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Composting process parameters of different types of manure in a bioreactor

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Abstract. Composting has been practiced since ancient times, where it was used to enhance soil fertility and support crop production. It is therefore regarded as the oldest known method of biowaste treatment. Over time, the process has been systematically optimized through studies on the dynamics of aerobic biodegradation of various organic substrates, making it one of the most extensively investigated biological treatment technologies. Despite this long history, composting remains an important research topic, particularly in the context of circular economy strategies and sustainable development objectives.
The aim of this study was to evaluate the composting dynamics of manure-based substrates differing in manure type, moisture content, and structural properties under controlled aerobic conditions. Experiments were conducted at the Ecotechnology Laboratory of the Poznań University of Life Sciences using four isothermal bioreactors (125 dm³ each) designed for controlled aerobic degradation. The tested materials included cattle manure (≈70% moisture), pig manure (> 80%), a mixture of cattle and pig manure (≈65%), and cattle manure (> 80%). During the process, O_2 and CO_2 concentrations, temperature, pH, bulk density, and mass loss were monitored, and dry matter, organic dry matter, organic carbon, and ash content were determined. The results showed clear differences in composting dynamics depending on manure type and moisture content. The cattle manure (70% moisture) exhibited rapid heating and a stable thermophilic phase, whereas highly moist pig manure showed slower temperature increase and lower intensity. The manure mixture demonstrated the highest microbiological activity, while excessive moisture in cattle manure (> 80%) reduced process efficiency. These findings confirm that manure type and moisture are key determinants of composting performance.

Key words: compost, composting process, manure composting, bioreactor, physico-chemical changes.

INTRODUCTION

Throughout history, the twenty-first century has proven to be groundbreaking for humanity in many ways (Humeniuk, 2025). Examples include the advanced development

of medicine, the rise in living standards, and a decrease in mortality rates. Additionally, the intensive development of new technologies can also be mentioned (Prus, 2023). Despite these achievements, this century presents humanity with numerous civilizational challenges, the most significant and widely discussed of which is global overpopulation (Uniyal et al., 2020). This is due to the fact that the number of people living on Earth continues to increase. The latest projections indicate that by 2050, the global population will reach approximately 9.7 billion people (Pison, 2022).

The continuous growth of the world population can be observed through direct indicators such as population data, natural increase, and fertility rates. However, this phenomenon is also evident when analyzing indirect indicators, such as energy consumption, transportation and mobility patterns, urbanization, waste production, water usage, and increased food consumption. The uninterrupted growth of the global population results in a steadily rising demand for food. In response to this demand, agricultural and livestock production have been intensified (Cafaro et al., 2022).

Animal production deserves particular attention, as according to OECD-FAO data, global meat production in 2024 amounted to approximately 365 million metric tons, while the same organization projects that by 2034, global meat production will reach 406 million metric tons. This significant increase in meat production will be primarily driven by rapid population growth and rising incomes. It is estimated that 45% of the global increase in meat consumption will occur in upper-middle-income countries. Among the types of meat produced, the largest growth in consumption is expected in poultry (OECD/FAO, 2025).

In order to ensure high levels of meat production, it is necessary to further intensify the already intensive livestock production. This action will have a significant impact, including increased emissions of odors and greenhouse gases, higher demand for drinking water, and increased agricultural production to provide sufficient feed for farm animals (Moekti, 2020).

The increase in livestock production will also be associated with a rise in manure production (Kozłowski et al., 2019). This material is valuable from an agricultural perspective, as it can be used to fertilize crops due to its provision of a wide range of micro- and macronutrients, and it also contributes to increasing the organic matter content in the soil (Sadeghpour & Afshar, 2024). Despite these advantages, manure can pose a challenge for modern intensive livestock production due to difficulties in its disposal. One reason for this is that, despite its numerous benefits, farmers often choose to use mineral fertilizers because they frequently provide higher concentrations of nutrients for plants.

Furthermore, this system of livestock production, due to the significant overproduction of manure, presents a considerable risk to human health. Untreated manure emits unpleasant odors, attracts insects and rodents, and promotes the spread of pathogens. Manure from livestock production is one of the most widely generated organic wastes worldwide, and improper management can lead to eutrophication and contamination of surface waters, creating serious environmental hazards (Li & Lemiasheuski, 2023; Liu et al., 2023).

Modern livestock production technologies generate manure in both solid and liquid forms. Pig production systems most commonly produce slurry, whereas poultry systems generate manure either as slurry or in a solid fraction. Manure is characterized by a

complex composition of dry matter. Its main components include carbohydrates, proteins, lipids, lignin, and volatile fatty acids. It is also common for manure to contain most of the elements essential for plant growth, with the highest concentrations being nitrogen, phosphorus, and potassium (Liu & Wang, 2020; Akash et al., 2022).

