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Justification and Selection of Optimal Options for the Operation of Municipal Solid Waste Management System in Order to Ensure Effective Incineration



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Abstract

Introduction. Over the past decades, the issue of household and industrial waste management in Russia and worldwide has gained increased importance due to growing urbanization, increased consumption, and limited landfill space. The traditional disposal model — landfilling — is associated with environmental and public health risks and low levels of resource recovery. Alternative strategies are being developed, among which the key ones are separate collection and mechanical-biological treatment (MBT), as well as thermal disposal methods. A literature review shows that international studies (Europe, Japan) demonstrate the positive effects of a combination of separate collection and MBT, while Russian studies emphasize the barriers: insufficient infrastructure for separate collection, low public participation, and municipal financial constraints. The analysis highlights the importance of an integrated approach, where technological solutions are accompanied by organizational measures and economic incentives. Currently, there is a lack of comprehensive assessments of the MTB implementation, taking into account various separate collection and local logistics scenarios. Existing studies are often limited to technical and technological aspects or present calculations at the level of individual pilot sites, without assessing the systemic economic impacts or providing a detailed sensitivity analysis of key parameters. Therefore, the aim of this study is to identify optimal MSW sorting options for subsequent incineration, based on combustion heat and pollutant emissions.

Materials and Methods. The author collected and analyzed statistical data on the functioning of the MSW management system at the regional level using publicly available information from the Federal State Statistics Service and the Federal Service for Supervision of Natural Resources (Form 2-TP (waste))¹ as sources. Data and reports from IFC (International Finance Corporation)² and the public legal company Russian Environmental Operator (REO)³ were studied and analyzed. To achieve the set goals, the author has developed a research algorithm, including the use of regression analysis, the construction of a ranked series of the specific heat of MSW combustion by morphological composition with subsequent division into groups I and II, the formation of alternative waste sorting options by changing the proportion of MSW groups (I and II) in the conditionally accepted scenarios, followed by solving a multi-criteria problem of choosing the optimal option for MSW sorting for the purposes of further incineration. The research was conducted in MS Excel and Statistica software.

Results. An analysis of statistical data on the solid municipal waste management system and composition revealed that the morphological composition for the purposes of further incineration remained relatively stable over the past 5 years with minor seasonal fluctuations. A clear correlation was observed between population size and waste accumulation volume, as well as between waste volume and the level of waste sorting. Simulation modeling of a feasible set of alternative MSW sorting options made it possible to determine the optimal balance between the economic efficiency of incineration and environmental pollution. In this setting, batches were simulated for subsequent incineration with different ratios of solid municipal waste from groups I and II in the ratio of 10/90, 30/70, 50/50, 70/30, 90/10,

¹ Open data. Rosprirodnadzor. (In Russ.) URL: <https://rpn.gov.ru/opendata/> (accessed: 05.03.2026)

² THE WORLD BANK GROUP ANNUAL REPORT 2025. URL: <https://www.worldbank.org/en/about/annual-report/world-bank-group-downloads> (accessed:05.03.2026)

³ Russian Environmental Operator. (In Russ.) URL: <https://reo.ru/about#docs> (accessed:05.03.2026)

respectively. Optimal options for MSW sorting for further incineration were determined by calculating a function that determined the degree of approximation of each of the sorting alternatives under consideration to the ideal value (ideal point), which was based on the values of minimum emissions (fly ash, sulfur oxide, nitrogen oxide, carbon monoxide) and the maximum value of the calorific value (the energy value of MSW based on the morphological composition). The sensitivity coefficients to changes in the basic values of the sorting parameters and the gross emission of pollutants were calculated. Optimal options for MSW sorting from the perspective of further incineration were obtained based on the calculation of combustion heat and pollutant emissions (including carbon footprint indicators).

Discussion. The main result of the study is a developed approach to the efficient sorting of municipal solid waste for subsequent thermal recycling. The solution to this problem was based on principles that allowed for a classical solution to the direct and dual problem of achieving maximum efficiency from the municipal solid waste incineration process while minimizing the negative impact on the environment. The obtained results will enable the effective separation and sorting of municipal solid waste despite the production constraints of incineration plants at municipal solid waste landfills. The analysis of the morphological composition of municipal solid waste for subsequent sorting and thermal recycling made it possible to identify waste separation options with the highest energy value based on heat of combustion of individual components and characterized by a minimum amount of pollutant emissions.

Conclusion. The analysis of statistical data from the municipal solid waste management system revealed the prevalence of landfill disposal and the ineffectiveness of the sorting process. Regression models revealed increasing trends in the volume of waste removed and sorted, necessitating further targeted and effective sorting for recycling purposes. Simulation modeling of alternative MSW sorting options and the solution of an optimization problem made it possible to identify effective MSW sorting options for further thermal disposal, with minimal pollutant emissions and maximum combustion heat values. In conclusion, during the research, optimal options for municipal solid waste sorting were obtained based on the morphological composition of batches for maximum efficiency of thermal disposal and minimum emissions of pollutants into the atmosphere.

