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FORMATION OF A REGIONAL STRATEGY FOR MUNICIPAL SOLID WASTE MANAGEMENT CONSIDERING GREENHOUSE GAS EMISSIONS[1]

Abstract. Currently, Russia is going through a global transformation in the field of waste management, which is mainly caused by the exhaustion of the capacities of existing landfills. The country's goal is to reduce landfill and ensure 36 % recycling of all municipal solid waste (MSW) by 2024. Meanwhile, the discussion about the choice of disposal methods continues. We propose to look at the choice of the optimal MSW management strategy at the regional level through the prism of its total greenhouse gas (GHG) emissions. In this regard, the purpose of the article is to determine the total carbon footprint of the regional MSW management system in order to consider the "contribution" of each of the methods of waste management and make the considered criterion suitable for assessing the sustainability of the whole regional waste management system under various scenarios of its development. To achieve this goal, the methodology of the Intergovernmental Panel on Climate Change was used to assess the current situation in the field of MSW management in the Sverdlovsk region. Further, the study developed the conditions for three industry development scenarios (basic, inertial, innovative); substantiated the factors of direct and prevented GHG emissions; calculated GHG emissions from the MSW management sector in the Sverdlovsk region for 2023-2030 for each of the three scenarios. The calculations showed that, by 2030, the basic scenario ("as is", business-as-usual) has the maximum carbon footprint of 1558.5 thousand tonnes of CO_2-eq. The innovative scenario has minimum net emissions of 82.6 thousand tonnes of CO_2-eq. by creating a full-fledged separate waste collection and recycling more waste. The findings can be useful in the formation of regional strategies for waste management, considering GHG emissions.

Keywords: waste management system, municipal solid waste, greenhouse gas emissions, carbon footprint, specific greenhouse gas emissions, waste recycling, separate waste collection

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ИССЛЕДОВАТЕЛЬСКАЯ СТАТЬЯ

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Формирование региональной стратегии обращения с твердыми коммунальными отходами с учетом выбросов парниковых газов

Аннотация. В настоящее время в России происходит глобальная трансформация в сфере обращения с отходами, в основном связанная с исчерпанием мощностей существующих полигонов. Цель государства — сокращение полигонного захоронения и обеспечение к 2024 г. 36 % утилизации всех твердых коммунальных отходов (ТКО). При этом продолжается дискуссия на тему выбора способов утилизации. Авторы данной статьи предлагают посмотреть на выбор оптимальной стратегии обращения с ТКО на уровне региона через призму ее совокупных выбросов парниковых газов. В связи с этим целью статьи является определение совокупного углеродного следа региональной системы обращения с ТКО, что позволяет учесть вклад каждого из способов обращения с отходами и делает рассматриваемый критерий подходящим для оценки устойчивости региональной системы обращения с отходами в целом по различным сценариям ее развития. Для достижения поставленной цели использована методология Межправительственной группы экспертов по изменению климата. Авторами дана оценка текущей ситуации в сфере обращения с ТКО в Свердловской области; разработаны условия для трех сценариев развития отрасли: базового, инерционного, инновационного; обоснованы факторы прямых и предотвращенных эмиссий парниковых газов; произведены расчеты выбросов парниковых газов от сектора обращения с ТКО для Свердловской области на 2023–2030 гг. по каждому из трех сценариев. Проведенные расчеты показали, что к 2030 г. максимальным углеродным следом в 1558,5 тыс. т эквивалента CO_2 обладает базовый сценарий (подход «как есть», «бизнес как обычно»). Минимальные чистые выбросы в 82,6 тыс. т эквивалента CO_2 приходятся на инновационный сценарий за счет создания полноценного раздельного сбора ТКО и вовлечения большего количества отходов в повторное использование. Полученные выводы могут быть полезны при формировании региональных стратегий обращения с отходами с учетом выбросов парниковых газов.

Ключевые слова: система обращения с отходами, твердые коммунальные отходы, выбросы парниковых газов, углеродный след, удельные выбросы парниковых газов, переработка отходов, раздельный сбор отходов

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1. Introduction

The rapid development of cities, the growth of people's well-being have led to the fact that the volume of waste generation in urban agglomerations has been growing rapidly (Das et. al, 2019). In 2016, 2.01 billion tonnes of municipal solid waste (MSW) were generated in the world. If this trend continues, the volume of generated MSW can reach 3.4 billion tonnes per year by 2050 (Kaza et. al, 2018). On the one hand, this is a negative environmental factor, since landfill and incineration in waste incineration plants, among other things, affect the health and life expectancy of the urban population (García-Pérez et. al, 2013). On the other hand, there is a problem associated with the disposal of MSW — there are no suitable areas, approved by local communities, for new landfills near cities, which affects transport costs and, consequently, the tariff for MSW management.

