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PERSPECTIVES FOR THE DEVELOPMENT OF ORGANIC WASTE PROCESSING TECHNOLOGIES IN ASTANA CITY CONSIDERING GERMAN EXPERIENCE

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The article examines the issues of forecasting the volumes of organic waste generated in the production process at school canteens in Astana city, as well as assessing the potential for their processing into biogas and compost. The research aims to analyze the dynamics of organic waste fraction accumulation and determine opportunities for its rational use in the period 2025–2030. Initial data include statistics on the number of students and calculated waste generation volumes based thereon. The prognostic model was built using MATLAB tools, which allowed identifying a trend of steady growth in the amount of organic waste by 2030. A direct dependence between the increase in the number of students and waste volumes was established, reflecting the need to improve processing systems. Additionally, an assessment of the potential use of waste for biogas and compost production was conducted. For comparison, the German experience is presented, where similar programs for processing organic waste in municipal and educational sectors have shown significant reductions in greenhouse gas emissions and an increase in the share of renewable energy sources. The research results demonstrate that the introduction of similar approaches in Kazakhstan can significantly enhance the environmental sustainability of school infrastructure. The application of mathematical modeling confirmed the effectiveness of digital tools in forecasting and planning environmentally safe waste management technologies.

Keywords: waste management, school nutrition, organic waste, biogas, compost, ecology, sustainable development.

ГЕРМАНИЯ ТӘЖІРИБЕСІН ЕСКЕРЕ ОТЫРЫП, АСТАНА ҚАЛАСЫНДА ОРГАНИКАЛЫҚ ҚАЛДЫҚТАРДЫ ҚАЙТА ӨҢДЕУ ТЕХНОЛОГИЯЛАРЫН ДАМЫТУ ПЕРСПЕКТИВАЛАРЫ

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Мақалада Астана қаласының мектеп асханаларында өндіріс процесінде пайда болатын органикалық қалдықтардың көлемін болжау, сондай-ақ оларды биогаз бен компостқа қайта өңдеу әлеуетін бағалау мәселелері қарастырылады. Зерттеудің мақсаты қалдықтардың органикалық фракциясының жинақталу динамикасын талдау және оны 2025-2030 жылдар аралығында ұтымды пайдалану мүмкіндіктерін анықтау болып табылады. Болжамдық модель 2030 жылы органикалық қалдықтардың тұрақты өсу тенденциясын анықтайтын MATLAB құралдарын қолдана отырып жасалған. Қайта өңдеу жүйелерін жетілдіру қажеттілігін көрсететін білім алушылар санының артуы мен қалдықтар көлемі арасында тікелей байланыс орнатылды. Сонымен қатар, биогаз бен компост алу үшін қалдықтарды пайдалану әлеуетін бағалау жүргізілді. Салыстыру үшін Германияның тәжірибесі келтірілген, онда коммуналдық және білім беру секторларындағы ұқсас органикалық қалдықтарды қайта өңдеу бағдарламалары парниктік газдар шығарындыларының айтарлықтай төмендеуін және жаңартылатын энергия көздерінің үлесінің артуын көрсетті. Зерттеу нәтижелері Қазақстанда осындай тәсілдерді енгізу мектеп инфрақұрылымының экологиялық тұрақтылығын айтарлықтай

арттыра алатынын көрсетеді. Математикалық модельдеуді қолдану қалдықтарды басқарудың экологиялық таза технологияларын болжау мен жоспарлауда цифрлық құралдардың тиімділігін растады.

Түйін сөздер: қалдықтарды басқару, мектептегі тамақтану, органикалық қалдықтар, биогаз, компост, экология, тұрақты даму.