Keywords: municipal solid waste, waste sorting, incineration, morphological composition, combustion heat, pollutant emissions, mechanical and biological treatment, thermal utilization, optimization, regression analysis

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Оригинальное теоретическое исследование

Обоснование и выбор оптимальных вариантов функционирования системы обращения твердых коммунальных отходов для целей эффективной инсинерации

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Аннотация

Введение. За последние десятилетия проблема обращения с бытовыми и промышленными отходами в России и мире приобрела повышенную значимость вследствие роста урбанизации, увеличения потребления и ограниченности полигонных площадей. Традиционная модель утилизации — захоронение на полигонах — сопровождается рисками для окружающей среды и общественного здоровья, а также характеризуется низким уровнем восстановления ресурсов. Развиваются альтернативные стратегии, среди которых ключевыми являются раздельный сбор и механико-биологическая обработка (МБО) отходов, а также термические методы утилизации. Обзор литературы показывает, что зарубежные исследования (Европа, Япония) демонстрируют положительный эффект от комбинации раздельного сбора и МБО, а российские исследования акцентируют внимание на барьерах: недостаточной инфраструктуре для раздельного сбора, низком уровне общественного участия и финансовых ограничениях муниципалитетов. Анализ указывает на важность интегрированного подхода, где технологические решения сопровождаются организационными мерами и экономическими стимулами. В настоящее время отсутствуют комплексные оценки внедрения МБО с учётом разных сценариев раздельного сбора и локальной логистики. Существующие исследования часто ограничены технико-технологическими аспектами или представляют расчёты на уровне отдельных пилотных объектов, без оценки системных экономических последствий

и детального анализа чувствительности ключевых параметров. Поэтому целью данной работы является определение оптимальных вариантов сортировки ТКО с позиции дальнейшей инсинерации на основе учета теплоты сгорания и выбросов загрязняющих веществ.

Материалы и методы. Осуществлен сбор и анализ статистических данных о функционировании системы обращения ТКО на региональном уровне. В качестве источников использовалась открытая информация Федеральной службы государственной статистики и Федеральной службы по надзору в сфере природопользования (Форма 2-ТП (отходы)). Были изучены и проанализированы данные и отчеты IFC (International Finance Corporation) и публичной правовой компании «Российский экологический оператор» (РЭО). Для решения поставленных задач был разработан алгоритм проведения исследований, включающий применение регрессионного анализа, построение ранжированного ряда удельной теплоты сгорания ТКО по морфологическому составу с последующим разделением на группы I и II, формирование альтернативных вариантов сортировки отходов за счет изменения доли групп ТКО (I и II) в условно принятых сценариях с последующим решением многокритериальной задачи выбора оптимального варианта сортировки ТКО для целей дальнейшей инсинерации. Исследования проводились в программах MS Excel и Statistica.

Результаты исследования. Анализ статистических данных системы обращения и состава твердых коммунальных отходов позволил выявить, что морфологический состав для целей дальнейшей инсинерации за последние 5 лет оставался относительно стабильным с незначительными сезонными колебаниями. Наблюдалась четкая корреляция между численностью населения и объемами накопления отходов, а также между объемом отходов и уровнем их сортировки. В результате имитационного моделирования допустимого множества альтернативных вариантов сортировки ТКО был определен оптимальный баланс между экономической эффективностью от инсинерации и экологическим загрязнением окружающей среды. В такой постановке были имитационно сформированы партии для последующего сжигания с различным соотношением в них твердых коммунальных отходов из групп I и II в соотношении 10/90, 30/70, 50/50, 70/30, 90/10, соответственно. Определены оптимальные варианты сортировки ТКО для целей дальнейшей инсинерации посредством расчета функции, определяющей степень приближения каждой из рассматриваемых альтернатив сортировки к идеальному значению (идеальной точке), в качестве которой были использованы значения минимальных выбросов (летучая зола, оксид серы, оксид азота, оксид углерода) и максимальное значение теплоты сгорания (энергетическая ценность ТКО исходя из морфологического состава), а также рассчитаны коэффициенты чувствительности к изменению базовых значений параметров сортировки и валового выброса загрязняющих веществ. Получены оптимальные варианты сортировки ТКО с позиции дальнейшей инсинерации на основе учета теплоты сгорания и выбросов загрязняющих веществ (в т.ч. показателей углеродного следа).

Обсуждение результатов. Основным результатом исследования является разработанный подход к эффективной сортировке твердых коммунальных отходов (ТКО) для целей их последующей термической утилизации. В основу решения поставленной задачи положены принципы, обеспечивающие получение классического решения прямой и двойственной задач оптимизации, направленных на достижение максимальной эффективности процесса инсинерации ТКО при условии минимизации негативного воздействия на окружающую среду. Полученные результаты позволяют осуществить эффективное разделение ТКО с учетом ограничивающих производственных факторов мусоросжигательных заводов на полигонах. Анализ морфологического состава ТКО для целей их последующей сортировки и термической утилизации позволил выявить варианты разделения отходов, обладающие наибольшей энергетической ценностью исходя из теплоты сгорания отдельных компонентов и характеризующиеся минимальным количеством выбросов загрязняющих веществ.

