreactors (ROTAMETR, Gliwice, Poland). The construction and principle of operation of laboratory bioreactors used in this study, as well as the essence of the UFMSW biostabilization process and the method of aeration were presented graphically and described, among others, by Baran et al. [46] and Malinowski et al. [13]. Waste in the bioreactors was periodically aerated with the following three different average airflow rates: 0.1; 0.2 and 0.4 $m^3 \cdot d^{-1} \cdot (kg\ org\ DM)^{-1}$, referred to further as "0.1", "0.2" and "0.4", respectively. The aeration intensity used in the experiments was selected based on the works of Yuan et al. [18], Tom et al. [47], and Neugebauer et al. [48] and regulated (controlled) depending on the waste temperature. Papers published by Dziedzic et al. [3], Wolny-Koładka et al. [8] and Gliniak et al. [49] show that such a flow does not lead to sub-cooling of the material.

The experiments were carried out under laboratory conditions at a stable temperature (19.6 ± 1.0 °C) [14]. UFMSW were mixed with biochar (varying weight percentages) in a dusty form (> 80% carbon content) and placed in bioreactors. The weight of UFMSW placed in the bioreactor was approximately 50.5 ± 3.8 kg [14]. The analysis of each mixture was repeated three times due to the use of three aeration options. A total of 18 measurements were made (6 different doses of biochar in 3 aeration options). Waste was not turned during the tests.

Sampling and laboratory tests

The processed waste was subjected to the following laboratory analyses: material composition, pH, moisture content (MC) and organic matter (OM), heavy metal (HM) content, number and diversity of selected groups of microorganisms (described in Sect. 2.3) inhabiting the waste and respiration activity (AT4) were determined. Samples from subsequent replicates were collected for laboratory analysis at the beginning and after 7, 14 and 21 days of the aerobic biostabilization process. This was necessary to determine the physicochemical properties of treated waste (UFMSW), the abundance of microorganisms and the general changes in the intensive phase of the process conducted with the various biochar additives. The MC, OM, OM_{loss}, AT4 and number of selected groups of microorganisms in the UFMSW were tested for each sample collected during the process. The waste was validated for phytotoxicity after 21 days. The results of the study by Wang et al. [50], Kopeć et al. [51] and Malinowski et al. [29] show the positive effect of biochar addition on reducing the phytotoxicity of biowaste or byproducts (from food production). The impact of biochar additives on the phytotoxicity of UFMSW after biostabilization is unknown. The phytotoxicity of UFMSW has also not been analysed in the literature.

The UFMSW used for the study were taken from the MBT plant several times. The material composition of UFMSW was not formed in the laboratory according to a specific recipe; therefore, each sample of waste used for the study had to be tested. The material composition of waste used in the research was determined according to Jędrczak and Szpadt [52] methodology. It was necessary for determination of biodegradable waste share. According to Jędrczak and Szpadt [52] the share of biodegradable waste can be calculated as a sum of organics, paper and cardboard, 50% of wood and textiles, 40% composite waste and 30% fine fraction, i.e. < 10 mm. Three representative samples of waste (5006 ± 107 g each) were collected for determination of material structure, before the UFMSW was mixed with biochar at a specific dose and placed in a bioreactor. Each separated waste fraction was weighed on a RADWAG scale with an accuracy of 0.1 g (RADWAG, Kraków, Poland).

During process, waste samples were collected as follows: UFMSW without the addition of biochar (control—B0%), UFMSW + 1.5 wt% of mass addition of biochar (B1.5%), UFMSW + 3 wt% of mass addition of biochar (B3%), UFMSW + 5 wt% of mass addition of biochar (B5%), UFMSW + 10 wt% of mass addition of biochar (B10%) and UFMSW + 20 wt% of mass addition of biochar (B20%).

Wet bulk density (BD), HM content in DM, MC and OM contents in raw materials, mixtures and waste during and after the process were measured according to the methodology described by, e.g. Malinowski et al. [13]. The OM losses (OM_{loss}) were determined from the initial and final OM contents according to formula given by Parades et al. [53].

AT4 values were assessed using the OxiTop system (WTW, Wrocław, Poland) in accordance with Richtlinie

[54]. The operation of the OxiTop system for measuring AT4 and calculation of this parameter based on the transformed general gas equation is presented in detail by Malińska [55], Kopeć et al. [51] and Malinowski et al. [13]. All analytical tests of the raw materials and mixtures were run in triplicates.

Microbiological analyses

Microbiological analyses were performed for the biochar and UFMSW used in this study. In addition, the abundance of isolated microorganisms in UFMSW-biochar mixtures was evaluated after 7, 14 and 21 days of the process. To isolate microorganisms, from each sample 10 g of the tested material/waste/mixture were analysed. The isolation was conducted using Koch's serial dilution method described by Wolny-Kołądka and Żukowski [23].

After the incubation time of selected groups of microorganisms (Table 1) the grown colonies were counted. The results of observation were provided in colony-forming units per gram of sample DM (CFU·g DM^{-1}). Table 1 shows the groups of tested microorganisms, the name and manufacturer of the nutrients used in the tests.

Changing numbers of individual groups of microorganisms (bacteria and fungi) were essential for the assessment of the aerobic biostabilization process efficiency. Wolny-Kołądka et al. [24] and Wolny-Kołądka and Żukowski [23] indicate that the numbers of vegetative bacteria and spores point to a number of nutrients easily digestible for microorganisms in the studied raw materials.

Phytotoxicity tests of mixtures

The phytotoxicity of waste after 21 days of the aerobic biostabilization process conducted at different air-flow rates and with different biochar additions was evaluated using a commercial toxicity bioassay—Phytotoxkit™ test [56]. The description of the performance of the test was reported extensively by Brtnický et al. [57], Malinowski et al. [29] and Vaverková et al. [35].

