DOI: https://doi.org/10.21323/2618-9771-2025-8-1-36-41

Received 28.10.2024
Accepted in revised 26.02.2025
Accepted for publication 04.03.2025

Available online at https://www.fsjour.com/jour
Review article
Open access

OPTIMIZATION OF AEROBIC FERMENTATION FOR ORGANIC WASTE: KEY FACTORS AND THEIR IMPACT ON THE QUALITY OF THE FINAL PRODUCT

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KEY WORDS: food waste, composting, factors of aerobic fermentation, rational regimes

ABSTRACT
In modern economic conditions, waste management and food security are important areas of sustainable development. Currently, there are many technologies for organic waste recycling. One common method of processing is aerobic fermentation. Food waste is difficult to process due to its physicochemical and organoleptic characteristics, unstable composition, high moisture, and various pH values. This significantly limits the choice of processing technologies. One way to improve efficiency is by combining different types of waste. This article analyzes the process of aerobic fermentation of mixed organic waste, and determines the parameters influencing the fermentation process (optimal temperature, presence of oxygen, and microorganisms). The key factors (moisture, acidity, carbon, and nitrogen ratio) influencing the production of a high-quality secondary product with high added value are defined, and the optimal ranges of these factors and methods for improving the conditions for starting the fermentation process of food waste in combination with other organic waste are determined. The scientific research has been conducted since the 1996 study to the present, with particular emphasis on the period 2012–2024. The main results of the study are confirmation that the optimal values of the initial criteria for food waste differ from the acceptable values of other organic waste. The key task in the preparation of organic mass is to determine the optimal ranges of factors and the content of various types of waste depending on the final goal and the choice of secondary product. The key task in preparing organic matter is to determine the optimal ranges of factors and the content of various types of waste depending on the final goal and the choice of secondary product. Information on the optimal indicators of the resulting product is provided. In addition, fermentation patterns and quality requirements for the final product, as well as six basic principles of this process, are found based on the analysis of factors.

Поступила 28.10.2024
Поступила после рецензирования 26.02.2025
Принята в печать 04.03.2025

https://www.fsjour.com/jour
Обзорная статья
Open access

ОПТИМИЗАЦИЯ АЭРОБНОЙ ФЕРМЕНТАЦИИ ОРГАНИЧЕСКИХ ОТХОДОВ: КЛЮЧЕВЫЕ ФАКТОРЫ И ИХ ВЛИЯНИЕ НА КАЧЕСТВО КОНЕЧНОГО ПРОДУКТА

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КЛЮЧЕВЫЕ СЛОВА: пищевые отходы, компостирование, факторы аэробной ферментации, рациональные режимы

АННОТАЦИЯ
В современных экономических условиях важным направлением устойчивого развития является управление отходами и обеспечение продовольственной безопасности. В настоящее время существует множество технологий переработки органических отходов. Одним из распространенных методов переработки является аэробная ферментация. Пищевые отходы являются сложным для переработки материалом из-за своих физико-химических и органолептических характеристик, нестабильного состава, высокой влажности и различных значений pH. Это существенно ограничивает выбор технологий переработки. Одним из способов повышения эффективности является комбинирование различных видов отходов. В данной статье проанализирован процесс аэробной ферментации смешанных органических отходов и определены параметры, влияющие на процесс ферментации (оптимальная температура, наличие кислорода и микроорганизмов). Выявлены ключевые факторы (влажность, кислотность, соотношение углерода и азота), влияющие на получение высококачественного вторичного продукта с высокой добавленной стоимостью, установлены оптимальные диапазоны этих факторов и методы улучшения условий запуска процесса ферментации пищевых отходов в сочетании с другими органическими отходами. Научное исследование проводилось с 1996 года по настоящее время, с особым акцентом на период 2012–2024 гг. Основными результатами исследования являются подтверждение того, что оптимальные значения исходных критериев для пищевых отходов отличаются от допустимых значений других органических отходов. Ключевой задачей при подготовке органической массы является определение оптимальных диапазонов факторов и содержания различных видов отходов в зависимости от конечной цели и выбора вторичного продукта. Ключевой задачей при подготовке органического вещества является определение оптимальных диапазонов факторов и содержания различных видов отходов в зависимости от конечной цели и выбора вторичного продукта. Приведена информация об оптимальных показателях получаемого продукта. Кроме того, на основе анализа факторов выявлены закономерности ферментации и требования к качеству конечного продукта, а также шесть основных принципов этого процесса.