The composition of manure is influenced by many factors, including the type and composition of feed, the age and species of the animals, housing conditions, and the management of organic fertilizers. Manure from different animal groups exhibits characteristic properties. In cattle fed primarily on roughage, manure shows elevated levels of potassium, sodium, and calcium ions, as well as a high content of cellulose fibers. In the case of pigs and poultry, whose feed is richer in protein, manure composition reflects a higher proportion of nitrogenous compounds. Particularly high phosphorus content is typical of pig manure, due to frequent supplementation of feed with this element (Ather et al., 2022; Dong et al., 2022). It should also be noted that the phosphorus content of pig manure depends, among other factors, on whether phytase is included in feed rations, which can significantly reduce phosphorus excretion and thus its environmental load (Kristoffersen et al., 2021).

However, the use of manure is associated with certain environmental risks. The most significant include excessive loading of ecosystems with biogenic elements, the potential spread of pathogenic microorganisms, and gas emissions. Intensive fertilization of agricultural soils can lead to the leaching of nitrogen and phosphorus and their transport into surface waters, promoting eutrophication and the development of algal blooms. An additional concern is the presence of residues of heavy metals, antibiotics, and hormones in manure, which, when applied to soil, can become a diffuse source of water contamination (Liu & Wang, 2020).

Manure is also a significant source of gas emissions, including ammonia, methane, and nitrous oxide, as well as compounds responsible for unpleasant odors, such as hydrogen sulfide, phenols, indoles, and volatile organic acids. Methane and nitrous oxide are potent greenhouse gases that contribute significantly to global climate change. Emissions of ammonia and hydrogen sulfide can negatively affect the health of farm workers. Meanwhile, odor nuisance from manure remains one of the main causes of social conflicts and negative perceptions of intensive livestock production (Bojarski et al., 2022; Gunamantha et al., 2022; Li et al., 2022b).

Pathogenic microorganisms can survive for several months in improperly processed manure. During and after outbreaks of infectious diseases, this material can serve as a potential source of reinfection for animals, particularly when it is stored and reused within the farm. The application of contaminated manure on agricultural fields increases the risk of disease spread among animal populations and the transmission of pathogens to humans, especially when fertilizing crops consumed raw, such as lettuce (Lin et al., 2022).

Manure management involves a series of stages, from its generation, through collection, transport, and storage, to processing and final utilization. An effective system should consider the entire nutrient cycle and ensure their safe incorporation into the soil (Skliar et al., 2022). Management practices vary significantly across regions of the world. For example, in the southern United States, it is common to store diluted manure in lagoons and apply it to fields in liquid form. In Europe, particularly in European Union member states, anaerobic digestion has been widely adopted, allowing for both the safe treatment of manure and energy recovery (Bresz et al., 2022; El Mashad et al., 2023).

The primary goal of manure utilization remains the efficient management of the nutrients it contains and their reintegration into the natural biogenic cycle. Beyond its fertilizing function, manure also has significant energy potential. It can be used for the production of energy or fuels through biological and thermochemical processes. One of the most commonly applied solutions is anaerobic digestion, during which methanogenic microorganisms convert organic matter into biogas, with methane as its main component (Czekała et al., 2023; Marques-dos-Santos et al., 2023; Nowak et al., 2024).

Despite the intensive development of technologies aimed at improving agricultural production efficiency and reducing its costs, manure management practices in many farms have remained unchanged for years (El Mashad et al., 2023).

One of the most common and simultaneously one of the most cost-effective methods of manure processing is composting. This process relies on the activity of aerobic microorganisms, which decompose the biodegradable organic matter present in manure, producing heat, carbon dioxide, and water. As a result of composting, manure undergoes a series of beneficial changes that enhance its practical value. There is a significant reduction in moisture content and volatile organic matter, leading to a substantial decrease in the material's volume (Chen et al., 2024).

The product resulting from the composting process is easier to store and apply, cheaper to transport, and exhibits a reduced tendency to emit odors and other gaseous pollutants. The high temperatures achieved during biological decomposition promote the elimination of most pathogens and weed seeds, while producing a material that is safe for environmental use. Composted manure serves as a source of nutrients that are gradually released, thereby reducing the risk of nutrient leaching and negative impacts on water quality (Li et al., 2022b).

The composting process occurs in two main phases. The active phase is characterized by intense microbial activity, during which oxygen is consumed as easily degradable organic compounds, such as sugars, fats, and amino acids, as well as some more resistant components, including cellulose and hemicellulose, are broken down. In the maturation phase, the rate of biological processes slows down, and the dominant phenomena become the mineralization of recalcitrant matter and the humification of lignocellulosic compounds. As a result, the resulting compost may exhibit a volume reduction of up to 60%, a moisture decrease of approximately 40%, and a mass reduction of up to half (Bojarski et al., 2023).