For the all phytotoxicity tests, *Lepidium sativum* L. was chosen because of its high sensitivity [29]. Using the Phytotoxkit™, the growth of young roots and the seed germination

after 3 days of the exposure to the contaminated matrix (mixtures), which were compared to the control (OECD soil) were analysed [58]. Three concentrations (25%, 50% and 100%) of UFMSW were assessed with different doses of biochar addition (B1.5%, B3%, B5%, B10%, B20% and B0%). The percentage of root growth inhibition (GI) was determined using the following formula [59]:

$$GI = (A - B)/A \times 100$$

where *A*—is the mean root length in the control, and *B*—is the mean root length in the test samples.

Statistical analysis

Statistical analysis of the results was carried out using Statistica 13 software (StatSoft). An analysis of variance was performed in order to check the significance of the differences in respiratory activity and selected physicochemical properties in samples obtained at different stages of the UFMSW aerobic biostabilization process with biochar addition.

Results and discussion

Characteristics of raw materials

The technological properties of biochar used in this study was described in detail in papers by Malinowski et al. [29] and Malinowski and Famielec [60]. The MC of biochar was 4.5%, the OM content was 93.4% and the C content was 81%. Its density was 219.6 kg·m^{-3}, and AFP was over 85% [14, 60]. The biochar contained trace amounts of HM, which is characteristic of this substance [27].

Because UFMSW was collected for tests at different times of the year, the material composition was examined. The results of UFMSW material composition analyses are shown in Table 2 separately for each measurement run (before mixing the waste with a specific dose of biochar). The composition was dominated by fine fraction < 10 mm, organic waste and inert waste (glass, metal, stones). Since the composition of the waste used in the analysis was heterogeneous but similar (the differences in the content of the

Table 1 Incubation conditions for selected groups of microorganisms

Microorganism groups	Nutrient	Temperature of incubation [°C]	Time of incubation [days]
Vegetative bacteria	MPA agar, BTL	37	1
Spores bacteria			
Mould fungi	Malt extract agar—MEA, BTL	28	5
Actinobacteria	Pochon's agar, BTL	28	7

Table 2 Material composition of UFMSW

Waste group	Share [wt%]					
	Run 1 (B0%)	Run 2 (B1.5%)	Run 3 (B3%)	Run 4 (B5%)	Run 5 (B10%)	Run 6 (B20%)
Fine fraction < 10 mm	36.9 ± 3.5	33.2 ± 3.2	31.1 ± 3.7	34.8 ± 3.9	33.6 ± 2.0	28.7 ± 5.9
Organics (i.e. kitchen waste, grass and leaves)	20.8 ± 3.2	22.6 ± 2.1	24.5 ± 3.1	19.6 ± 3.8	21.7 ± 1.9	24.2 ± 2.6
Paper/cardboard	9.6 ± 2.0	9.8 ± 0.9	11.4 ± 2.2	9.5 ± 0.8	9.9 ± 0.9	10.8 ± 1.4
Plastics	15.2 ± 1.4	12.9 ± 1.1	13.1 ± 1.7	14.2 ± 1.9	14.7 ± 2.2	12.7 ± 1.3
Metal	2.4 ± 0.3	2.2 ± 1.0	2.7 ± 0.6	3.0 ± 0.7	2.9 ± 0.5	3.3 ± 0.6
Glass	8.6 ± 1.9	12.2 ± 1.3	10.8 ± 1.9	11.5 ± 1.4	4.5 ± 0.9	12.6 ± 1.2
Textiles/clothing	1.1 ± 0.5	1.5 ± 0.7	0.9 ± 0.3	2.1 ± 0.5	2.2 ± 0.3	2.4 ± 0.4
Wood	2.6 ± 1.6	2.1 ± 1.7	0.7 ± 0.6	1.6 ± 1.1	1.3 ± 1.2	2.2 ± 1.1
Hazardous waste	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
Inert and other categories	2.7 ± 0.5	3.4 ± 1.1	4.7 ± 1.3	3.6 ± 1.1	4.1 ± 1.2	3.0 ± 0.6
Biodegradable waste – total	42.0 ± 3.0	43.1 ± 3.1	45.7 ± 3.2	40.6 ± 4.1	44.3 ± 2.9	44.8 ± 3.1

Mean ± standard deviation of mean ($n = 3$)

different waste groups were not statistically significant), it was decided that the results of the other analyses could be compared with each other. In addition, Table 2 also provides information about the content of biodegradable waste, which is essentially transformed by the action of microorganisms during the aerobic biostabilization process [8]. The proportion of biodegradable waste in the mixtures was relatively low (43.4 ± 1.9 wt%) compared to the values reported by Dziedzic et al. [3], but comparable to the findings of Wolny-Koładka et al. [8], who reported 37.4 – 46.4 wt%, and Malinowski et al. [14], who reported 41.9 ± 5.7 wt%.

Table 3 summarizes the physicochemical characteristics of UFMSW with and without biochar additives. The initial MC value for UFMSW was 43.2 ± 0.9 wt%. The addition of biochar generally caused a decrease in the moisture content of the mixtures, but this trend was not linear (the highest initial MC was recorded for B1.5%). The mean MC of the studied mixtures was 40.9 ± 3.5 wt%. According to

Jedrczak [61], MC above 40% is favourable for the growth of microorganisms in waste during the biological treatment process. The analysed UFMSW had a relatively low initial OM content (47.9 ± 0.8% DM), compared to the values reported by Malinowski et al. [14] and Wolny-Koładka et al. [8], i.e. 64.1 ± 4.6 wt% and 60.3 ± 1.2 wt%, respectively. On the other hand, Jędrczak and Suchowska-Kisielewicz [9] report that the average OM content of UFMSW subjected to the aerobic biostabilization process (based on analyses conducted at selected municipal enterprises) is 41.1 ± 8.2% DM. These differences are a direct result of the heterogeneous material composition of the waste analysed, which in turn may be dependent on where the MSW are generated. With each successive addition of biochar to UFMSW, the initial OM content of the test samples increased. The low initial OM value probably also affected the AT4 value, comparable to the results of studies by Jędrczak and Suchowska-Kisielewicz [9], but much lower than in the study by