FOR CITATION: **Uvarov, R. A, Ermochenko, A. I.** (2025). Optimization of aerobic fermentation for organic waste: Key factors and their impact on the quality of the final product. *Food Systems,* 8(1), 36–41. https://doi.org/10.21323/2618-9771-2025-8-1-36-41

ДЛЯ ЦИТИРОВАНИЯ: **Уваров, Р. А., Ермоченко, А. И.** (2025). Оптимизация аэробной ферментации органических отходов: ключевые факторы и их влияние на качество конечного продукта. *Пищевые системы*, 8(1), 36–41. https://doi.org/10.21323/2618-9771-2025-8-1-36-41

1. Introduction

The concept of sustainable development is a model of economic progress that focuses on reducing, reusing, and recycling resources to minimize waste generation. In the context of global environmental challenges such as climate change and depletion of natural resources, this concept is of particular importance for the food industry.

Recycling organic waste, including food waste, helps reduce greenhouse gas emissions resulting from the decomposition of organic materials in the landfills. In addition, recycling can become an additional source of raw materials to produce biogas, compost, and other valuable products, which helps reduce dependence on fossil resources and supports economic sustainability [1,2].

According to the World Health Organization (WHO), improper waste management can lead to serious environmental and health problems, including soil and water pollution, as well as the spread of infectious diseases. In the context of global warming and climate change, effective waste management becomes even more relevant [3]. A key aspect of sustainable development is the transformation of waste into new products or goods with increased added value, as well as their use as raw materials for other processes. Recycling food and organic waste is an important step in this direction. This leads to a reduction in waste disposal volumes and contributes to the formation of new business models based on the principles of closed production cycles [4].

The circular economy involves a transition from a linear model of consumption to a more sustainable system in which resources are reused and recycled. If we draw an analogy with the life cycle assessment of food products, then most often we observe a linear cycle called "Cradle-to-Grave" (C2G). In this case, organic products end up in landfills, and this approach is an ineffective concept in today's sustainable development realities [5,6]. The correct solution is the "Cradle-to-Cradle" approach (C2C), in this case, the waste is returned to the production cycle which includes the recycling process, which allows the waste to be reused [7,8].

With the increasing volume of organic waste generated by human activities, especially in urban and rural areas, there is a need for effective methods of recycling it. In this context, aerobic fermentation is a key element to ensure the circularity of production processes and maximize resource efficiency. In recent years, there has been a growing interest in developing new technologies and methods for intensifying the processes of aerobic decomposition of organic waste. Research shows that the use of modern approaches to managing the processes of organic waste utilization can significantly improve their efficiency. Numerous researches have established that in conditions of a complex natural climate, characterized by a long winter period, relatively low ambient temperatures, and high humidity, one of the most effective technologies for the bioconversion of organic waste is aerobic fermentation, carried out in closed installations [9–12]. Aerobic fermentation is a complex process characterized by dynamic changes caused by the interaction of various factors. The advantages of this technology are low energy intensity of the process, low capital and operating costs, the relative simplicity of the technology, higher quality characteristics of the final product, and relatively short processing times [13]. The resulting product (compost) has high added value and can be used as feed additives and bedding for animals or as the fertilizers for crop production, which provides a beneficial effect on the development of agriculture and reduces the load onto the environment [14].

The physicochemical and organoleptic characteristics of food waste significantly limit the choice of technologies for their processing. One option for increasing efficiency is the combinatorial selection of various types of waste. The combination of more than one raw material can provide a good opportunity to extract the benefits of each component and optimize the entire procedure. This method is applicable in terms of reducing the burden on the environment and economic efficiency [15]. The purpose of this article is to summarize the available data on the physical and chemical processes occurring in organic material, to analyze the factors of aerobic solid-phase fermentation of food waste, to determine their rational values and combinations allowing them to reduce processing time and the emission of nutrients into the environment while retaining or improving the quality of the final product.