Заключение. Проведенный анализ статистических данных системы обращения ТКО позволил выявить преобладание полигонного захоронения и низкую результативность процесса сортировки. Регрессионные модели обнаружили возрастающие тенденции объемов вывозимых и отсортированных отходов, что предопределило необходимость целенаправленного и рационального разделения для целей утилизации. Имитационное моделирование альтернативных вариантов сортировки ТКО и решение оптимизационной задачи позволили определить наилучшие схемы распределения отходов для последующей термической переработки, характеризующиеся минимальными выбросами загрязняющих веществ и максимальными значениями теплоты сгорания. Таким образом, в ходе исследований получены оптимальные варианты сортировки твердых коммунальных отходов на основе учета морфологического состава партий, обеспечивающие наибольшую эффективность термической утилизации и минимизацию выбросов загрязняющих веществ в атмосферу.

Ключевые слова: твердые коммунальные отходы, сортировка отходов, инсинерация, морфологический состав, теплота сгорания, выбросы загрязняющих веществ, механико-биологическая обработка, термическая утилизация, оптимизация, регрессионный анализ

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Introduction. In the modern world, the process of urbanization of the population is taking place at a high rate. According to the United Nations, in 2024, the level of urbanization in Europe was 75.8%, in North America (USA and Canada) — 83.4%, and in Russia — 75%⁴. The increase in the urban population in Russia, according to Rosstat, for the period 2000–2024 amounted to 25%, clearly indicating a shift in lifestyle towards urban agglomerations⁵. Modern conditions of urbanization, providing comfort for living and shaping increasing needs of urban population, require adherence to the principles of rational management of municipal solid waste generated during human activities. Its significant accumulation and inadequate disposal contribute to rapid deterioration of the environmental situation.

Municipal solid waste (MSW) is the waste generated by individuals and households during consumption of goods. It includes waste that has lost its consumer properties due to use in residential areas to meet personal and household needs⁶. In the EU and the USA, the proportion of waste disposed of through burial does not exceed 40%. Recycling rates reach 60%, with the leading countries in Europe being Scandinavia, the Netherlands, Germany, and Belgium, where utilization rates reach 50–68% and burial rates are only 1%⁷.

The choice of a specific method of MSW disposal in different countries is determined by the specifics of economic development, state policy in the field of separate waste collection, as well as the area of the state's territory and the density of its population. The main generally accepted types of MSW disposal are: landfill disposal, biological disposal and incineration.

According to data from the Federal State Statistics Service⁸ and the Federal Service for Supervision of Natural Resource Usage in Russia⁹, approximately 82% of all MSW is currently sent to landfills. Over the past five years, the proportion of sorted waste has increased to a record high of 53%, but it should be noted that most of this waste is still going to landfills. These figures clearly show that Russia's MSW disposal process lags behind the world's leading practices. Consequently, the development of an effective MSW management system is an important task at the federal level. This is confirmed by the “Industrial Development Strategy for the Treatment, Disposal and Neutralization of Industrial and Consumer Waste in Russia until 2030”¹⁰, which aims to create an efficient waste recycling industry.

To date, theoretical and practical issues related to effective MSW management have been addressed in the open literature and are developing in several main areas. One of these areas is the construction of a technical and economic management system for MSW [1], as well as the creation of an organizational and logistic chain — from waste collection and initial sorting in urban agglomerations, through transportation and secondary sorting at specialized sorting complexes, to subsequent disposal [2]. These studies focus on initial sorting and timely garbage removal. For densely populated areas, the development of this field remains a pressing practical challenge. Despite the measures taken to sort waste, they have had little effect on reducing legal and illegal landfills [3].

Another direction is aimed at the development and implementation of technologies for MSW processing in order to obtain secondary raw materials (fabrics, building materials, etc.) and secondary energy — an alternative fuel with a high heat of combustion [4], considered as an energy carrier [5]. The most common and technically proven method of industrial MSW processing for secondary energy is combustion [6]. The main advantage of thermal waste treatment is a relatively low impact on land and water resources. However, it also has some disadvantages, such as atmospheric pollution with large amounts of exhaust gases and ash, and the negative impact on biodiversity [7]. In the context of the

⁴ *Ranking of countries in the world by the level of urbanization*. United National. URL: <http://www.un.org/en/desa> (accessed: 25.01.2026)

⁵ *The share of the urban population in the total population as of January 1*. EMISS State Statistics. (In Russ.) URL: <https://www.fedstat.ru/indicator/36057> (accessed: 28.01.2026).