The efficiency of composting largely depends on providing suitable conditions for the growth of aerobic microorganisms. Oxygen availability and material moisture are of key importance. The heat generated during the decomposition of organic matter leads to a temperature increase, which, with an appropriate choice of pile size and shape, can be maintained between 40 and 65 °C. Aeration is achieved through periodic turning of the material or the use of forced ventilation systems. These practices allow for the supply of oxygen and the removal of excess heat, moisture, and carbon dioxide. The optimal moisture content of the composting mass is typically between 40 and 60%, although depending on climatic conditions, additional watering or protection of the pile from excessive drying may be necessary (Janczak et al., 2022; Czekała et al., 2023).

Fresh manure often does not possess properties conducive to direct composting. The most common problems include excessive moisture, low porosity, and an unfavorable carbon-to-nitrogen ratio. High water content and poor material permeability

hinder gas exchange, while a high nitrogen concentration relative to carbon promotes its loss as ammonia or through leaching. The optimal C:N ratio for composting is approximately 25:1 to 30:1, whereas manure typically contains much more nitrogen than readily degradable carbon (Sołowiej et al., 2017). In practice, the first step in preparing the material is often mixing manure with a bulking agent characterized by high carbon content, such as straw, wood chips, or other low-moisture agricultural residues with a high C:N ratio and coarse structure. This improves porosity and aerobic conditions (Aguilar-Paredes et al., 2023; Bojarski et al., 2023).

In practice, several basic composting methods are used, including turned windrows, static piles, and enclosed systems. In the windrow method, material is arranged in elongated piles through which air can flow. However, in the absence of active aeration, there is a risk of oxygen deficiency, which promotes the formation of unpleasant odors and greenhouse gas emissions. This problem is mitigated through mechanical turning of the windrows using loaders, spreaders, or specialized turners, which restore the material's structure and oxygen availability. An alternative solution is static piles, in which air flow is provided by ventilation pipe systems embedded within the compost mass. These setups are often insulated to minimize heat loss and maintain a uniform temperature. The greatest control over the process is offered by enclosed systems, typically implemented in rotating drums, where intensive mixing and forced aeration allow precise regulation of temperature, oxygen supply, and moisture content, thereby optimizing the rate of organic matter decomposition (Oshins et al., 2022; Czekała et al., 2023).

A particularly promising approach to assessing the quality and maturity of produced compost is digital image analysis supported by advanced software tools, including those based on artificial intelligence algorithms (Boniecki et al., 2009). Within the agricultural sector, such methods are applied not only for evaluating compost maturity, but also, for example, for the assessment of vegetable quality parameters (Boniecki et al., 2013; Koszela et al., 2013).

Despite extensive research on composting processes, there is still limited understanding of how different manure-based substrates, characterized by varying moisture content and structural properties, behave under controlled bioreactor conditions without standardization of these parameters. In particular, the combined effect of these factors on process dynamics remains insufficiently described.

The aim of the study was to analyze differences in key parameters of the composting process among manure-based substrates with varying initial properties. The research focused on describing the course of composting under different conditions and identifying differences in process parameters, including temperature development, moisture changes, and organic matter degradation. The observed differences are discussed in relation to the initial physicochemical characteristics of the substrates and the applied process conditions.

MATERIALS AND METHODS

The research presented in this study was conducted at the Ecotechnology Laboratory affiliated with the Department of Biosystems Engineering, Faculty of Environmental and Mechanical Engineering, Poznań University of Life Sciences.

Four different manure-based substrates were used in the study, each assigned to a separate bioreactor:

- Sample 1: Cattle manure (straw content: 4 kg/head/day, medium moisture, approximately 70%),
- Sample 2: Pig manure (straw content: 3.5 kg/head/day, high moisture, above 80%),
- Sample 3: Mixture of pig and cattle manure in a 50:50 mass ratio (straw content: >5 kg/head/day, medium moisture, approximately 65%),
- Sample 4: Cattle manure (straw content: 3.5 kg/head/day, high moisture, above 80%).

The experiment was conducted without replication, with one bioreactor assigned to each substrate variant. The materials were used in their natural form without standardization of moisture content or structure in order to reflect practical conditions of manure management.

The composting experiment was preceded by basic physicochemical analyses of the manure, which included the determination of pH, dry matter, organic dry matter, and the carbon-to-nitrogen (C:N) ratio. The analyses were conducted at the Ecotechnology Laboratory using standard procedures in accordance with Polish Standards (Wolna-Maruwka & Dach, 2009; Kupryaniuk et al., 2025).

Composting was carried out in four isothermal bioreactors, each with a capacity of 125 dm^3. This equipment is used in studies investigating processes occurring during the aerobic degradation of organic matter (Wolna-Maruwka & Dach, 2009). Numerous studies have shown that the applied reactors faithfully replicate composting conditions observed at a real scale (Czekała et al., 2022; Bojarski et al., 2023).

After filling the reactors with the respective types of manure, three digital LCD thermometers were installed in each, allowing continuous temperature monitoring within the substrate. The sensors were placed at different levels of the material: the first approximately 20 cm from the bottom, with the others positioned above at intervals of about 15 cm. This measurement arrangement enabled observation of temperature changes in the vertical section of the bioreactor and improved the accuracy of determining maximum temperatures reached during the process.