2. Materials and methods

The object of research is the industry of processing organic waste by the method of aerobic fermentation, narrowing to food waste. Theoretical, fundamental, and applied research on specialized and related topics, which became the basis for systematized (generalized) data, were analyzed as research materials.

The search for sources was carried out using scientific databases Web of Science, Scopus, and Google Scholar and scientific electronic libraries CyberLeninka, eLIBRARY, as well as open Internet sources.

Data collection was carried out in Russian and English using the keywords: «компостирование» ("composting"), «переработка пищевых отходов» ("food waste processing"), «аэробная ферментация» ("aerobic fermentation"), «продовольственная безопасность» ("food safety").

Theoretical methods such as analysis, synthesis, induction, deduction, comparative analysis, and systematization were used as research methods.

3. Main factors influencing the process of aerobic fermentation

In food systems, including agriculture, aerobic fermentation is a biochemical process of decomposing complex organic substances into simpler components using microorganisms and protein catalysts (enzymes) with a change in the physicochemical composition of the final product, which has certain humic properties and which is free from pathogenic microflora. The selected technology requires oxygen to start [16,17]. Optimization of this process allows to increase its efficiency, reduce processing time, and improve the quality of the final product (compost).

Although aerobic fermentation is a process that can occur naturally, it requires monitoring and control of several factors to ensure efficient processing. The ability to vary controllable factors distinguishes aerobic fermentation from long-term holding and active/passive composting. The advantage of this technology is that it imitates the natural habitat of most microorganisms, requires less energy for disinfection, and is less susceptible to bacterial contamination, which allows the use of solid agro-industrial waste as secondary material resources without increasing the moisture content of the final product. All these features lead to lower capital and operating costs, as well as reduced waste processing time and increased efficiency.

Depending on the purpose of the study, aerobic fermentation factors can be divided into process factors (temperature, O_2 content, etc.) and material factors (moisture, pH, C/N ratio, etc.), and they can also be considered as controlled, manageable, and optimizable factors.

3.1. Temperature

The temperature reached by the fermented material during the process of self-heating due to the activity of mesophilic and thermophilic microflora is the main indicator of the successful progress of the process. With an optimal ratio of factors, it is possible to increase the reaction rate and reduce the loss of nutrients in the final mixture. The main condition for the process of aerobic fermentation of organic waste is the passage through several main temperature phases, in which different communities of microorganisms predominate (Figure 1).

During the "active" stage of decomposition, two main phases occur — mesophilic and thermophilic ones, where microorganisms decompose available organic material and their population increases, thus releasing heat that accumulates inside the mass. The mesophilic phase begins almost immediately, and the temperature in the mass gradually increases to the mesophilic range (from 40 °C to 55 °C). This period is marked by accelerated metabolism in microorganisms, with intensive decomposition of organic matter, the release of carbon dioxide and heat, and an increase in the level of available nitrogen, all of which promote the growth of the microbial population [19].

Next, the thermophilic phase comes. It is characterized by an increase of temperature up to 70 °C with duration of 5 to 25 days or more. Under such temperature and time conditions, complex organic compounds (for example, cellulose and lignin) undergo intensive decomposition, pathogenic microorganisms are destroyed at high temperatures, and the volume of the initial raw material is significantly reduced [20,21].