ПЕРСПЕКТИВЫ РАЗВИТИЯ ТЕХНОЛОГИЙ ПЕРЕРАБОТКИ ОРГАНИЧЕСКИХ ОТХОДОВ В АСТАНЕ С УЧЕТОМ НЕМЕЦКОГО ОПЫТА

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В статье рассматриваются вопросы прогнозирования объемов органических отходов, образующихся в процессе производства в школьных столовых города Астаны, а также оценки потенциала их переработки в биогаз и компост. Целью исследования является анализ динамики накопления фракции органических отходов и определение возможностей их рационального использования в период 2025-2030 годов. Исходные данные включают статистические данные о количестве учащихся и рассчитанные на их основе объемы образования отходов. Прогностическая модель была построена с использованием инструментов MATLAB, что позволило выявить тенденцию устойчивого роста количества органических отходов к 2030 году. Была установлена прямая зависимость между увеличением числа студентов и объемами отходов, что отражает необходимость совершенствования систем переработки. Кроме того, была проведена оценка потенциального использования отходов для производства биогаза и компоста. Для сравнения представлен опыт Германии, где аналогичные программы по переработке органических отходов в муниципальном и образовательном секторах показали значительное сокращение выбросов парниковых газов и увеличение доли возобновляемых источников энергии. Результаты исследования показывают, что внедрение аналогичных подходов в Казахстане может значительно повысить экологическую устойчивость школьной инфраструктуры. Применение математического моделирования подтвердило эффективность цифровых инструментов в прогнозировании и планировании экологически безопасных технологий обращения с отходами.

Ключевые слова: управление отходами, школьное питание, органические отходы, биогаз, компост, экология, устойчивое развитие.

Introduction. In Kazakhstan, approximately 4.5 million tons of municipal solid waste (MSW) are generated annually, with organic waste constituting a significant share, including food residues, plant fractions, and other biodegradable materials [1]. Their processing allows reducing landfill volumes, obtaining secondary resources (biogas, compost), and lowering greenhouse gas emissions. However, this is possible only if legislative provisions on mandatory separate collection of organics are introduced. For Kazakhstan, the topic of effective organic waste management is particularly relevant due to urban population growth, industrial and agricultural development, and the need to reduce negative environmental impacts [2]. Improper disposal of organic waste leads to soil, water, and air pollution,

greenhouse gas emissions contributing to climate change, as well as the spread of diseases and threats to biodiversity [3]. The main portion of organic waste is generated in the food sector, especially in schools and educational institutions. In school canteens, a large volume of organic waste is produced at the production stage, primarily vegetable waste after sorting and peeling. For

the disposal of generated waste, school canteens conclude contracts with companies that organize collection and removal of garbage; these companies also provide separate containers for food waste collection. The generated waste is not processed; it is transported to city landfills for burial. The volume of this waste will increase annually due to the commissioning of new schools, especially in the capital Astana. In Germany, schools also conclude contracts with local Müllentsorgung (municipal companies), and separately collected bio-waste in special containers goes to composting plants or anaerobic biogas facilities rather than landfills [4]. According to data from Statistisches Bundesamt - the German Federal Statistical Office - in 2023, household waste accounted for 35% or 12.8 million tons. About a quarter of household waste consisted of bio-waste, i.e., organic waste (28%, or 10.1 million tons) [5]. In Germany, strict restrictions on landfilling food waste came into force in 2025. In every municipality, there are organic containers (Bio-Tonne) where food residues suitable for processing must be disposed. Fines are imposed for violations. Regulation is carried out through the Bio-waste Ordinance (BioAbfV), EU Directive 2008/98/EC, and the national strategy to reduce food waste by 2030 [6].

German technology provides for the processing of food waste in the following ways:

1. Biogas plants (e.g., SARIA Bio-Industries, BSN BioService Nord GmbH): organic residues undergo anaerobic digestion, producing biogas and fermented fertilizers.

2. Composting: widely used in agriculture to improve soil structure.

3. Thermochemical conversion: cogeneration plants are used to produce heat and energy.

4. Social and educational programs are also implemented: Foodsharing.de: free distribution of surplus products via a digital platform. School projects (Restlos glücklich, “Down to the last crumb”): training in rational consumption [7].