Air was supplied to the bioreactors using a blower. The flow rate was monitored with gas meters, while control valves regulated the airflow. The gas leaving the reactor was directed to a cooler, where condensates were separated and collected in a designated container.

After passing through the cooler, the gas stream entered a distribution system, where its chemical composition was analyzed twice daily using a GA5000 analyzer (Geotech). The gas was then vented outside the installation. All results were recorded in a system that continuously monitored process parameters, enabling rapid identification of potential irregularities.

In addition to the condensate collected in a separate container, liquids accumulating in the reactor chamber and leachate generated during composting were also removed. A diagram illustrating the structure and operation of the described system is provided below.

In Fig. 1, the components of the experimental setup are numbered from 1 to 12. The blower is indicated as number 1, the gas flow control valve as 2, and the gas meter as 3.

The bioreactor is numbered 4, and the leachate container is 5. The composting material is labeled 6, the thermometers 7, and the gas cooler leaving the reactor 8. The condensate tank from the cooler is number 9. Number 10 corresponds to the set of gas sensors, 11 to the data recorder, and 12 to the blower control system.

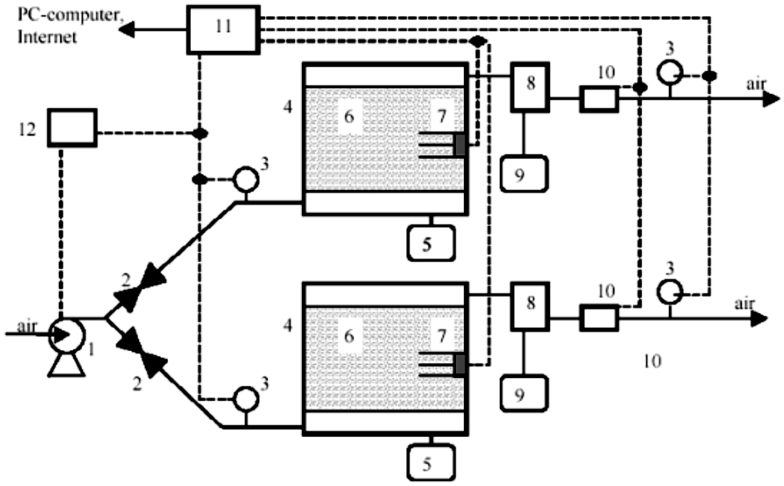

Figure 1. Diagram of a composting station, reflecting the actual conditions of this process (Czekała et al., 2015).

After filling the bioreactors with material, the distance from the surface of the substrate to the top edge of each reactor was measured. Measurements were taken at the center of the four walls, and the arithmetic mean of the obtained values was calculated. Based on these data, the initial volume and bulk density of the substrate were determined. The reactors were then sealed so that all gas supplied to the interior could exit only through the cooler.

Once the system was closed, aeration of the composting mixture was initiated. During the experiment, the intensity of aeration was adjusted to maintain elevated temperatures inside the reactors for as long as possible and to ensure that the oxygen content for the microorganisms remained within the range of 13–21% (Wang et al., 2021).

The process began on November 20, 2024, and continued until December 15, 2024. Every day, at approximately 12-hour intervals, the highest temperature recorded in each bioreactor and the amount of air supplied were logged. Simultaneously, the gas composition was analyzed using a GA5000 analyzer (Geotech).

On the twelfth day of the experiment, it became necessary to aerate the mixture. This was due to an increase in the bulk density of the material, caused by the ongoing decomposition of organic compounds. The need for intervention was indicated by the gas analysis results and temperature measurements, which showed a drop in reactor temperatures, an increase in oxygen concentration, and a decrease in carbon dioxide content.

The aeration process involved emptying the bioreactors of composting substrates, which were then intensively mixed. The contents of each reactor were mixed separately.

This procedure aimed to loosen the material and, most importantly, to evenly distribute moisture and microorganisms responsible for the composting process throughout the substrate (Li et al., 2022a; Peng et al., 2023).

The duration of the composting process varied among the four manure types, ranging from 16 to 25 days, reflecting differences in the biological activity of each substrate. In each case, the end of the process was determined based on the same criteria: a decrease in bioreactor temperature to ambient levels, elevated oxygen concentrations, and low carbon dioxide levels in the exhaust gas stream. These parameters collectively indicated the cessation of microbial activity and, consequently, the completion of the composting process (Luo et al., 2024).

RESULTS AND DISCUSSION

The evaluation of composting performance depends on the selected criteria (e.g. temperature development, mass loss, or final material properties), which varied between the tested substrates. Therefore, no single treatment can be identified as universally superior, and the results are discussed in terms of specific process parameters. It should also be noted that the experimental variants differed not only in manure type but also in moisture content, straw addition, and aeration conditions, which were adjusted individually during the process. As a result, the observed differences reflect the combined effect of these factors rather than the influence of a single variable.