After completion of the active stage, the cooling process begins. The decomposition of the remaining organic matter continues, and the diversity of the microbial population increases, which contributes to a more

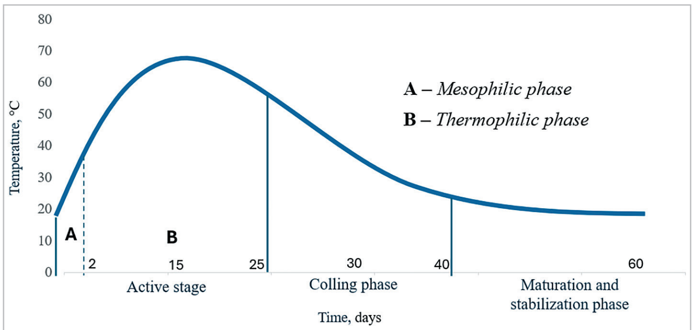

Figure 1. **Dynamics of the aerobic fermentation process [18]**
Рисунок 1. **Динамика процесса аэробной ферментации [18]**

complete decomposition of the remains; humic substances are formed, which improves the quality of the final product. Mesophilic microorganisms begin to dominate again at a comfortable temperature for them (from 40 °C to 55 °C) [22,23].

The final stage is maturation and stabilization with relatively low microbial activity and temperature, compared to the previous stages. This indicates the completion of biochemical processes, stable organic compounds are also formed, and the characteristic smell of finished compost appears [24]. The entire process of decomposition of organic matter occurs with the emission of carbon (in the form of CO_2) and nitrogen (in the form of NH_3) into the atmosphere in varying volumes [25].

The process of recycling food waste by aerobic fermentation may become less efficient due to the long-term prevalence of the same temperature regime:

- at temperatures below 30 °C, microbial metabolism slows down, resulting in longer fermentation times and a decrease in the overall efficiency of the process. The development of pathogenic microorganisms and weed seeds is also possible, which can negatively affect the quality of the compost;
- if temperatures above 60 °C persist for a long time, the activity of most mesophilic microorganisms decreases and protein denaturation begins, which can also slow down the decomposition process. Although thermophilic bacteria continue to function, too high a temperature can negatively affect their activity and lead to a decrease in the biodiversity of the microbial population.

The ability to control and manage temperature is a prerequisite for controlled aerobic fermentation:

- installation of thermometers or temperature sensors allows for real-time temperature monitoring;
- regulation of air flow helps to maintain the optimum temperature through heat exchange and prevention of overheating, in addition, in the biooxidation phase it is necessary to provide microorganisms with a sufficient amount of oxygen, and in the maturation phase it is necessary to remove excessive heat by evaporating moisture from the processed material;
- regular mixing of the processed mass using specialized equipment promotes uniform heat distribution and prevents the formation of "anaerobic loci";
- to protect from the external environment and changing weather conditions, insulating materials or special structures are used for the aerobic fermentation process.

3.2. Microorganisms

The entire process of aerobic fermentation is regulated by microbial activity aimed at ensuring the decomposition of complex organic compounds and their transformation into simpler substances. Microorganisms actively synthesize specific enzymes that decompose organic substrates into water and carbon dioxide. This leads to a decrease in the volume of waste and the formation of humus — an important component of finished high-quality compost. Aerobic microorganisms help destroy pathogenic bacteria and helminth eggs due to the heat released during the fermentation process. The temperature can reach 60–70 °C, which ensures sterilization of the material and increases the safety of the final product (finished compost). As a result of the activity of microorganisms, compost is enriched with macro- and microelements (N, P, K), which makes it a valuable fertilizer for agriculture.

To speed up and regulate the process, it is important to control microorganisms at various stages. The microbial community structure is critical for determining the maturity of the organic matter as it will change and evolve during the fermentation process. Chemical and biological changes during composting of various organic wastes indicate a change in the microbial population depending on the temperature reached during composting [26–28].

During the mesophilic phase (at temperatures of 40–55 °C) fungi predominate (*Penicillium citrinum, Rhizopus nigricans, Aspergillus flavus, Aspergillus niger)* [20] and acid-forming bacteria (*Lactobacillus* spp. and *Acetobacter* spp.*),* and also *Amycolicicoccus subflavus, Bacillus subtilis, Bacillus polymyxa, Mycobacterium xenopi, Mycobacterium thermoresistibil* [20].