⁶ *Federal Law “On Production and Consumption Waste” dated June 24, 1998 No. 89-FZ*. (In Russ.) URL: <https://docs.cntd.ru/document/901711591> (accessed: 01.10.2025).

⁷ *Sustainable waste management: what the EU is doing*. URL: <http://www.europarl.europa.eu/news/en/headlines/society/20180328STO00751/eu-waste-management-infographic-with-facts-and-figures> (accessed: 29.09.2025).

⁸ *Municipal waste*. EMISS State Statistics. (In Russ.) URL: <https://www.fedstat.ru/indicators/search?searchText=коммунальные+отходы> (accessed: 11.09.2025).

⁹ *Information on the formation, treatment, disposal, neutralization, and disposal of industrial and consumer waste*. Federal Service for Supervision of Natural Resource Usage. (In Russ.) URL: <https://rpn.gov.ru/open-service/analytic-data/statistic-reports/production-consumption-waste/> (accessed: 17.09.2025).

¹⁰ *Decree of the Government of the Russian Federation dated January 25, 2018 No. 84-R*. (In Russ.) URL: <https://www.garant.ru/products/ipo/prime/doc/71767672/> (accessed: 21.01.2026).

problem of garbage incineration [8], the construction of incinerators is mainly considered in the literature [9]. Only a few authors take into account the specifics of the effectiveness of incineration with the morphological composition of MSW [10]. At the same time, the variability in the morphological composition of MSW and the relationship between efficient sorting and subsequent treatment options, including thermal treatment, has not been fully explored.

The aim of this work is to identify the optimal options for MSW sorting from the perspective of its subsequent incineration, taking into account heat of combustion and emissions of pollutants.

To achieve this goal, the following objectives have been formulated:

- collection and analysis of statistical data on the MSW treatment system and composition;
- modeling of regression relationships between exported and sorted waste volumes and population size;
- simulation modeling of an acceptable set of alternative MSW sorting options;
- determination of optimal MSW sorting options for incineration.

Materials and Methods. As part of the assigned tasks, statistical data and information on the functioning of the MSW management system at the regional level were collected and analyzed. The open data from the Federal State Statistics Service and the Federal Service for Supervision of Natural Resource Usage was used as sources. Additionally, the data and reports from the IFC (International Finance Corporation) and the public legal company Russian Ecological Operator (REO), as well as materials obtained by other authors during research in the southern [11] and central [12] regions of Russia, were studied and analyzed.

Within the framework of the objectives of this study, the following procedures were implemented:

- the dependencies of the volume of exported and sorted waste on the total amount of collected waste and the population were determined;
- an initial set of alternative MSW sorting options was formed based on their morphological composition. The volumes of pollutant emissions, including the carbon footprint, were calculated for different incineration plant capacities;
- using the ideal point method, the search for the optimal MSW sorting alternative was carried out according to a set of evaluation criteria that included energy value and pollutant emissions during incineration.

The main sequence of the research was as follows:

1. Based on the regression analysis of the values from the generated statistical sample, we obtained regression dependencies between the volume of waste and the population, as well as between the volume of sorted waste and the total volume of collected waste. These models were then tested for adequacy and statistical significance using correlation coefficients ($R^2 > 0.75$), the Student's t-test, and Fisher's F-test ($p > 0.95$).

2. Based on the reference information [12, 13], we formed a ranked range of specific heat values for MSW combustion based on the morphological composition, which was determined as part of collecting statistical data. These ranked values were then divided into two main groups: I — heat of combustion $22\text{--}45 \times 10^3$ kJ/kg; II — heat of combustion $17\text{--}21 \times 10^3$ kJ/kg (Fig. 1).

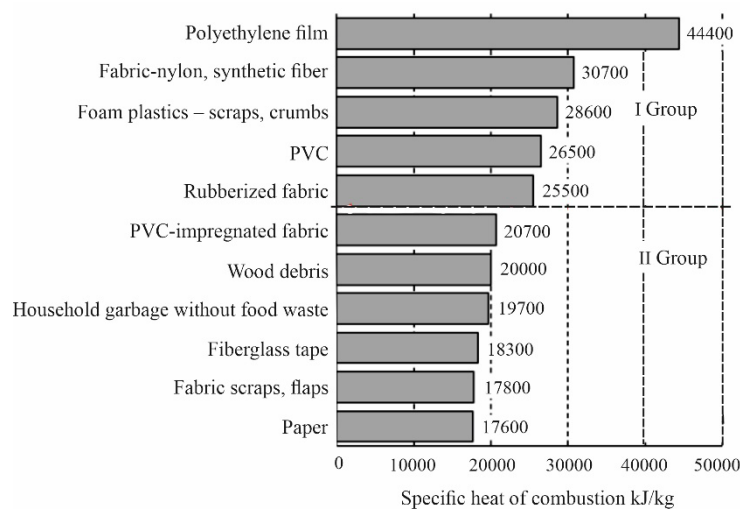


Fig. 1. Specific heat of combustion during MSW incineration (by morphological composition), kJ/kg

In this context, incinerating the entire volume of collected waste is often not practical or efficient, as there is not only a concern about the economic benefits of energy production, but also a serious issue with environmental pollution from combustion products [13].