Weight loss

During the experiments, a successive decrease in mass was observed for each type of manure. All tested manure samples exhibited very similar patterns of mass change. The results of these changes are presented in Fig. 2 below.

The greatest mass loss was observed in Sample 3, which had the highest straw content. The initial mass of this Sample was 36.30 kg, and by the end of the composting process it had decreased by 39%, resulting in a final mass of 22 kg. Manure from Sample 1, with a similar material composition, experienced a 25% mass reduction, decreasing from 43 kg to 32 kg. For Samples 2 and 4, mass losses were 26% and 29%, respectively. The initial mass of Sample 2 before placement in the bioreactor was 53 kg, and it decreased to 39 kg by the end of the experiment. For Sample 4, the corresponding values were 48 kg and 34 kg. Mass loss during composting is a well-documented phenomenon, widely reported in the scientific literature by numerous researchers investigating this process (Pezzolla et al., 2021; Oshins et al., 2022; Waqas et al., 2023).

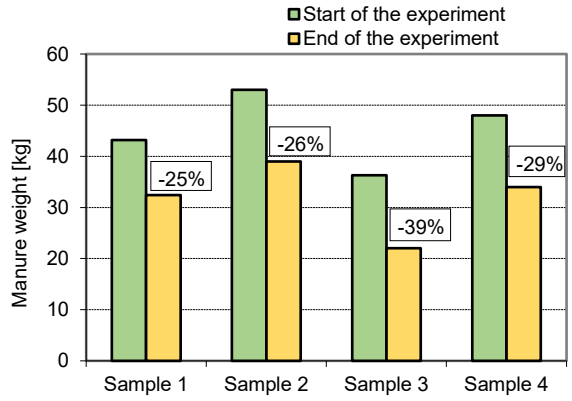

Figure 2. Weight changes for individual manure samples.

Temperature changes

The most characteristic phenomenon observed during composting was the increase in temperature within the tested manure samples (Wang et al., 2022; Wang et al., 2024). Fig. 3 below presents the temperature change graphs in relation to the amount of air passing through each Sample during the composting process. The airflow rate on the graph is expressed on an hourly basis.

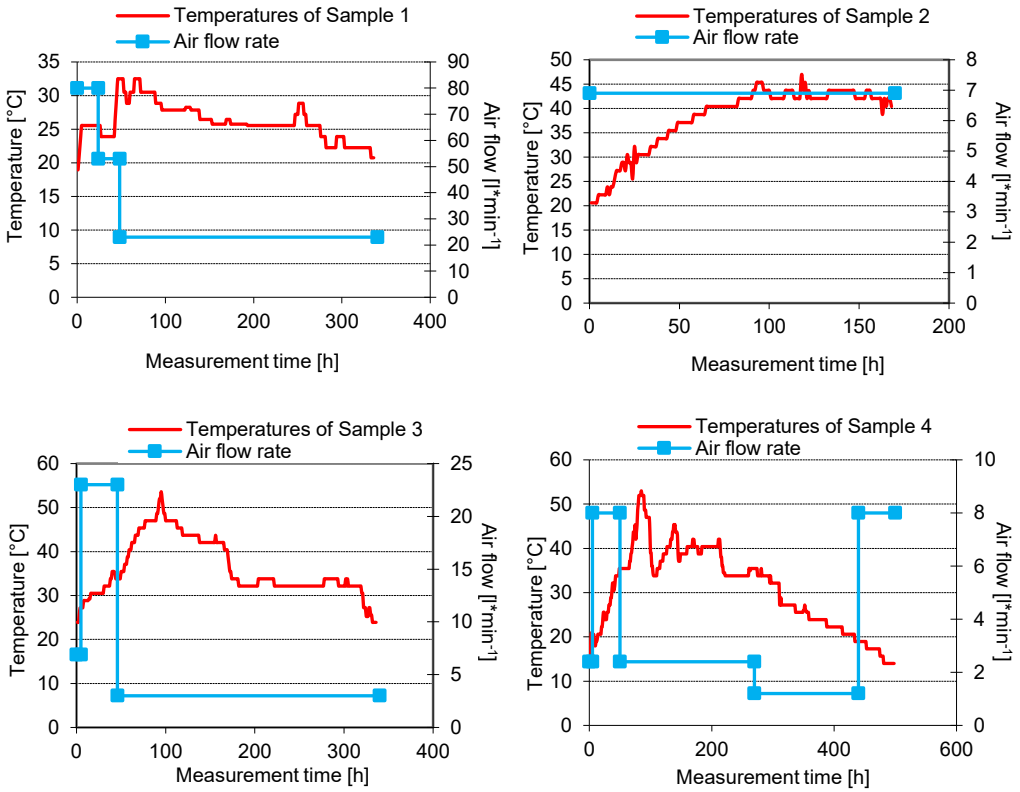

Figure 3. Temperature changes during composting of the tested samples in relation to the amount of air flow. The layout of the graphs corresponds to the order of the samples (1, 2, 3, and 4).