At the active stage of the thermophilic phase (up to a temperature of 70 °C), *Talaromyces thermophilus, Talaromyces* sp., *Thermomyces* sp. (fungi), *Kyrpidia tusciae, Mahella australiensis, Solibacillus silvestris, Thermomonospora curvata* (bacteria) are of great importance [21]. When the temperature decreases, the microorganisms are again replaced by mesophilic ones and completely disappear at the final stage of maturation and stabilization.

Aerobic bacteria are the main participants in the process of aerobic fermentation. They use oxygen for respiration and decomposition of organic matter. Microorganisms feed on dead organic matter and promote its decomposition, secreting enzymes that break down complex molecules into simpler ones, which facilitates further absorption of products by other microorganisms (for example, saprophytic bacteria). Another part of microorganisms (for example, azotobacters) plays an important role in the nitrogen cycle, fixing atmospheric nitrogen and converting it into forms accessible to plants and thus helping improve the structure of compost, increasing its nutritional value.

Fungi are also involved in the process of decomposition of organic matter. They are able to decompose cellulose and lignin, which makes them indispensable for the processing of organic residues. Fungal mycelia form a network that promotes the aggregation of compost particles, improving its structure and aeration.

Finally, after the aerobic fermentation is over due to the action of the above specified microorganisms, organic waste is converted into mature organic mass, which can then be used as a fertilizer or as a substrate for feed additives or as animal bedding — a useful secondary organic product.

3.3. Moisture

Paying attention to the substrate moisture as one of the factors of the fermentation process, it was found that with an optimal ratio of factors the moisture decreases during the thermophilic phase when the temperature begins to increase during the fermentation of organic waste [29]. This factor directly determines the activity of microorganisms, the rate of decomposition of organic materials, and the quality of the finished compost.

When there is a lack of moisture (below 50%), the metabolic activity of microorganisms slows down. This leads to a decrease in the rate of decomposition of organic materials, an increase in fermentation time, and a deterioration in the quality of the compost. In conditions of insufficient moisture, the risk of developing anaerobic processes also increases, which can cause the accumulation of unpleasant odors and toxic substances.

When the moisture level, on the contrary, is excessive (more than 65%), negative consequences are possible, such as "flooding" of the fermented mass and lack of oxygen. This leads to the transition of the process to the anaerobic mode, which reduces the efficiency of decomposition and worsens the sanitary characteristics of the final product. Anaerobic conditions contribute to the formation of methane and other volatile organic compounds, which negatively impact the environment.

Various methods can be used to ensure optimal moisture levels during aerobic fermentation:

- adjusting the composition of the source material by mixing components with different moisture contents (e. g. sawdust, coal, green-cut fodder, kitchen waste, etc.) allows achieving the optimal moisture level;
- watering the fermented mass to maintain the required level of moisture. However, excessive watering should be avoided, as this can lead to overwatering;
- Regular mixing of the compost mass to ensure even distribution of moisture and prevent the formation of "dry" or "wet" zones.

When measuring the parameters, authors most often determine only the initial moisture content in organic waste [30,31]. At the initial stage, some authors measure the moisture content of each type of waste in the organic mass of the waste. For example, in [32] mixed organic waste was processed in a reactor with a fan and a grinder using aerobic fermentation technology. The initial moisture content of certain types of mixed waste was in the ranges from 7–15% (garden waste) and 8–11% (rice husks) to 70–80% (food waste). Measuring the moisture content of individual types of mixed waste makes it difficult to analyze the fermentation process and identify new patterns in the influence of moisture on the production of new products with high added value.

However, several recent research [33,34] note the importance of the total initial moisture content of organic waste and the final moisture content of the resulting product. The initial moisture content varies from 7–15% for certain types (e. g. rice husks and sawdust). On average, the overall values are 50–55%. The highest moisture content is 83.6%, which is reduced by adding coal to food waste, the share of coal in the total mass is 10–15%) [35].

Effective moisture management through monitoring and regulation of fermentation conditions can significantly improve the recycling results of organic waste and ensure sustainable production of high-quality compost.

3.4 Acidity/pH level

For most aerobic microorganisms, the optimal pH level is in the range of 5.5–8.0. Within this interval, the maximum activity of bacteria and fungi is achieved, which contributes to the effective decomposition of organic matter.