According to the Federal Environment Agency, in 2022, 14.09 million tons of bio-waste were actually subjected to biological treatment in Germany. Of these, 6.66 million tons were processed at plants operating solely on composting. According to statistical data, 7.44 million tons, or approximately 53% of the total volume of organic waste, were processed at anaerobic digestion plants or combined composting and anaerobic digestion plants. From the collected organic waste, approximately 1.21 million tons of compost from bio-waste, 2.12 million tons of compost from green waste, and 4.02 million tons of digestate and composted digestate were produced [8]. In this context, the German experience, as one of the world leaders in separate collection and processing of bio-waste, is of great interest. The purpose of this article is to assess the potential for processing organic waste from schools in Astana based on German experience using biogas technologies and composting. The following tasks were set: forecasting the generation of organic waste in Astana schools for 2025-2030; forecasting the reduction of greenhouse gas emissions during organic waste processing; forecasting the volumes of organic waste processing and production of biogas and compost.

Materials and methods. To assess the potential volume of organic waste generated in school institutions in Astana, the expert forecasting method was applied based on statistical data on the number of students and specific waste generation per student. This approach allows determining trends in waste volume changes considering demographic growth and seasonal factors, as well as comparing the effectiveness of possible processing scenarios with German experience.

Statistical data on the number of students in general education schools in Astana for 2025 were used [9]. Specific waste norms per student were calculated based on the “Prospective menu layout for organizing nutrition in educational institutions of Astana city,” approved by the head of the Astana Education Department, using vegetable waste norms from the “Collection of recipes for dishes and culinary products for public catering enterprises” [10]. Analyzing statistical data on the number of students in general education schools in Astana from 2010 to 2025, the average

annual growth rate of students in percentage was considered. Considering vacations, a seasonality coefficient was adopted for the 2025 academic year. Based on processing data from literary sources, the share of organic waste processing (for Kazakhstan and Germany) was applied. All initial data are summarized in Table 1.

Table 1 - initial data for 2025

Source / assumption	Indicator	Value	Unit
Statistical data on the number of students in general education schools in Astana for 2025	Number of students	286,633	students
Specific norms of organic waste per student (calculated using own methodology)	Organic waste generation rate	0.02	kg/student·day
Average annual growth rate of the school population	Growth rate	2	% per year
Current recycling rate in Kazakhstan	Recycling rate	10	%
Organic waste recycling rate in Germany	Recycling rate	70	%

The model was implemented in the MATLAB environment. Built-in functions readtable, plot, bar, and disp were used for data analysis and visualization.

Discussion and results. ***Forecast of organic waste generation in astana schools for 2025-2030.***

The conducted modeling showed that the volume of organic waste generated in school institutions in Astana has a steady growth trend due to the increase in the number of schoolchildren and stable food consumption norms. Based on the initial data (see Table 1), the total volume of organic waste was calculated (see Table 2):

Table 2 - Total volume of organic waste in Astana schools for 2025–2030

Year	Number of students	Waste, tons/day	Waste, tons/month
2025	286,633	5.7	137.6
2026	292,365	5.85	140.4
2027	298,212	5.9	141.6
2028	304,176	6.08	146.0
2029	310,259	6.2	149.0
2030	316,464	6.33	151.9

Thus, over five years, an increase in organic waste generation in Astana schools by 12–13% is expected.

Annual dynamics and forecast. Figure 1 presents a graphical interpretation of the annual forecast. The graph reflects a gradual increase in the total waste volume, associated with the growth in the number of students. The growth curve is close to exponential but can be approximated by a linear dependence within the studied period.

Seasonal fluctuations. Analysis of seasonal dynamics (Fig.2) showed significant differences between academic months and the summer vacation period. Minimum values occur in June-August, explained by the absence of school meals, while peaks are observed in October-December and February-April.