Since Sample 1 was the first to be tested in the bioreactor, the optimal air supply for proper decomposition was initially unknown. Therefore, during the first 26 hours of the experiment, the blower operated at its maximum capacity of 80 L min^{-1}. The use of gas meters allowed for precise determination of the volume of air supplied to the chamber. According to literature data, the temperature in the first two days of proper composting should rise to approximately 50 °C, therefore, the air supply was reduced to 53 L min^{-1} (Amuah, et al., 2022).

The initial temperature of Sample 1 at the time of placement in the chamber was low, only 7 °C, as the material was taken from a field pile at an ambient temperature of −10 °C. This also explains why the temperature increase during the first days was not significant. An airflow of 53 L min^{-1} raised the temperature to approximately 33 °C by the 48th hour of measurement. However, this temperature was deemed too low for the

proper progression of the thermophilic phase. Consequently, the air supply was further reduced to 23 L min^{-1}. This reduction in aeration at the 48th hour of measurement caused minor fluctuations in O_2 concentration. Despite this adjustment, the temperature remained around 33 °C, with minor fluctuations, until the 75th hour of measurement. Further aeration only caused a decline in temperature. Similar observations regarding the effect of aeration management on the composting process have been reported in the scientific literature (Zhao et al., 2022; Lai et al., 2024).

The oxygen content in the air discharged from the bioreactor chamber served as the primary reference base for determining, controlling, and adjusting aeration intensity across the experimental variants. The O_2 level was treated as a key indicator of aerobic conditions inside the chamber, and thus as a parameter enabling assessment of whether the applied airflow was sufficient for the proper progression of the composting process. Oxygen content measurements were conducted at hourly intervals. The changes in oxygen content in the air discharged from the bioreactor chamber are presented in the figure below (see Fig. 4).

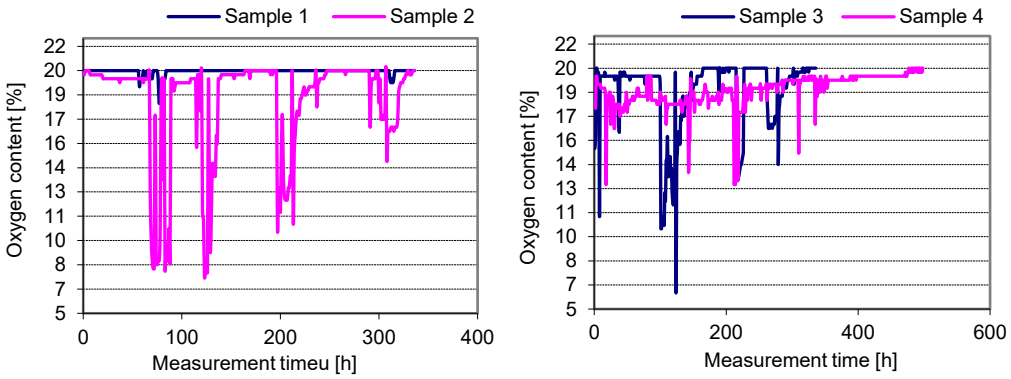

Figure 4. Changes in the oxygen content in the air discharged from the bioreactor chamber for samples 1, 2, 3, and 4.

Sample 1 was characterized by the most stable oxygen content profile, which resulted from the continuous blower operation and the associated large volume of air supplied to the bioreactor chamber. The reduction in airflow to 53 L·min^{-1} after 26 hours did not cause a significant decrease in oxygen content in the discharged air. In the subsequent hours of the experiment, oxygen content remained at a relatively constant level, indicating that the applied airflow continued to ensure aerobic conditions inside the chamber. The total volume of air supplied to the bioreactor chamber in Sample 1 amounted to 460,115 dm^3.

The manure used in this experiment had a medium straw content. Conducting the study with relatively high airflow on material with such characteristics caused rapid drying, resulting in an incomplete decomposition of organic matter, as confirmed by the smallest observed mass loss. Due to the porous structure created by the straw, the material lost moisture easily; however, excessive airflow led to over-drying, partially suppressing microbial activity.

For Sample 2, a different air supply regulation method was applied. An automatic timer was used to control the blower, maintaining an airflow of 23 L min^{-1} but reducing the actual aeration time to 18 minutes per hour (18 minutes of blower operation and 42 minutes of rest). The maximum temperature of 47 °C was reached in the 118th hour of measurement. Similar trends have been described in previous studies (Meng et al., 2023).