When the acidity value does not reach the optimal range (pH below 5.5), the activity of many beneficial microorganisms is suppressed. This leads to a slowdown in the decomposition process and a decrease in the overall efficiency of fermentation. Low acidity promotes the development of pathogenic bacteria, which negatively affects the sanitary characteristics of the final product.

Under circumstances where acidity values are higher than permissible level (pH is more than 8.0), a decrease in the activity of aerobic bacteria and fungi is observed. High alkalinity leads to protein denaturation and inhibition of metabolic processes, which negatively affects the decomposition of organic matter.

In aerobic fermentation of food waste, aerobic microorganisms develop differently depending on the pH level. For example, mesophilic bacteria generally grow better under neutral conditions (pH around 7), while some thermophilic species may be more tolerant to pH fluctuations.

Unlike the moisture factor, the pH level is mainly determined at the beginning and end of the fermentation process [36]. For example, in 2019, food waste (vegetables, fruit peels, coffee grounds, eggshells, and tea leaves) with fillers to increase porosity and reduce moisture (chopped wheat straw, sawdust, rice bran, corn stalks) was analyzed. The technology chosen was aerobic fermentation with a rotating container. In the research. the pH level was shown to increase from 1.1 to 8.5 [37]. However, in some cases, the initial determination of the indicator is made for individual types of waste, which are then combined. For example, when processed by aerobic fermentation with a stirrer and a fan, food waste (rice, noodles, vegetables, meat, and seafood) had an acidity pH of 3.8–6.5; garden waste (raked leaves and mown grass) — had 5.8–6.6; and rice husks with an acidity of 7.1 — had 7.3. After maturing the mixed waste, the acidity of the product was pH 3.8–8.9 [38].

To optimize the process of aerobic fermentation and stabilize the level of porosity and pH acidity, fillers are added to food waste. For example, dry sawdust and MgO and K_2HPO_4 are added to food waste (bread, rice, cabbage, and boiled pork) [29], in another study, the same author adds lime to the above-mentioned mass [30].

Thus, the initial pH level varies from 2 to 7, generally the lowest value being for food waste (as a separate type during subsequent mixing) and the highest being for food waste with fillers (for example, lime, sawdust, biochar, etc.) [34]. The average value is for mixed waste (e. g. food together with garden waste) [39,40]. At the end of the fermentation process, the pH value is fixed at 4–9.

In addition to stirring the fermentation mixture and monitoring the pH level, other methods are possible to regulate this factor:

- in case of deviation from the optimal pH level, “correctors” are used (sulfuric or citric acid is added to increase acidity, and lime or dolomite flour is added to decrease it);
- to adjust the acidity of the mass, various components with different pH values are mixed (for example, adding green plant residues reduces the pH level due to the release of organic acids).

3.5. C/N ratio

It is impossible to identify any single factor characterizing the efficiency of biothermal processes, but many researchers agree that one of the key parameters is the carbon-to-nitrogen ratio (C/N). This factor plays an important role in creating a high-quality secondary product with high added value since the basis of the aerobic fermentation process is biological decomposition, and with the correct ratio, microorganisms actively decompose organic matter and synthesize humus [26–28,41,42]. When analyzing scientific sources, it was revealed that the authors pay the greatest attention to this factor [44]. Of particular importance are the proportions of C and N in materials assigned for aerobic fermentation. C is the main source of energy and an elemental component for microorganisms, and N is necessary for the growth of microbes, and the synthesis of amino acids, proteins, and nucleic acids. The C/N ratio during composting affects the rate of decomposition. Higher values slow down the rate of decomposition, while lower values increase N losses.

When the carbon to nitrogen (C/N) ratio is too high (e. g. above 35), microorganisms are starved of available nitrogen, which can lead to a condition known as “nitrogen starvation”. Under these conditions, the decomposition of organic matter slows down and some nitrogen is lost as gases such as ammonia (NH_3) and nitrous oxide (N_2O). This negatively affects the efficiency of waste disposal and degrades the sanitary properties of the finished compost.