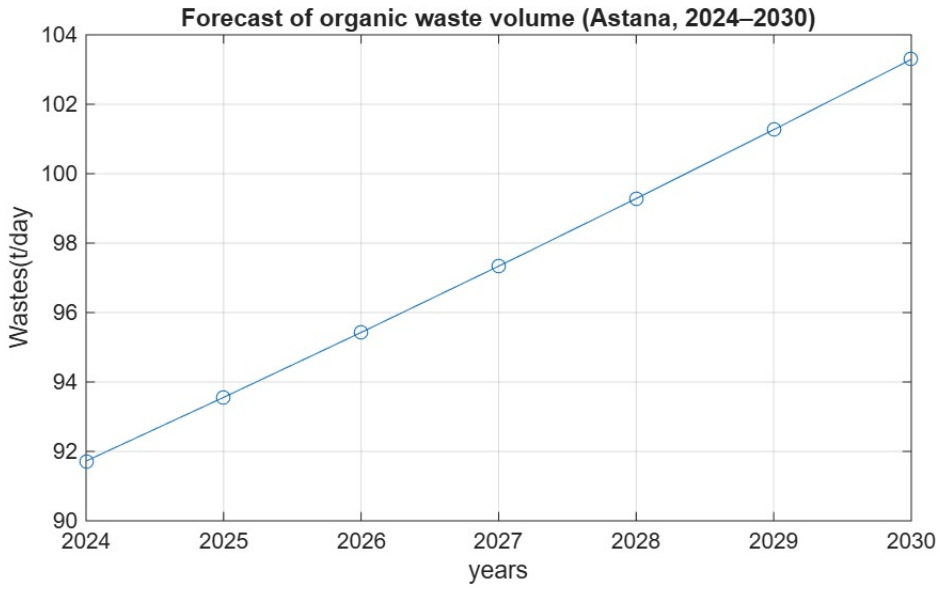


Fig.1 - Forecast of changes in the volume of organic waste in Astana schools for 2024–2030.

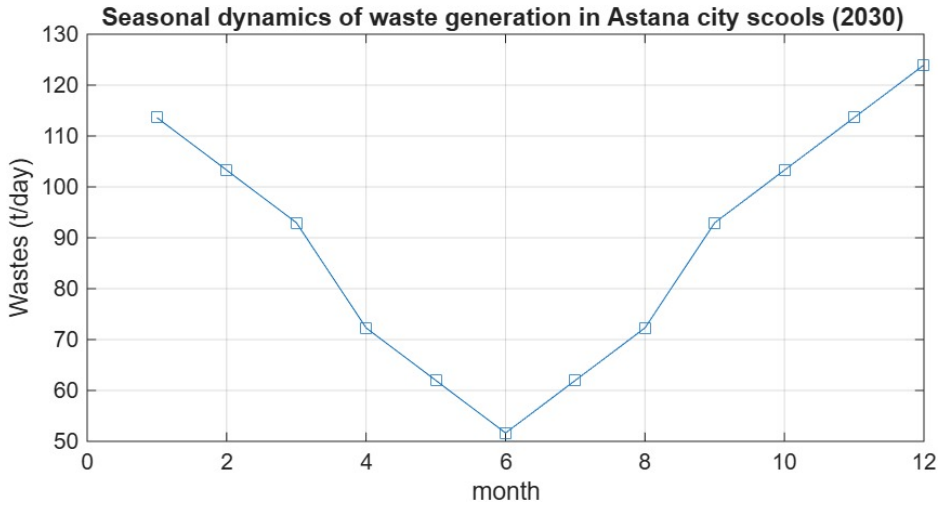


Fig.2 - Seasonal variability of organic waste generation in school institutions (example for 2030).

Such dependence confirms the need for flexible planning of waste removal and processing considering the academic calendar.

Forecast of greenhouse gas emission reductions during organic waste processing.

To assess the environmental effect of organic waste processing, a forecast of carbon dioxide (CO_2) and methane (CH_4) emission reductions for the period 2025-2030 was performed. Calculations were carried out using a mathematical model implemented in MATLAB Online. Initial data were the forecasted volumes of organic waste generation presented in Table 1. For each year, potential greenhouse gas emissions that could arise without processing were calculated and compared with the volumes of avoided emissions as a result of using organic waste for biogas or compost production.