Table 3 Physicochemical characteristics of UFMSW

Parameters	Unit	Trial 1 (B0%)	Trial 2 (B1.5%)	Trial 3 (B3%)	Trial 4 (B5%)	Trial 5 (B10%)	Trial 6 (B20%)
MC	wt%	43.2 ± 0.9	46.4 ± 4.4	39.2 ± 4.1	42.6 ± 2.0	38.1 ± 2.1	36.3 ± 2.4
OM	% DM	47.9 ± 0.8	47.1 ± 0.7	48.6 ± 1.8	49.5 ± 3.6	55.3 ± 6.3	61.0 ± 4.4
AT4	mgO_2 g DM^1	19.9 ± 3.3	18.3 ± 3.9	17.2 ± 2.3	17.0 ± 3.1	16.8 ± 2.6	27.2 ± 0.2
pH	–	6.4 ± 0.1	6.2 ± 0.5	6.3 ± 0.2	6.5 ± 0.3	6.7 ± 0.5	6.6 ± 0.4
Cd	mg·kg DM^{-1}	16.6	29.6	33.0	30.2	24.8	31.2
Cr	mg·kg DM^{-1}	579.6	445.9	547.6	504.6	508.4	386.1
Cu	mg·kg DM^{-1}	1280.3	814.6	2781.0	2090.5	2489.8	1890.2
Zn	mg·kg DM^{-1}	4474.2	9963.3	5069.6	6134.8	9174.6	5383.8
Ba	mg·kg DM^{-1}	1703.0	1507.9	1226.5	2197.7	1500.5	1894.5

MC moisture content, *OM* organic matter, *AT4* respiration activity

Mean ± standard deviation of mean ($n = 3$)

Wolny-Koładka et al. [24], who indicated AT4 of 26.3 ± 0.7 mgO$_2$·g DM^{-1}, and studies in which the organic fraction of MSW (OFMSW) was composted [29] (AT4 values higher than 30 mgO$_2$·g DM^{-1}). Respiration activity with a significantly higher value was recorded only in the case of the B20% mix. The pH of the studied waste was close to the volumetric one, while the HM content varied greatly due to the separation of the analysed wastes from the MSW and their previous contact with many different inorganic contaminants. The addition of biochar was not found to affect the initial HM content of UFMSW.

Biochar impact on the aerobic biostabilization process of UFMSW

Malinowski [11] discusses the impact of biochar additives and different air-flow rates on temperature changes and O$_2$ concentration in UFMSW in air-filled spaces between waste and gases emitted during process (for the same experimental conditions). Malinowski [11] and Malinowski and Famielec [60] stated that in each of the conducted experiments, the waste reached thermophilic temperatures (over 45 °C). On the other hand, temperatures above 65 °C were obtained with the air-flow rates 0.2 and 0.4 [60]. Figures 1, 2 and 3 present the changes that occurred in MC, OM and AT4, respectively, during the biostabilization process of UFMSW.

After 21 days of processing, in each experiment a decrease in MC in the UFMSW was observed. MC losses from the baseline were statistically significant, especially for the air-flow rates of 0.2 and 0.4. The decrease in MC in the UFMSW for these two air-flow rates averaged 28.8% (for 0.2) and 32.3% (for 0.4) over the initial MC. The smallest MC changes were observed when the air-flow rate of 0.1 was used (MC decrease was 18.3% on average). The dynamics of MC changes in the waste were found to be higher for B0% and B1.5% experiments (higher MC losses). On the other hand, the addition of biochar of more than 3 wt% to UFMSW resulted in decreasing dynamics of MC changes, and consequently there was accumulation of water in the waste. Wei et al. [62] and Li et al. [63] found that the addition of biochar (due to its porous structure) to OFMSW also causes water retention in the waste, which promotes the proliferation of microorganisms during the process.

OM content after aerobic biostabilization and OM$_{loss}$ are the two main parameters (besides AT4) determining whether UFMSW after the process can be considered as the "well-stabilized waste". Generally, Kasiński et al. [64], as well as Jędrczak and Suchowska-Kisielewicz [9], report that this one phase, short period (2 or 3 weeks) of the biostabilization process is insufficient for the waste to be stabilized and then it has to be subjected to a disposal process (on a landfill) or recovery by sieving out the fraction below 20 mm [16]. The OM decreased in each trial in the conducted studies.

However, neither after 14 days (the most common process length in an MBT installation) nor after 21 days of processing, OM was recorded below 35% DM in any of the experiments, which is a value required by law [19] and could confirm that a second phase of the so-called "maturation" process is needed. The lowest OM value after 21 days of processing (36.1% DM) was recorded for experiment B5% with an air-flow rate of 0.2.

The highest OM$_{loss}$ was observed in those experiments in which the dynamics of OM change were the greatest, i.e., at the air-flow rates of 0.4 and 0.2, for which OM$_{loss}$ were $34.0 \pm 4.4\%$ and $33.2 \pm 8.1\%$, respectively. The smallest OM$_{loss}$ was found for the air-flow rate of 0.1, amounting to 29.9 ± 4.7 (differences between means were not statistically significant). In contrast, the addition of biochar varied the achieved OM$_{loss}$ in a statistically significant manner. In the control samples (B0%), the averaged OM$_{loss}$ was 26.6%, while at 5%, 10% and 20% addition of biochar, OM$_{loss}$ was 35.9%, 38.6% and 35.3%, respectively. Only in the case of the experiment with B5% (at 0.2 air-flow rate) the value of OM$_{loss}$ below 40% (42.4) was achieved, but only after 3 weeks of the process. The OM$_{loss}$ values achieved in these analyses are significantly lower than those presented in a study by Malinowski et al. [14], in which digestate was the bulking agent added to UFMSW.

Having considered the fact that OM reduction is an important parameter of a proper biostabilization process, it should be concluded that the addition of biochar insufficiently stimulated the biological degradation of OM during the intensive phase. This could be the reason for the low initial OM content and low MC, which was observed in low OM losses already in experiments without biochar additives. In a study by Malinowski et al. [14], OM$_{loss}$ for not supplemented UFMSW was 35.6%, which is 10% higher than in the conducted study.