3. In order to assess the preference of a multi-alternative choice of MSW sorting options, an initial set of criteria for assessing emissions/discharges of pollutants was formed, based on the idea of identifying the preference structure for municipal solid waste sorting [14]. The alternative sorting options in the selection task were a sequential change in the proportion of MSW groups (groups I and II), respectively, in conditionally accepted ratios (10/90, 30/70, 50/50, 70/30, 90/10).

4. The multi-criteria problem of choosing the optimal MSW sorting option for further incineration has been solved. One of the approaches to solve this problem was the method of constructing value functions [15], and the search for the best alternative was carried out on the basis of the “ideal” point method. The value function determined the degree of approximation of the obtained solution to the ideal point, as the coordinates of which the maximum (minimum) values of individual criteria could be used, i.e. the best values. As a rule, the obtained criteria values were normalized to one according to the following formula (1):

$$Z_{inorm} = (Z_i - Z_{imin}) / (Z_{imax} - Z_{imin}), \tag{1}$$

where Z_{inorm} — normalized value of criterion Z_i ; Z_{imin} , Z_{imax} — maximum and minimum values of the i -th criterion, respectively.

The modeling was conducted for a specific morphological composition of municipal solid waste. For this waste, sorting and disposal (incineration) options were developed. These options were characterized by the maximum energy value (electricity generation) based on the heat of combustion of individual components, and the minimal emissions of pollutants (including carbon footprint (greenhouse gases)) (Table 1).

Table 1

Formation of the initial set of alternatives for sorting and evaluation criteria for pollutant emissions (including carbon footprint) and MSW incineration (base plant capacity 0.5 tons/hour)

| MSW sorting options (group I / group II), % | Criteria for estimating pollutant emissions (including carbon footprint (greenhouse gases)) and the effectiveness of incineration | | | | |
|---|---|---|---------------------------------|-----------------------------------|---------------------------------|
| | Heat of combustion (energy value of MSW (according to the morphological composition of the sorting))* (kJ/kg) | Gross emissions of pollutants (kg/h) / (t/year) | | | |
| | | Fly ash | Sulfur oxide (SO ₂) | Nitrogen oxide (N ₂ O) | Carbon oxide (CO ₂) |
| Opt. 1 (10/90) | 4033 | 0.05/0.30 | 0.07/0.36 | 0.18/1.03 | 0.40/2.23 |
| Opt. 2 (30/70) | 5782 | 0.14/0.76 | 0.11/0.59 | 0.41/2.42 | 0.79/4.43 |
| Opt. 3 (50/50) | 8532 | 0.22/1.22 | 0.15/0.82 | 0.64/3.60 | 1.18/6.63 |
| Opt. 4 (70/30) | 11282 | 0.30/1.68 | 0.19/1.05 | 0.87/4.88 | 1.57/8.83 |
| Opt. 5 (90/10) | 14031 | 0.39/2.14 | 0.23/1.28 | 1.10/6.17 | 1.96/11.03 |

Note: *The calculation was based on the elemental composition of the components in the municipal solid waste (MSW) working mass, the yield of volatile substances, the percentage of each component, and the lowest calorific value of each component.

The research was conducted in the MS Excel and Statistica programs (data analysis and regression analysis modules).

Results. According to statistical data, it was revealed that the morphological composition of MSW over the past 5 years remained relatively stable with minor seasonal fluctuations and included (the data of the average and standard deviation): organic waste — 49.3±5.4%; secondary waste (plastic —10.2±2.1%, paper — 10.2±5.3%, metals — 10.2±3.1%, glass — 8.1±2.2%, other waste — 12±4%). At the same time, there was a clear correlation between the population size (PS) and the volume of waste accumulation (WV). Based on the least squares method, using the data of the collected statistics, a dependence was obtained ($WV = 442 \ln(PS) - 5585.5$, $R^2 = 0.67$) followed by the calculation of the pairwise correlation coefficient (Fig. 2).