The model accounts for the conversion of avoided methane (CH_4) mass into carbon dioxide equivalent (CO_2-equivalent) using the global warming potential (GWP) of 28 according to IPCC methodology. Modeling results are presented in Figure 3 as an effective measure to reduce anthropogenic greenhouse gas emissions.

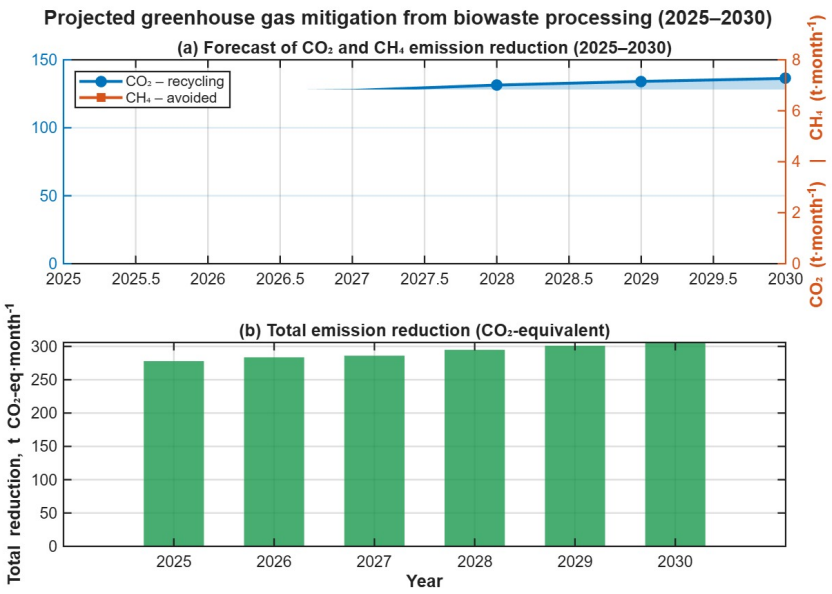


Fig.3 - Forecast of CO_2 and CH_4 emission reductions (a) and total reduction in CO_2-equivalent (b) during organic waste processing in 2025-2030

Where: 3a) shows forecast values of CO_2 emission reductions and avoided CH_4 emissions, 3b) presents the total reduction converted to CO_2-equivalent.

As a result of calculations, it was established that with the processing of the forecasted volume of organic waste, a steady reduction in CO_2 and CH_4 emissions is expected throughout the considered period. The total emission reduction converted to CO_2-equivalent by 2030 may amount to more than 3.6 thousand tons of CO_2-equivalent per month.

Forecast of organic waste processing volumes and biogas and compost production.

One of the key directions for increasing the environmental efficiency of organic waste management is their processing to obtain secondary products - biogas and compost. Such technologies allow simultaneously solving the tasks of reducing greenhouse gas emissions and restoring the resource potential of waste. For quantitative assessment of processing potential, a forecast of biogas and compost yield for the period 2025–2030 was conducted. Initial data were the values of forecasted organic waste volumes (Table 1). Calculations were performed in MATLAB Online using standard product yield coefficients:

$$k_{\text{biogas}} = 100\text{–}120\ \text{m}^3/\text{ton of waste}, \qquad k_{\text{compost}} = 0.25\text{–}0.35\ \text{t/ton of waste} \tag{1}$$

Biogas and compost yields were calculated using the formulas:

$$V_{\text{biogas}} = Q_{\text{waste}} \times k_{\text{biogas}}, \qquad M_{\text{compost}} = Q_{\text{waste}} \times k_{\text{compost}} \tag{2}$$

where Q_{waste} is the volume of processed organic waste (tons/month).