In all study series, the value of AT4 decreased (Fig. 3). It is important to note that in the case of the experiments with the highest air-flow rate (0.4), all analyses resulted in reaching the required AT4 value after 3 weeks of the process (10 mgO$_2$·g DM^{-1}). In contrast to the changes in OM, at each of the air-flow rates used, there was a decrease in AT4 to the regulatory value for at least two of the biochar waste mixtures. Regardless of the applied air-flow rate fed to the biostabilization process, the addition of biochar at 3 wt% and 5 wt% allowed for the achievement of AT4 < 10 mgO$_2$·g DM^{-1}. In these two cases, it can be concluded that the UFMSW was stabilized after 21 days of the process. The lowest dynamics of AT4 changes concern UFMSW without biochar addition (B0%) and the B10% and B20% experiments, for which, similarly to OM content analysis, the smallest changes were recorded.

The low initial AT4 value (less than 20 mgO$_2$·g DM^{-1}) may have influenced the achievement of the desired value.

Fig. 1 Moisture content changes during biostabilization: (**a**) air-flow rate 0.1 (**b**) air-flow rate 0.2 (**c**) air-flow rate 0.4 m^3·d^{-1}·(kg org DM)$^{-1}$
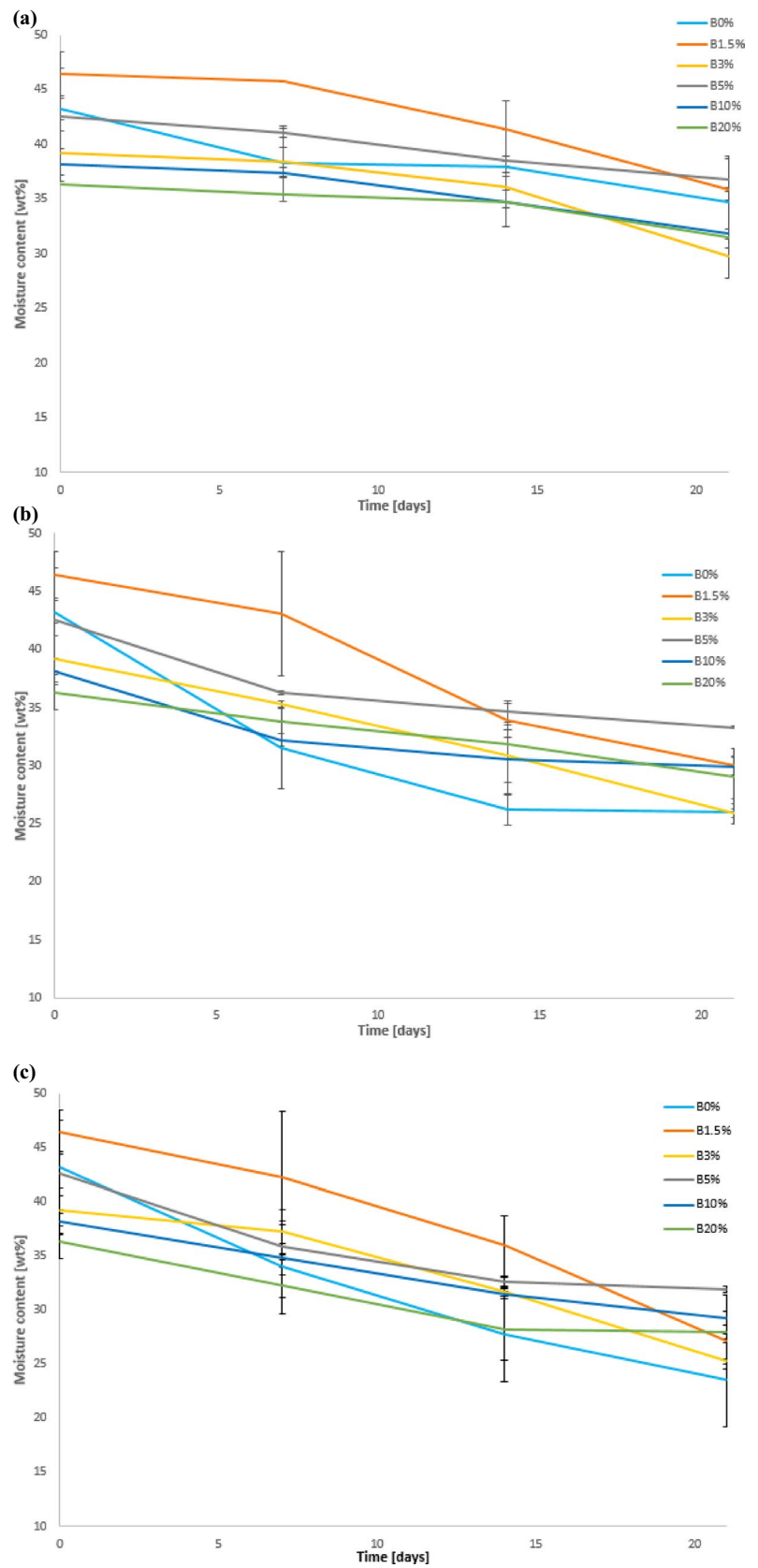
Fig. 2 Organic matter changes during biostabilization: (**a**) air-flow rate 0.1 (**b**) air-flow rate 0.2 (**c**) air-flow rate 0.4 $m^3 \cdot d^{-1} \cdot (kg\ org\ DM)^{-1}$
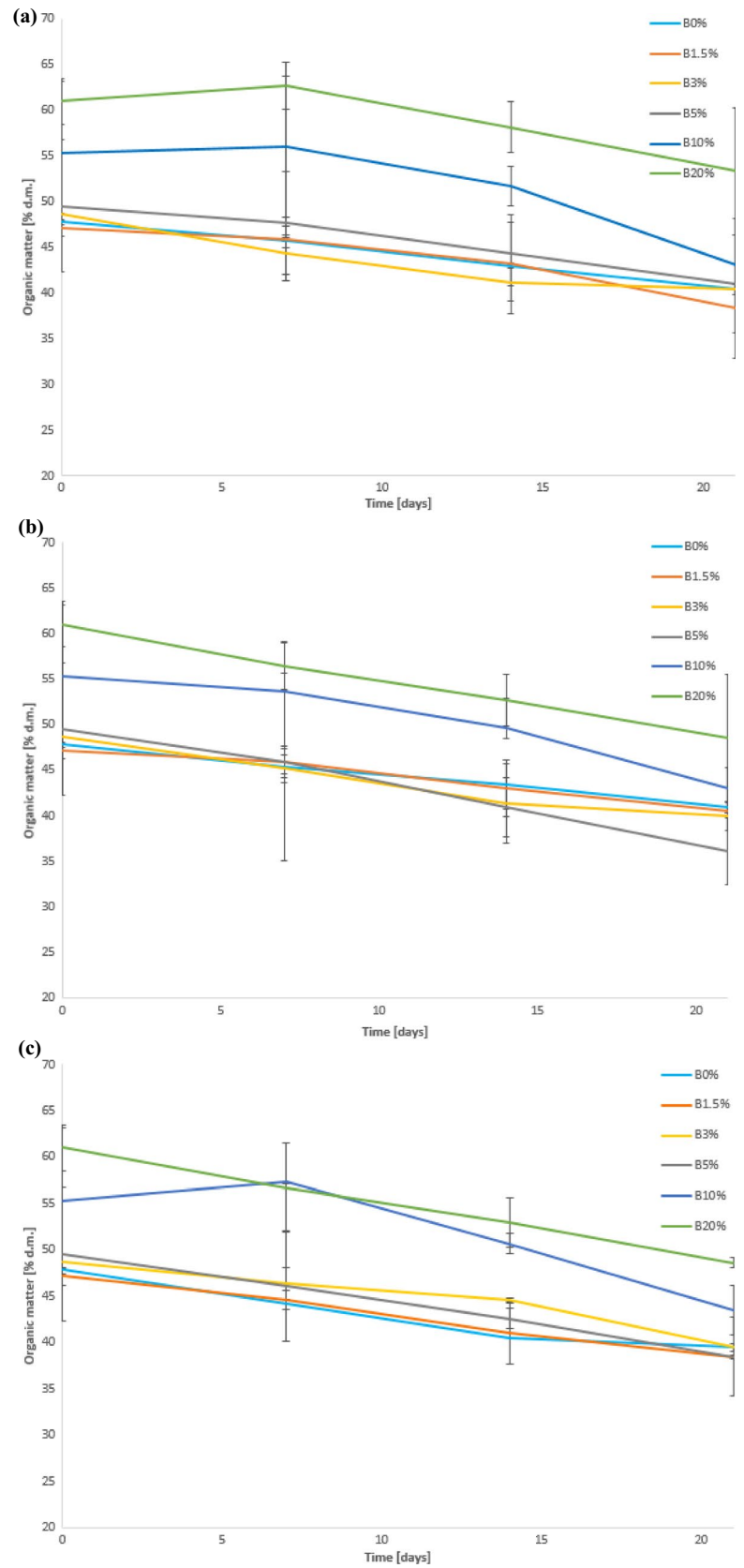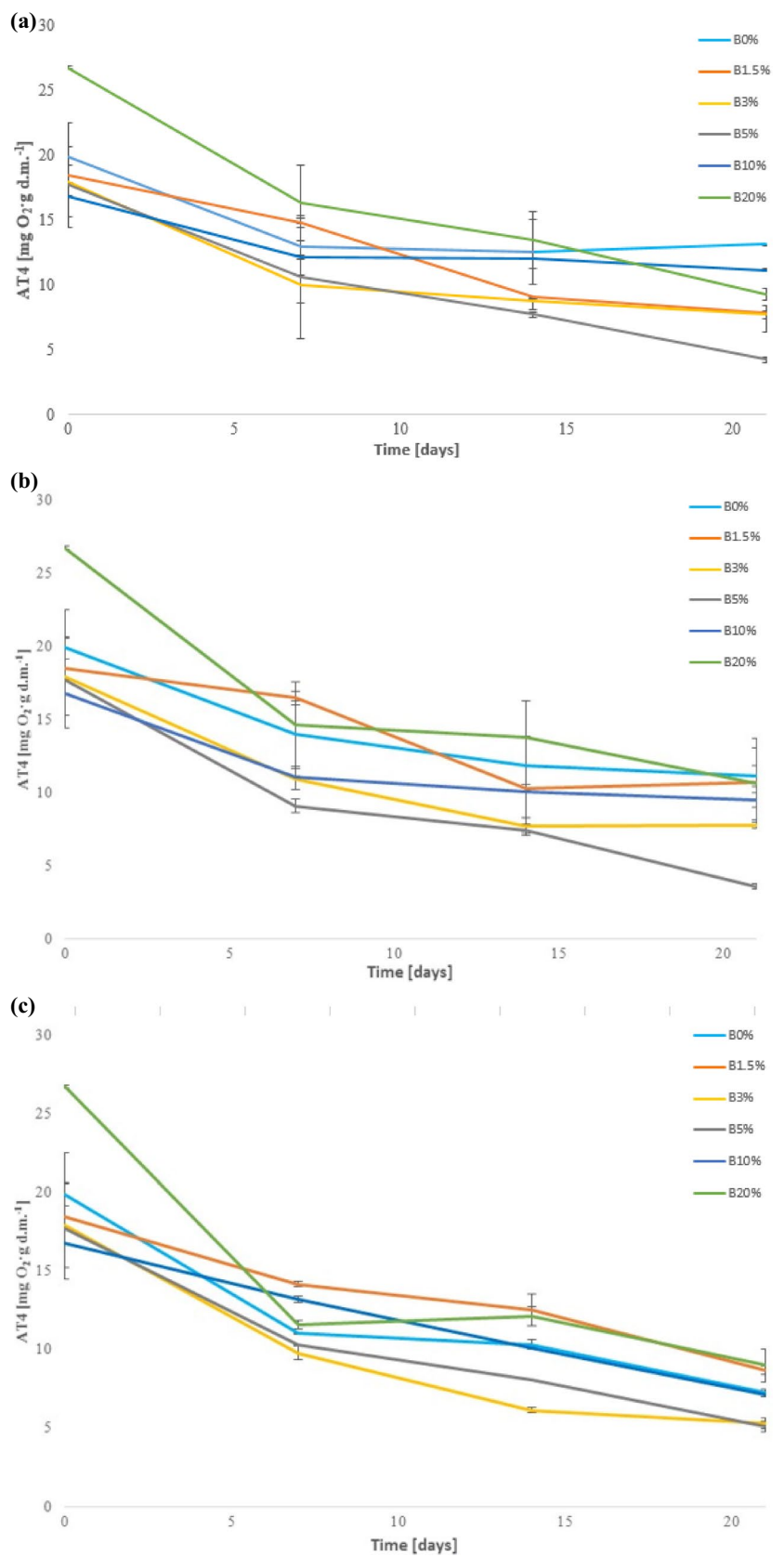
Fig. 3 Respiration activity changes during biostabilization: (**a**) air-flow rate 0.1 (**b**) air-flow rate 0.2 (**c**) air-flow rate 0.4 $m^3 \cdot d^{-1} \cdot (kg\ org\ DM)^{-1}$