On the other hand, if the ratio is too low (e. g. below 15), there is excessive loss of nitrogen into the atmosphere, which reduces the nutritional properties of the final product and increases the emission of unwanted gases into the environment. Also, high ammonia content causes unpleasant odors [45].

In the case of the *C/N* ratio factor, the authors measure this indicator less frequently for individual components of organic waste. An example is research on the processing of organic waste by the method of aerobic fermentation with a mixer and a fan of food waste (*C/N* — 8.85) together with garden waste (*C/N* — 52.4) and a filler in the form of rice husk (*C/N* — 34.2). The final product has a C/N ratio of 14.5–19.6 which is confirmed by several experimental studies [32].

To achieve the desired C/N ratio, it is recommended to mix materials with a high carbon content (such as straw, sawdust, or wood chips) with nitrogen-containing components (manure or sewage sludge). If the C/N ratio is higher than the acceptable one, urea or superphosphate is added to increase the content of available nitrogen. This method helps to prevent "nitrogen starvation" of microorganisms and accelerates the decomposition process. Atmospheric nitrogen fixation is possible by adding an inoculum (a specific microbial population) to prevent a lack of available nitrogen.

3.6. Initial characteristics of aerobic fermentation factors

Each of the identified factors plays a critical role in determining the rate of decomposition of organic materials and the quality of the final product.

Maintaining optimal conditions for certain parameters accelerates the decomposition process and improves the nutritional properties of the compost. For example, the correct C/N ratio ensures active reproduction of microorganisms, and control over the pH and moisture levels prevents the development of pathogenic organisms and improves the sanitary characteristics of compost.

The method of solid-phase aerobic fermentation is one of the most promising approaches to processing food waste, especially in the conditions of the northwestern region. The main task in the preparation of organic matter is to determine the optimal ranges of factors and composition of waste types, depending on the final goal (Table 1). This allows obtaining a secondary product with high added value, which makes the process more economically advantageous.

It has been found that the processing of food waste by aerobic fermentation cannot be carried out without mixing with other organic waste or without adding a filler. These manipulations play an important role in optimizing the value of the main factors of the fermentation process — the C/N ratio, moisture, and pH. In addition, food waste types also has different values of the factors among themselves. This shows the main difference between food waste and other organic matter, which must be considered when approving the optimal ranges for each type of initial mass.

Table 1. **Initial characteristics of aerobic fermentation factors of mixed organic waste**

Таблица 1. **Начальные характеристики факторов аэробной ферментации смешанных органических отходов**

Factor	Designation	Measurement units	Acceptable value of organic waste [27]	Optimal value of food waste	Source
Moisture	W	%	40–75	50–55	[29–35]
Acidity	pH	—	5,5–9	4,5–6	[36–40]
C/N ratio	C/N	—	20–40	25–35	[44,45]

It was found that when the moisture content of organic waste is high, it is necessary to add biochar, rice husks, or sawdust. In addition to improving moisture content, it also increases the porosity of the organic matter, which has a positive effect on the fermentation process. The porous structure improves aeration, providing the necessary oxygen access for microorganisms, which is critical for maintaining the aerobic process.

At low pH values, it is recommended to add lime, potassium phosphate (K2HPO4), or sodium acetate (NaAc). These additives help neutralize acidity and create more favorable conditions for the life of beneficial microorganisms. Carbon to nitrogen (C/N) ratios can be adjusted by adding organic waste of a different composition, which simultaneously helps control the moisture content of the mass.

3.7. Assessment of the quality of the resulting product

Assessing the quality of the resulting compost substrate is an important stage in the process of its production, as it determines its suitability for use in the agro-industrial sector and agriculture. The quality of compost affects its nutritional properties, environmental safety, and the health of the fertilized plants.

The main requirement for the safe use of the resulting product is a high degree of stability and maturity. This is manifested in a relatively constant content of organic matter, the absence of phytotoxic compounds, and pathogenic microflora. Substrate maturity is assessed by its potential for plant growth, whereas stability is related to the level of microbial activity. These two terms are often used interchangeably because phytotoxic compounds are produced by microorganisms under unstable substrate conditions [46,47].