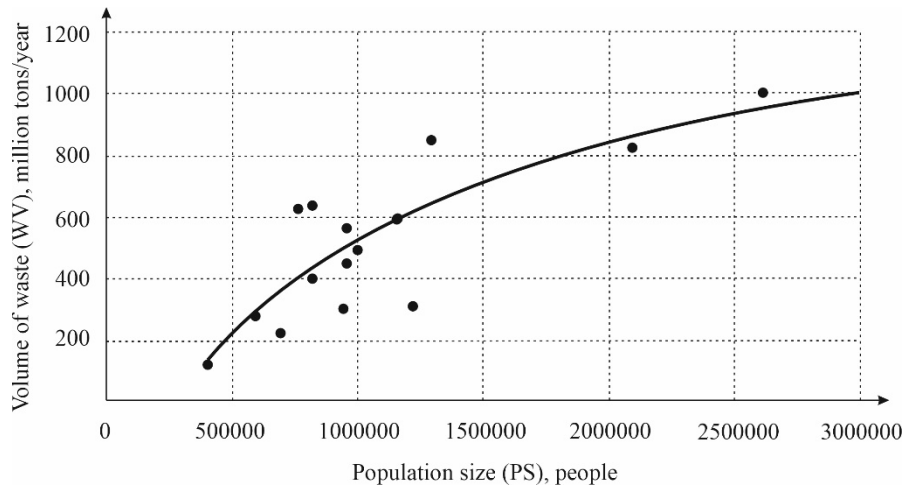


Fig. 2. Dependence of the volume of waste disposed of (WV, million tons/year) on the population size (PS, people)

In addition, another problem related to the waste sorting process was identified at MSW landfills. The analysis showed that when the volume of collected waste (CW) exceeded 600 thousand tons, the amount of sorted waste (SW) practically did not change ($(SW) = 37484(CW)^{0.2062}$; $R^2 = 0.79$), which, in turn, affected the efficiency of further recycling (Fig. 3). This conclusion confirmed the expediency and relevance of the applied research related to the analysis of the MSW management system, structural sorting by morphological composition and adaptive formation of waste streams.

As noted above, one of the most common methods of industrial waste processing is incineration, and the basic indicator of its effectiveness is the amount of energy produced by incineration, characterized by the specific heat of incineration of a particular type of MSW [16].

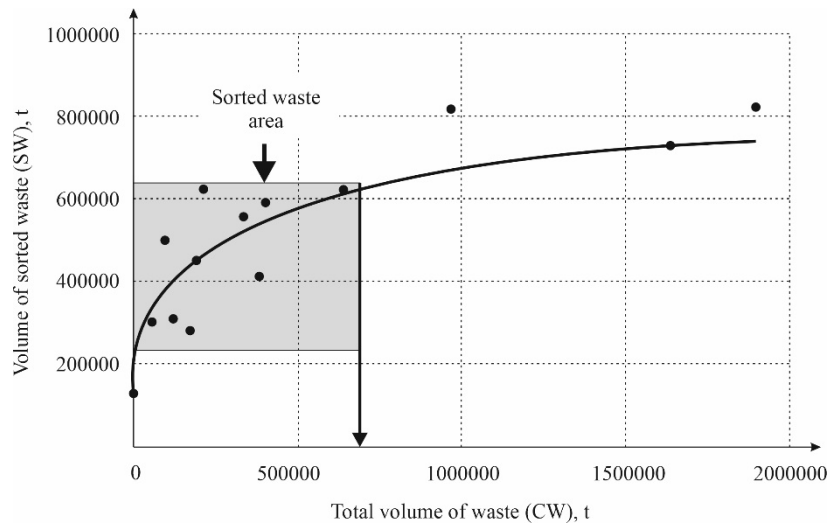


Fig. 3. Dependence of the volume of sorted waste (SW, t) on the total amount of waste collected (CW, t)

In the course of the research, a function was calculated that determined the degree of approximation of each sorting alternative to an ideal value (ideal point). The minimum emission values (fly ash, sulfur oxide, nitrogen oxide, and carbon oxide), as well as the maximum value of the heat of incineration (MSW energy value, determined based on the morphological composition) were used as such values. When calculating the distance to the ideal point, the weight (significance) of each of the evaluation criteria was assumed to be equivalent. If necessary, the model could be supplemented with expert modeling procedures that established weighting coefficients for specific sorting and incineration tasks. The optimal alternatives for this method included options 3–5 (Fig. 4). Due to the presence of different sizes, the normalization procedure and calculation of the sensitivity coefficients of the multiple linear regression model, the function of MSW incineration heat, were carried out (Table 2).

Table 2

Functions of sensitivity coefficients of the incineration efficiency model (energy value (EV)) of MSW to the change of the values of sorting parameters and gross emission of pollutants

| Parameter | Ratio sensitivity coefficient TCr/ X | | | | |
|-----------------------------------|--|------------------|--------------------|-------------------|-------------------|
| | Opt.1 (10/90) | Opt.2 (30/70) | Opt. 3* (50/50) | Opt.4* (70/30) | Opt.5* (90/10) |
| Fly ash | 1681.31 | 2141.82 | 2981.76 | 3167.61 | 3998.43 |
| Sulfur oxide (SO ₂) | 2619.16 | 4314.19 | 5514.26 | 6412.13 | 7571.51 |
| Nitrogen oxide (N ₂ O) | 8314.19 | 9368.14 | 11365.91 | 13591.21 | 15910.12 |
| Carbon oxide (CO ₂) | 1323.12 | 1436.84 | 1509.43 | 1609.19 | 1943.18 |
| Consolidated member | 1423.12 | 1556.81 | 1919.35 | 2193.45 | 3005.45 |
| Correlation coefficient | 0.79 | 0.89 | 0.82 | 0.76 | 0.81 |

Note: * Optimal MSW sorting options (according to Table 1).