In contrast to Sample 1, Samples 2, 3, and 4 exhibited a markedly more dynamic oxygen content profile. The periodic drops in O_2 concentration observed in these samples indicate intensive aerobic microbial activity and rapid oxygen consumption during phases of increased organic matter biodegradation. According to literature data, aerobic conditions in a composting environment are maintained when oxygen content is at least 10% by volume (Nguyen et al., 2023). This criterion was generally met in the studied samples, although short-term decreases in oxygen content indicated the need for aeration adjustments and periodic mixing of the material. In Samples 2, 3, and 4, CO_2 content during the experiments oscillated around 10%, confirming intensive oxygen consumption by microorganisms. After the first aeration event, CO_2 concentration in each of these samples rose sharply, reaching values in the range of 13–16%. Combined with the rapid temperature increase, this indirectly indicates intensive development of microflora responsible for organic matter decomposition, which is beneficial for the composting process. Subsequent mixing of the material improved aeration conditions inside the samples and contributed to maintaining a constant presence of oxygen in the bioreactor chambers.

Sample 3 consisted of a mixture of pig and cattle manure with a high content of rye straw. As in the previous experiment, an automatic timer was used in the same operational mode. At the 4^{th} hour of measurement, the blower mode was changed from 18/42 (18 minutes on, 42 minutes off) to continuous operation to quickly reduce moisture content. The intensified aeration improved drying but inhibited temperature rise. Therefore, at the 46^{th} hour, the air supply was reduced to 10 L min^{-1}, equivalent to 3 L min^{-1} on an hourly basis. From this point, a rapid temperature increase was observed, reaching a maximum of 53.5 °C at the 95^{th} hour. These observations are consistent with previous studies indicating that aeration conditions play a key role in shaping composting dynamics (Puspitaloka et al., 2022).

Sample 3 demonstrated the highest heating capacity among all composted samples. The final material obtained after removal from the chamber was free of manure odor, smelled like forest litter, had a dark brown color, and a loose, crumbly texture.

Cattle manure with rye straw, used in Sample 4, was subjected to aeration with variable frequency. This experiment lasted 21 days, the longest of all conducted so far. From the start, the air supply was reduced to 8 L min^{-1}. Immediately after starting the bioreactor, a rapid temperature increase was observed, indicating that the manure quickly reached the thermophilic phase. During the first 5 hours, the blower operated in the 18/42 mode, equivalent to an hourly flow of 2.4 L min^{-1}. For the next 45 hours, the blower ran continuously. Despite continuous aeration, the temperature increased rapidly. At the 50^{th} hour, airflow was reduced by switching the blower back to the 18/42 mode. Sample 4 reached its maximum temperature of 53 °C at the 85^{th} hour. Comparable trends have been described in the literature (Zhang et al., 2021; Tang et al., 2023).

The differences in maximum temperatures achieved indicate variations in the degree of organic matter decomposition among the composts. The highest level of decomposition was observed in Sample 4, which reached a maximum temperature of 53 °C. The higher temperature in this Sample suggests more intensive microbial activity, resulting in a faster and more advanced composting process compared to the other samples.

The total volumes of air supplied to the bioreactor chambers in Samples 2, 3, and 4 amounted to 414,003, 332,012, and 113,002 dm^3, respectively. Throughout the measurements, the sum of determined oxygen and carbon dioxide contents ranged from 20.0 to 20.5%. On this basis, it can be assumed that the share of other gases, such as methane or nitrogen oxides, was negligible and did not exceed 1%. These results further confirm that changes in O_2 and CO_2 content were the primary indicators of the intensity of biological transformations occurring in the bioreactor chambers and served as the basis for interpreting the applied aeration volumes.

Changes in pH

An increase in pH during composting is an indicator of proper process progression (Ho et al., 2022; Bojarski et al., 2023). Each type of manure used in the study had different initial values of this parameter.

In Sample 1, the initial pH was very low compared to the other samples, at only 6.7 (Lalremruati & Devi, 2023). Measurements using a pH meter during successive aeration cycles indicated a gradual increase in this parameter. Ultimately, characteristic of the compost maturation phase, the pH reached 7.9. A similar trend was observed in Sample 3, which exhibited the greatest rate of pH increase and the highest variability. The maximum pH value of 8.7 was reached at the 268th hour of the experiment. This increase resulted from high temperatures and the associated mineralization processes occurring during the thermophilic phase of composting (Geisseler et al., 2021). After the third aeration, a slight decrease in pH occurred, reaching a final value of 8.3 at the end of the experiment. The pH results for this Sample confirm the high quality of the compost obtained (Shi et al., 2022).

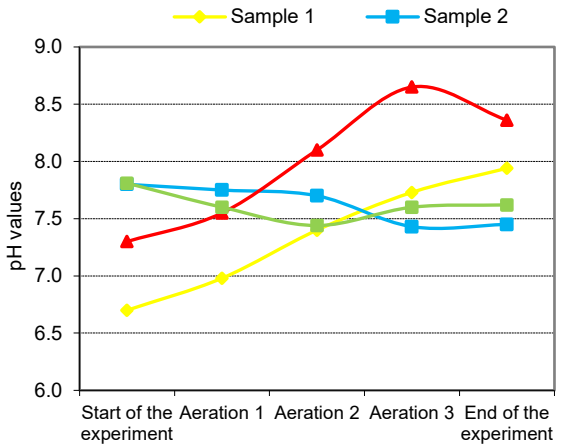

Figure 5. pH changes during composting for all manure samples tested.