Calculation results showed that with the forecasted increase in organic waste from 137.6 t/month in 2025 to about 155 t/month by 2030, biogas yield may increase from 13.8-16.5 thousand m³/month to 15.5-18.6 thousand m³/month. The compost volume increases from 34-48 t/month to 39-54 t/month (Table 2). Figure 4 presents the modeling results of biogas production and compost obtaining dynamics in 2025-2030.

A steady increase in indicators is noted as organic

waste processing volumes grow. Value ranges reflect possible variations in yield coefficients depending on waste composition and processing technology. The width of the shaded area reflects the uncertainty range associated with variations in technological yield coefficients. Thus, the authors [11] demonstrated various methods for extracting polyphenols, dietary fibers, and proteins from food waste, which can be used in functional food systems (Fig.5).

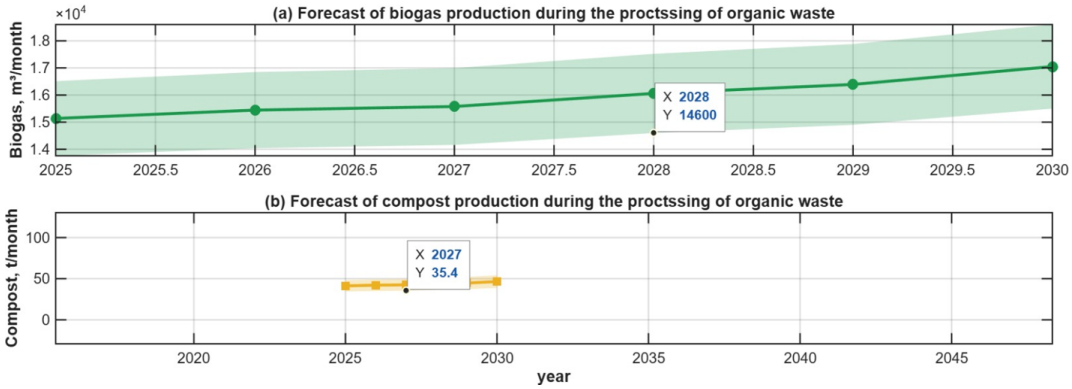


Fig.4 - Forecast of biogas production (a) and compost obtaining (b) during organic waste processing in 2025-2030

Where: 4a - change in forecasted biogas volume; 4b - trend of compost production growth

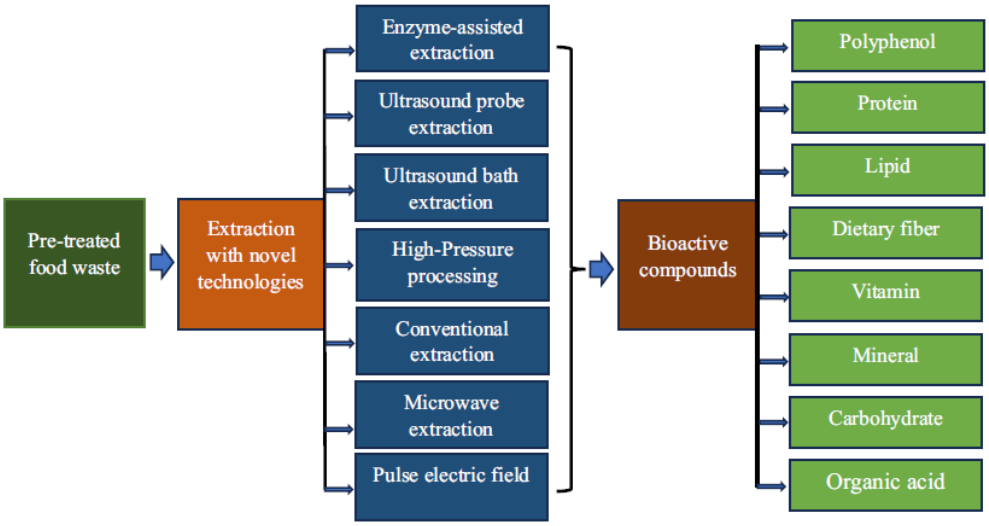


Fig.5 - Process of extracting biologically active substances from food waste

Overall, the results indicate a significant resource-energy potential of organic waste. Even with a conservative estimate (100 m³ of biogas per 1 ton of waste), the total volume of produced biogas can provide up to 3.9×10^9 kJ/year, equivalent to more than 1000 MWh of electricity. Thus, comprehensive processing of organic waste can make a significant contribution to the development of renewable energy and reduction of the region' s carbon footprint.