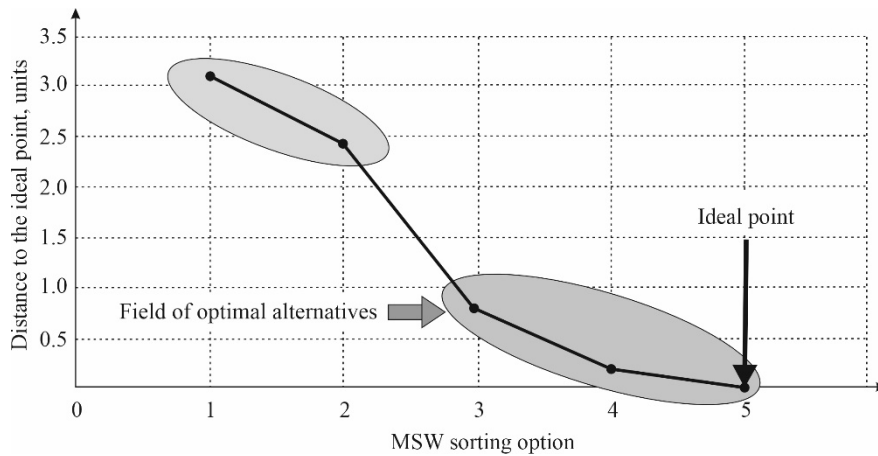


Fig. 4. Determination of the degree of approximation of the obtained solutions for MSW sorting options to the ideal point

Thus, in the course of our research, we have identified optimal options for sorting MSW from the perspective of incineration, taking into account heat of combustion and emissions of pollutants, including carbon footprint indicators.

In order to create a set of parameters for the incineration efficiency model, which, according to the initial formulation, were subject to variation based on the results of the proposed sorting, taking into account the morphological composition of MSW, in addition to sensitivity coefficients, statistical characteristics of variation and correlation are determined. Based on the analysis of the obtained sensitivity coefficients of the MSW incineration efficiency model, the maximum possible absolute values of these coefficients were established and conclusions were formulated on the need to consider those structural elements of morphological composition, the combustion of which would ensure the lowest emissions of pollutants into the atmosphere.

Discussion. The results of the study have allowed us to develop a number of significant recommendations regarding the optimization of the MSW sorting process for incineration.

The revealed logarithmic relationship between the population and the volume of waste removed ($R^2 = 0.67$) was consistent with the research results of other authors in the southern [11] and central [12] regions of Russia, where a nonlinear nature of MSW accumulation in urbanized territories was also noted. The obtained correlation coefficient indicated the presence of stable relationship, however, the value of $R^2 < 0.7$ indicated the influence of additional factors (consumption level, seasonality, economic activity) that were not taken into account in the model. This limitation required further research to expand the set of variables to improve the accuracy of predicting the volume of MSW formation.

Of particular interest was the discovered power-law dependence of the volume of sorted waste on the total amount collected waste ($R^2 = 0.79$), demonstrating the saturation effect when exceeding the threshold of 600 thousand tons. This result was explained by the limited capacity of existing sorting facilities and the insufficient development of recycling infrastructure in regions with high levels of waste generation. Similar conclusions were drawn in a research paper [17], where the authors pointed out the technological and organizational barriers to scaling sorting processes. The revealed limitation underlined the need not only to increase the capacity of sorting stations, but also to introduce a separate collection system at the level of primary sources of MSW formation.

The relative stability of MSW morphological composition over a five-year period, with organic waste accounting for $49.3 \pm 5.4\%$ and recycled materials — approximately 50%, corresponded to global trends in countries with developing waste management systems [5]. The predominance of the organic fraction was typical of regions with low levels of separate collection and distinguished Russian practice from that of Scandinavian countries and Western Europe, where the proportion of organic material had been reduced to 20–30% through active composting and biological treatment [11]. These differences explained the lower average calorific value of Russian MSW compared to that of its European counterparts.

The application of the ideal point method for the multi-criteria selection of optimal sorting options was an adaptation of the classical decision theory approach to the specific task of waste management. The obtained optimal options (group I/II ratios: 50/50, 70/30, 90/10) demonstrated a compromise between maximizing energy value (heat of combustion from 8532 to 14031 kJ/kg) and minimizing environmental damage from emissions. It was important to note that an increase in the proportion of high-calorie fractions (group I) led to a proportional increase in gross emissions of pollutants — fly ash ranging from 0.22 to 0.39 kg/h; SO₂ ranging from 0.15 to 0.23 kg/h; N₂O ranging from 0.64 to 1.10 kg/h, and CO₂ ranging from 1.18 to 1.96 kg/h. This was consistent with the fundamental laws of thermal processing, as described in the works of Khantimirov [6], Konovalov [7], Vaitikunene [13] and other authors, where it was shown that materials with high heat of combustion (plastic, rubber) generated more toxic combustion products.