Cossu and Raga [65] report that the initial AT4 value for UFMSW was 38 mgO$_2$·g DM^{-1} in their study, while Kasiński et al. [64] report that the AT4 value for MSW was over 50 mgO$_2$·g DM^{-1}. In analyses by Jędrczak and Suchowska-Kisielewicz [9] (UFMSW treatment in real conditions) and Malinowski et al. [13] (UFMSW processing with digestate), it was found that the intensive phase is not sufficient to achieve AT4 values below 10 mgO$_2$·g DM^{-1}. Biochar is, therefore, a substance that can intensify the biostabilization process to such an extent that it is possible to obtain the "well-stabilized waste" in a short time (without an additional maturation phase).

Microbiocenotic composition

The biochar used in the analyses did not contain any of the tested microorganisms. The mean abundance of analyzed microorganisms in the UFMSW and mixtures with different rates of biochar addition and different air-flow rates were presented in Table 4. The initial microbial content was similar to the results of Wolny-Kołądka et al. [10], who studied, e.g. UFMSW with brewery hot trub, and Malinowski et al. [13], who researched UFMSW with digestate. Initial differences in microbial abundance in biochar waste mixtures may have been influenced primarily by the heterogeneous composition of the waste [23].

Based on the study, it was found that the microbial abundance during the process varied greatly and changed depending on the addition of biochar and the day of sampling for the study. In the vast majority of cases, incomplete (limited) but sufficient sanitization of the tested waste was found. The exceptions were the experiments with 20 wt% addition of biochar, where in several cases, there was an increase in the abundance of tested microorganisms in relation to the initial value at the final stage (after 21 days of process). It is important to note that the highest microbial counts were recorded mainly in 7 day of the process, when the reached temperatures were the highest [14, 60].

The greatest sanitation of the UFMSW was achieved in terms of fungi. In B1.5%, B3%, and B5% samples, their abundance decreased by more than 98%, regardless of the air-flow rate. Air-flow rates of 0.2 and 0.4 resulted in more than 90% reduction in mold fungi abundance, regardless of biochar addition. Complete sanitation was achieved for Actinobacteria when the addition of biochar was less than 5 wt%. At B20% and the air flow rates of 0.1 and 0.4, there was an increase in Actinobacteria abundance by 24% and 68%, respectively, compared to the initial value.

The highest dynamics of changes in microbial abundance were observed for vegetative bacteria. In almost every case analyzed, their abundance increased during the process. Finally, after 21 days of the process, their abundance in the experiments with 3 wt% and 5 wt% biochar addition decreased by more than 90% (compared to the initial value) regardless of the air-flow rate. Malinowski and Famielec [60] stated that thermophilic temperatures were maintained for the longest at 3 and 5 wt% biochar additions, which should have allowed for this limited sanitation of waste.

The lowest losses were observed in the spores bacterial population. Numerous isolated microorganisms, including spores bacteria, are able to survive unfavorable dormancy or produce spores [23]. The observed differences in the abundance of spores bacteria may be due to the presence of the "competition for a niche" phenomenon in the microbial world, in this case related to the fact that the applied parameters of aerobic biostabilization influenced the elimination of a certain part of the population of these bacteria and also stimulated the development of other (more resistant) ones [24].

The lowest sanitization was achieved for the B10% and B20% samples, where the large quantitative addition of biochar resulted in high final abundance of the bacteria and Actinobacteria tested. According to Lehmann and Jospeh [66], this situation is a direct result of the properties of biochar, which is a good source of mineral substances for microorganisms, including Mg, Ca and carbonates. The effects of biochar additives on microbial growth during biological waste treatment were also observed by Wei et al. [62], Lehmann et al. [67] and Beheshti et al. [68]. Increasing microbial abundance required the consumption of oxygen supplied to the waste, which may explain the very low proportion of oxygen in the waste gas and the formation of anaerobic zones in the treated waste with 10 wt% and 20 wt% biochar addition described by Malinowski [14].

During the process, the pH of the analyzed wastes increased to 7.4 ± 0.4 (the differences between the mean values were not statistically significant). The pH of the wastes also showed no significant correlation with the abundance of microorganisms.