Substrate maturity indicators are based on various properties: physical, chemical, and biological, including microbial activity (Table 2). Physical characteristics such as color, odor, and temperature provide a general idea of the stage of decomposition achieved but provide insufficient information on the degree of maturation [48]. Mature compost should have a uniform, loose texture, dark color (brown to black), and an earthy odor. The presence of large particles or foreign materials may indicate insufficient decomposition. A dense or lumpy structure may indicate insufficient aeration during the fermentation process. Unpleasant odors (ammonia or rot) indicate problems with aerobic activity or the presence of pathogens.

Table 2. **Indicators of mature compost**
Таблица 2. **Показатели зрелого компоста**

Indicator	Unit of measurement	Value	Source
Organic matter content	%	> 30	[31–34]
C/N ratio	—	10–15:1	[37,38]
pH	—	6–8	[44,45]
Pathogenic microflora	pcs/cm^3	< 1	[20,21]
Availability of plant seeds	—	are missed	[46,47]
Ammonia smell	—	are missed	[48]

Compost should contain essential microelements such as iron, copper, and zinc in concentrations that are safe for plants. Heavy metals and toxic substances should be kept to a minimum to avoid negative impacts on plants and the ecosystem. The study of the chemical composition, in particular the C/N ratio in the solid fraction and liquid extract, the content of water-soluble carbon, the ratio of water-soluble carbon to water-soluble nitrogen, the presence of volatile organic acids, and the determination of the stage of nitrification and denitrification processes is possible only in analytical laboratories [26–28,41]. The finished secondary product must be free of pathogenic microorganisms and weed seeds. For this purpose, it is important to control the temperature regime during the composting process, as high temperatures contribute to the destruction of pathogens. The main indicator of the biological maturity of a substrate is its microbiological stability: the amount of microbial biomass and its metabolic activity, as well as the concentration of easily biodegradable compounds [26–28,41–43].

To check the quality of the final product (compost), laboratory tests are carried out to determine the content of essential nutrients (nitrogen, phosphorus, potassium) and microelements (iron, copper, zinc). This chemical analysis allows establishing the benefits of application of the product into the soil. The presence of heavy metals (lead, cadmium, mercury) and toxic compounds (e. g. pesticides) is determined using toxicological analysis to assess the safety of the compost mixture and its impact on the environment.

Microbiological analysis is carried out to detect the presence of pathogenic microorganisms (e. g. *E. coli, Salmonella*) and weed seeds to confirm the sanitary safety of the compost.

4. Conclusions

Optimization of aerobic fermentation of organic waste is an important task that has high significance for sustainable waste management. This article reviewed key factors affecting the aerobic fermentation process, such as temperature, humidity, pH, carbon-nitrogen ratio (C/N), and the role of microorganisms.

This process is an important step towards efficient resource management and reduced environmental impact. Using high-quality compost helps increase agricultural productivity and improve soil health.

In addition, based on the analysis of the factors and patterns of fermentation and the requirements for the quality of the final product, six basic principles of this process are defined:

1. Determining the purpose of the product with a clear understanding of what the final product will be used for.
2. Selection of technology considering the natural, climatic, and sanitary conditions of the region.
3. Optimization of the initial raw materials through the selection of their physicochemical characteristics, such as the adjusting its carbon-to-nitrogen ratio, pH level, moisture, and porosity.
4. Monitoring fermentation processes such as regular checking up of temperature, humidity, oxygen content, and gas emissions.
5. Control of the fermentation process by stimulating the processes with aeration and stirring.
6. Quality control by analyzing the final product for nutrient content and the absence of pathogenic microflora.

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Contribution	Критерии авторства
Authors equally relevant to the writing of the manuscript, and equally responsible for plagiarism.	Авторы в равных долях имеют отношение к написанию рукописи и одинаково несут ответственность за плагиат
Conflict of interest	**Конфликт интересов**
The authors declare no conflict of interest.	Авторы заявляют об отсутствии конфликта интересов.