The calculated sensitivity coefficients for the model (Table 2) allowed us to quantify the impact of different types of emissions on the energy efficiency of incineration. Heat of incineration demonstrated the greatest sensitivity to changes in nitrogen oxide emissions (coefficients ranging from 8314.19 to 15910.12), which was explained by the specifics of oxidative processes during high-temperature combustion of nitrogenous components of MSW. The obtained values of correlation coefficients of the models (0.76–0.89) indicated sufficient reliability of the regression relationships, although option 4 showed a relatively lower value (0.76), which could indicate nonlinear effects with this ratio of components.

The assumption made in the research that all evaluation criteria had equivalent weighting coefficients was a simplification that could be justified at the initial stage of analysis. However, it required clarification for specific practical tasks, depending on regional environmental priorities and air quality standards. Different types of emissions could require a differentiated approach. For example, in urban agglomerations with tense environmental situation, CO₂ emissions criterion (carbon footprint) could have more weight due to Russia's climate commitments.

The limitation of the presented model was the basic capacity of the incinerator (0.5 t/h), which was typical for small and medium-sized incinerators. When scaling up to large plants with a productivity of 10–50 t/h, it was necessary to adjust emission parameters by taking into account scale and using modern gas purification systems. Additionally, the model did not consider the economic aspects of sorting and incineration — capital and operating costs, the cost of electricity, which limited the possibility of practical application of the results without additional feasibility studies.

Practical significance of the results lies in the possibility of their use in planning and optimizing the MSW management system at the regional level. Certain optimal sorting options can serve as targets for waste management operators when forming technical specifications for sorting complexes and coordinating waste flows between sorting stations and incinerators. The calculated sensitivity coefficients make it possible to quickly assess changes in environmental and energy indicators when adjusting the morphological composition of the sorted MSW.

A comparison of the results obtained with international practices showed that the proposed approach was in line with the trends of incorporating environmental criteria into waste management [8]. However, in order to reach the indicators of leading European countries (utilization rates of 50–68%, burial rate of 1%), a comprehensive transformation of the entire MSW management system is necessary, including not only optimizing sorting for incineration but also developing alternative processing methods such as organic composting, recycling of recyclable materials, and production of RDF fuels.

It is advisable to focus further research on the development of dynamic models that take into account seasonal variability of MSW morphological composition, as well as on the integration of expert assessments to determine the weighting coefficients of criteria depending on regional specifics. A promising direction is the creation of digital platforms for monitoring and managing garbage flows in real time using the obtained regression dependencies and optimization models.

Conclusion. In the course of the work, the main goal was achieved — optimal sorting options for municipal solid waste were determined for incineration based on the heat of combustion and emissions of pollutants.

The following tasks have been solved:

1. Statistical data of the MSW management system were collected and analyzed; relative stability of the morphological composition of waste over a five-year period was established (organic — $49.3 \pm 5.4\%$, recycled materials — approximately 50%).

2. Regression dependencies of the volume of waste collected on the population (logarithmic, $R^2 = 0.67$) and the volume of sorted waste on the total amount collected (power-law, $R^2 = 0.79$) were obtained; the effect of saturation of sorting capacities at volumes over 600 thousand tons was revealed.

3. A set of five alternative MSW sorting options has been formed according to the ratio of groups with different energy values (group I: $22\text{--}45 \times 10^3$ kJ/kg; group II: $17\text{--}21 \times 10^3$ kJ/kg), the volumes of pollutant emissions (fly ash, SO_2 , N_2O , CO_2) for each option at the plant base capacity of 0.5 t/h have been calculated.

4. Using the ideal point method, three optimal MSW sorting options have been identified (ratios of groups I/II: 50/50, 70/30, 90/10), providing a compromise between maximizing energy value (heat of combustion 8,532–14,031 kJ/kg) and minimizing environmental impact.

The sensitivity coefficients of the incineration efficiency model have been calculated, showing the greatest effect of nitrogen oxide emissions on the energy characteristics of the process. The regression models obtained have sufficient statistical significance (correlation coefficients of 0.76–0.89).

The research results can be used by regional waste management operators when planning the operation of sorting complexes and incinerators, as well as when forming strategies for the development of MSW processing infrastructure in accordance with the goals of the “Industrial Development Strategy for the Treatment, Disposal and Neutralization of Industrial and Consumer Waste in Russia until 2030”¹¹.

Prospects for future research include the development of dynamic models that take into account seasonal variability in the composition of MSW, the implementation of expert procedures to determine the weighting coefficients of criteria, and a feasibility analysis of the sorting options obtained for different production scales.

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