Scenario comparison of organic waste processing in countries: Kazakhstan and Germany.

To assess the potential for implementing foreign experience, a comparison of two scenarios was built: Current situation (Kazakhstan) - about

10% of organic waste is processed. German experience - processing reaches 70% due to a developed collection system and biogas plants. Calculation results (Fig.6) showed that transitioning to the German processing level would increase the volume of utilized organics by more than 7 times, significantly reducing the load on landfills and greenhouse gas emissions.

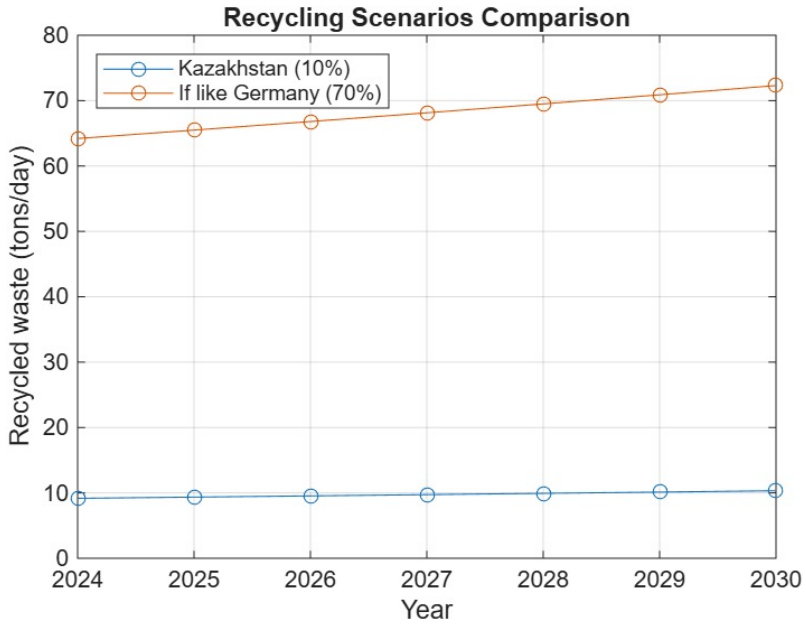


Fig.6 - Comparison of forecasted volumes of processed organic waste: current level (10%) and German level (70%).

The analysis shows that transitioning to an effective organic waste processing system similar to the German one can become a significant contribution to the city' s environmental sustainability. The most promising direction is the introduction of school programs for separate bio-waste collection, creation of mini-biogas plants, and information-educational projects among students. In addition, the model can be adapted for: assessing waste in other educational or social institutions, forecasting biogas volumes during organic processing, planning waste processing infrastructure on a city or regional scale.

Conclusions. The conducted research aimed at analyzing and forecasting the volumes of organic waste in school institutions in Astana showed that the bio-waste management system has significant potential for development and environmental effect.

The expert model developed in MATLAB allowed: assessing the current volume of organic waste generation in Astana schools (about 5.7 tons per day); forecasting waste volume growth to 149 tons per month by 2030 with a 2% annual increase in students; identifying seasonal dependence of waste generation, with a minimum in summer months and maximum during the academic period; conducting a scenario comparison between the current processing level (10%) and the German level (70%), showing the possibility of a sevenfold increase in organic utilization. Thus, modeling results confirm the need to implement a comprehensive program for managing organic waste in the city' s educational institutions. The German experience in organic waste processing can be successfully adapted for Kazakhstan with methodological, infrastructural, and educational support. The proposed MATLAB model is a tool that can be used both for scientific analysis and for planning in the real economy sector.

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