During the other composting experiments with pig and cattle manure, no significant fluctuations in pH were observed, as illustrated in Fig. 5.

Changes in dry matter content

The initial dry matter content, as well as its progression, varied considerably across all tested samples. A summary of the changes in dry matter content is presented in Fig. 6.

In Sample 1, the initial dry matter content was 44.9%, one of the highest among all tested samples. Despite this, the changes in dry matter content occurred in an irregular manner.

At the start of the experiment, the dry matter content dropped sharply to 33%. This may have been related to the release of a large amount of water vapor and its condensation in the upper part of the bioreactor chamber (Wojcieszak et al., 2021). Assessment of the content of dry matter and dry organic matter in compost with neural modelling methods (Agriculture, 11(4), 307). After the first aeration, the dry matter content increased slightly; however, the subsequent aeration caused another decrease. Only the third aeration resulted in a rapid reduction of material moisture. At the end of the experiment, analysis of the final compost showed that the dry matter content had decreased by 2% compared to the initial value of the sample.

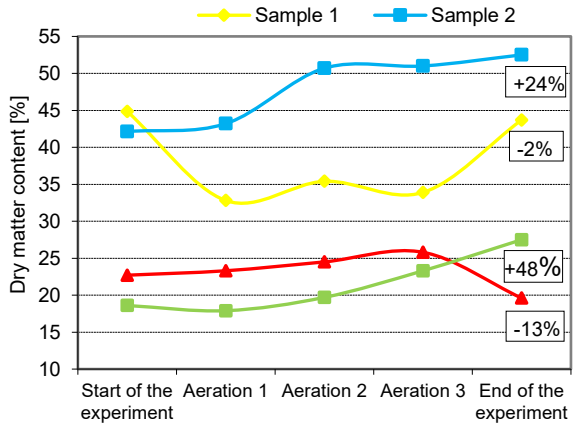

Figure 6. Changes in dry matter content during composting for all manure samples tested.

Sample 3 exhibited a gradual increase in dry matter content during the first two aerations. Despite the high straw content, the initial dry matter value was relatively low, around 22.7%. A decrease in dry matter content was observed after the third aeration. This may be related to the prolonged thermophilic phase and the redistribution of moisture within the material, including possible condensation of water vapor in cooler zones of the reactor. At the same time, it should be noted that the relationship between aeration intensity and moisture changes is complex, and the observed trend may result from the combined effect of airflow, temperature gradients, and internal moisture dynamics. As a result, at the end of the experiment, the dry matter content reached 19.6%, representing a 13% decrease compared to the initial value.

In Sample 4, the initial dry matter content at the start of the process was 18.6%. Such high initial moisture significantly hindered proper composting due to limited air penetration into the Sample (Takala, 2021). The high moisture content led to the production of a considerable amount of leachate throughout the process (Li et al., 2021). Combined with water evaporation caused by rapid temperature rise, this resulted in a slight decrease in dry matter content to 17.9%. The first aeration reduced the temperature but improved the air-moisture conditions inside the bioreactor chamber, which enhanced evaporation and consequently decreased moisture content. Sample 4 reached its

maximum dry matter content after three weeks of experimentation (504th hour), achieving 27.5%, representing a 48% increase.

Sample 2, similarly to Sample 4, showed an increase in dry matter content. At the start of the process, the dry matter content was 42.1%. After the first aeration, at the 88th hour, a rapid increase to 50.7% was observed, coinciding with the most intensive leachate production. The subsequent two aerations did not significantly affect the dry matter content. It stabilized at approximately 50.5%, reaching 52.5% at the end of the experiment, representing a 24% increase compared to the initial value.

CONCLUSIONS

The study demonstrated that differences in the initial parameters of the substrates can affect the course of the composting process. The observed composting dynamics were influenced by the combined effect of manure type, moisture content, and aeration conditions. Different manure types exhibited distinct microbial activity and varying potential for material stabilization. However, due to the lack of replication, these results should be interpreted with caution and cannot be generalized beyond the conditions of this study. The study is also limited by the lack of detailed data on nutrient losses, changes in chemical composition, and gaseous emissions. As a result, the interpretation focuses mainly on process dynamics, including temperature, oxygen and carbon dioxide concentrations, mass loss, pH, and dry matter changes. The findings nonetheless highlight the importance of careful substrate selection and preparation for optimizing composting performance and predicting process efficiency based on the initial properties of the materials. From a practical standpoint, the results suggest that prior assessment of substrate moisture content and manure type should be considered as a standard step in the planning of composting operations, as these parameters appear to substantially influence process dynamics and the quality of the final product.

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