Biochar's impact on UFMSW phytotoxicity

Results for the seed bioassays (GI for the biochar addition 0%, 1.5 wt%, 3 wt%, 5 wt%, 10 wt% and 20 wt%) used to evaluate changes of phytotoxicity of UFMSW mixed with biochar are shown in Fig. 4. Only GI results for 25% and 50% waste concentration after biostabilization process are presented in Fig. 4. Phytotoxicity analysis of UFMSW after the process (without the addition of OECD soil), regardless of the addition of biochar and the aeration used, inhibited plant growth at 98 to 100%, indicating its hazardous potential (in terms of placing such waste directly into the environment). The toxicity of 100% UFMSW (without biochar) was such that only 3% of the seeds germinated. This could have been directly related to the very high content of some HM in the samples and the short period of the process. The

Table 4 The mean abundance ($\times 10^2$ CFU·g DM^{-1}) of microorganisms in the tested samples (before and after aerobic biostabilization process)

Microorganisms	Day of process	Run 1 (B0%)	Run 2 (B1.5%)	Run 3 (B3%)	Run 4 (B5%)	Run 5 (B10%)	Run 6 (B20%)
Initial (before the process)							
Vegetative bacteria	0	279,057.0	276,100.0	228,250.0	98,555.6	391,666.7	149,000.0
Spores bacteria	0	2850.1	1901.1	980.7	240.2	268.9	1130.4
Mold fungi	0	1880.0	3800.0	980.0	320.1	575.5	900.3
Actinobacteria	0	0.1	0.2	0.1	14.5	0.9	5.4
Air-flow rate: 0.1 m^3·d^{-1}·(kg org DM)$^{-1}$							
Vegetative bacteria	7	156,000.0	157,300.0	152,450.0	457,000.0	282,150.0	602,000.0
	14	486,877.8	18,060.0	27,405.5	300,300.0	76,550.0	554,000.0
	21	79,866.3	22,710.0	10,455.5	7102.7	129,000.0	415,550.0
Spores bacteria	7	126.0	339.0	139.9	238.0	317.0	890.0
	14	37.5	349.0	172.2	32.0	784.0	1710.0
	21	56.1	842.0	155.2	175.8	111.1	264.0
Mold fungi	7	152.2	60.0	14.3	40.0	379.4	1460.0
	14	387.7	84.0	1.7	2.9	205.3	1010.0
	21	28.0	11.0	0.1	0.2	181.0	154.0
Actinobacteria	7	0.0	0.0	0.0	0.0	0.2	15.3
	14	0.0	0.0	0.0	0.0	0.1	11.2
	21	0.0	0.0	0.0	0.1	0.1	6.7
Air-flow rate: 0.2 m^3·d^{-1}·(kg org DM)$^{-1}$							
Vegetative bacteria	7	287,200.0	100,650.0	84,060.0	190,400.0	249,450.0	189,500.0
	14	228,400.0	202,750.0	49,450.0	223,466.6	243,150.0	393,000.0
	21	221,000.0	216,555.5	14,270.0	6,000.0	146,000.0	94,000.0
Spores bacteria	7	43.2	411.0	142.0	298.8	204.4	480.0
	14	178.0	453.0	209.7	40.5	153.2	630.0
	21	406.5	392.4	89.8	184.9	237.0	44.3
Mold fungi	7	340.2	90.0	79.0	30.0	113.0	480.0
	14	120.3	37.7	35.7	38.0	383.0	630.0
	21	143.8	10.0	17.5	4.7	20.3	18.9
Actinobacteria	7	0.0	0.0	0.0	0.0	0.1	3.5
	14	0.0	0.0	0.0	0.1	0.2	8.1
	21	0.0	0.0	0.0	0.0	0.1	4.3
Air-flow rate: 0.4 m^3·d^{-1}·(kg org DM)$^{-1}$							
Vegetative bacteria	7	352,981.1	623,500.0	417,933.3	258,000.0	162,150.0	615,000.0
	14	348,000.0	367,833.3	149,850.0	268,746.6	429,300.0	409,000.0
	21	30,556.7	164,000.0	13,067.8	7,840.0	39,600.0	49,000.0
Spores bacteria	7	168.0	242.0	152.5	165.4	435.0	465.0
	14	250.0	648.0	168.2	28.7	186.40	630.0
	21	198.0	248.0	204.0	65.7	251.2	376.0
Mold fungi	7	170.7	70.0	79.5	60.0	246.5	313.5
	14	1088.0	18.9	1.2	7.4	75.0	180.0
	21	135.5	10.0	1.7	3.4	25.9	71.5
Actinobacteria	7	0.0	0.0	0.0	0.1	0.1	9.5
	14	0.0	0.0	0.0	0.1	0.1	9.9
	21	0.0	0.0	0.0	0.1	0.2	9.1

phytotoxicity analysis of this waste is important because of the subsequent separation of the fraction with a paticle size below 20 mm and its use in recovery processes. Specifically this type of compost was studied by Vaverková et al. [16], showing its GI in the range of 88.9—97.8%.

The inhibition of root growth in all repetitions reached negative values. The lowest averaged GI values were

Fig. 4 Results of germination tests of UFMSW after aerobic biostabilization: (**a**) air-flow rate 0.1 (**b**) air-flow rate 0.2 (**c**) air-flow rate 0.4 $m^3 \cdot d^{-1} \cdot (kg\ org\ DM)^{-1}$
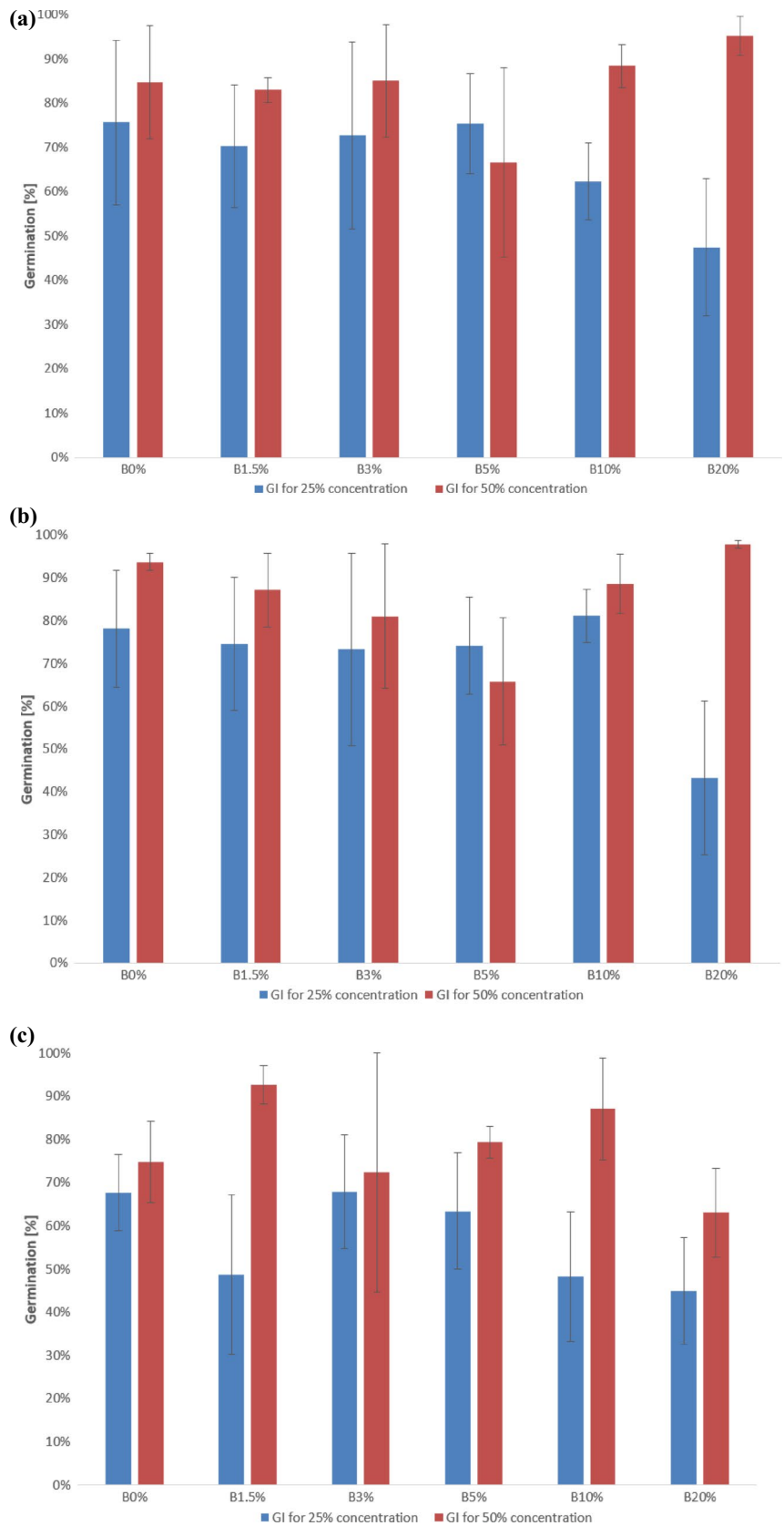
obtained for the waste from the tests with the highest air-flow rate (0.4): 56.8% and 78.2% for concentrations of 25% and 50%, respectively. At 25% waste concentration, a trend was found (at all air-flow rates) indicating that the greater the addition of biochar, the lower the germination index. At 25% waste concentration, GI < 50% was obtained in each replicate for B20%, and mean root lengths of *Sinapis alba L.* were statistically significantly longer than in the control sample (B0%). In conclusion, the addition of biochar in the amount of more than 20% can have a positive stimulating impact on the root growth of *Sinapis alba* L. However, it would be important to study the GI for UFMSW after 3 months of maturation in the context of separation of fractions below 20 mm and their use in recovery processes.

At 50% waste concentration, the negative effect on plant root growth was higher than at 25% concentration. Among all biochar additives, the following can be distinguished with the lowest GI values obtained: B5% at the air-flow rates of 0.1 and 0.2 (GI of 66.5% and 65.8%, respectively), and B20%, for which GI of 63.1% was obtained at the air-flow rate of 0.4.

Conclusions

The addition of biochar to UFMSW have a positive effect on the 3-week intensive phase of aerobic biostabilization. It was observed that the addition of biochar at more than 3% to UFMSW caused a decrease in the dynamics of MC changes followed by water accumulation in the waste (similarly to the composting of organic waste). It was found that the biochar additives insufficiently stimulated the biological degradation of OM, but it had a positive effect on respiration activity. Biochar can intensify the biostabilization process to obtain the "well-stabilized waste" in a short time. The air flow rate at the level of 0.4 m³·d⁻¹·(kg org DM)⁻¹ allowed to obtained appropriate value of the AT4 parameter, irrespective of the biochar addition used. The addition of biochar at 3 and 5 wt% made it possible to obtain AT4 < 10 mgO₂·g DM⁻¹.

Microbiological evaluation of the aerobic biostabilization process of UFMSW allowed for concluding that the addition of biochar helps to significantly reduce the abundance of analyzed microorganisms to an acceptable level (especially with 3 wt% and 5 wt% additives, which is related to the long thermophilic phase), while it does not completely sanitize the processed UFMSW. It is also important to note that the 10 wt% and 20 wt% addition of biochar to UFMSW causes rapid and significant multiplication of microorganisms, which may result in increased oxygen demand or formation of anaerobic zones.

It is necessary to conduct future analyses of the long-term influence of biochar addition on the aerobic biostabilization of UFMSW (analyses after 2–4 months). Moreover, it is interesting from the cognitive point of view to determine the effectiveness of biochar as a bulking agent additive in biofilters.

Author contributions I am single-author of this manuscript. The study conception and design, material preparation, data collection and analysis, the first draft of the manuscript were performed by myself.

Data availability All data derived during the experiments are available at the Faculty of Production and Power Engineering, University of Agriculture in Krakow. A summary of these results in the form of aggregate tables and graphs are presented in this article.

Declarations

Cnflict of interest The author have no relevant financial or non-financial interests to disclose.

Ethical approval The author declare no conflict of interest and declare that the funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Consent to publish I approved this version of manuscript to be submitted and published in the Journal of Material Cycles and Waste Management.

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