In the 2030 Agenda for Sustainable Development, the United Nations (UN) pays special attention to the problem of MSW management. One of the goals is to reduce the environmental impact of the cities, including the reduction of pollutant emissions and the generation of MSW[1]. Thus, there is a demand for the formation of an environmentally friendly, cost-effective, and

[1] UNEP (2015). Transforming Our World: the 2030 Agenda for Sustainable Development. United Nations. Retrieved from: https://sustainabledevelopment.un.org/post2015/transforming-ourworld/publication (Date of access: 20.06.2022).

socially acceptable regional system for the MSW management.

Since 2014, Russia has been undergoing a global reform of the waste management system. The purpose of the changes is to reduce landfill disposal and increase the share of MSW sent for recycling.

Despite the fact that the Russian strategic planning documents do not contain target values related to the reduction of the absolute amount of waste per capita, the main federal law regarding waste management[1] indicates the following distribution of priorities in waste management methods in descending order (which is in line with the EU waste management priorities, see Directive 2008/98/EC[2]): maximum use of raw materials; waste prevention; reduction of waste generation and reduction of hazardous waste at the sources of their generation; waste processing; recycling; waste disposal. This prioritisation is in line with the principles of the circular economy[3], which aims to maximise the reuse of goods and reduce the consumption of non-renewable natural resources.

In 2020, Russia identified seven pilot regions (including Sverdlovsk region), in which the MSW management system would be transferred to a closed cycle. In these regions, it is planned to form an infrastructure that provides not only the separate collection, transportation, processing and disposal of waste, but also the production of finished products from recovered materials.

At the initial stages, building a waste management system involves choosing the optimal strategy, which includes, among other things, the ratio between the waste management methods. This raises the question: how to evaluate the effectiveness of various methods of waste management and their combinations, what can be considered an efficiency criterion?

2. Theory

There is a large number of works that evaluate the effectiveness of a waste management system using a multi-criteria decision making (MCDM). One of the latest reviews concerning this group of methods is given in the work of Goulart Coelho, Lange and Coelho (2017). The review analysed 260 articles, which applied the MCDM method in the field of waste management. For the purposes of this study, the indicators and criteria that are used to evaluate the effectiveness of a waste management strategy are important. The authors of the review found the following combinations of factor types and their distribution: environmental, economic, social (46 %); environmental and economic (25 %); environmental (11 %), environmental and social (11 %), economic (4 %); economic and social (3 %). Since waste management is a complex socio-ecological and economic problem, the inclusion of these factors in the articles considered in the review is quite understandable.

If we consider the specific criteria and indicators used in the MCDM, Herva and Roca (2013) propose to rank different waste management methods using such criteria as: ecological footprint, water consumption, emissions of organic pollutants, emissions of solid particles, discharges of pollutants into water resources, and the area allocated for MSW landfills. It should be noted that all the criteria above are environmental.

In the paper of Jovanovic et. al (2016), the authors use the MCDM to evaluate six different MSW management strategies for the city of Kragujevac (Serbia) using the following parameters: methane emissions; carbon dioxide emissions; nitrogen oxide emissions; emissions of solid particles; fuel consumption; general operating costs; volume of MSW disposed of at the landfill. In this paper, the authors use a combination of environmental and economic factors that influence the formation of the MSW management strategy.

Generowicz, Kowalski and Kulczycka (2011) consider the following criteria for evaluating different MSW management strategies for the city of Krakow: reducing the amount of MSW entering the landfill; reducing the volume of organic waste entering the landfill; recovery of materials suitable for reuse; production of energy from waste; availability of operational documentation for the MSW landfill; compliance with the law; nature of the decision-making in terms of the prospects for the development of the sector; social acceptability; monthly fee for the treatment of MSW for one resident. In this paper, there are three types of factors: environmental, economic, social.

Coban, Ertis and Cavdaroglu (2018) conducted an expert assessment of various MSW management scenarios for Istanbul using the following

[1] Federal Law No. 89-FZ of June 24, “On production and consumption waste” (with amendments and additions). Retrieved from: https://base.garant.ru/12112084/ (Date of access: 28.06.2022).

[2] Directive 2008/98/EC of the European Parliament and of the Council of the European Union of 19 November 2008 “On waste and repealing certain Directives”. Retrieved from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098 (Date of access: 21.06.2022).

[3] Ellen Macarthur Foundation. 2012. Towards the Circular Economy. Retrieved from: http://www.ellenmacarthurfoundation.org/business/reports (Date of access: 21.06.2022).

environmental and economic criteria: initial investment costs; operating costs; transportation costs; environmental risks; infrastructure requirements; personnel qualification requirements.

It should be noted that the review by Goulart Coelho, Lange and Coelho (2017) does not include factors directly related to the circular economy among the analysed factors affecting the efficiency of the MSW management system (Stahel, 2016). Meanwhile, the relationship between the circular economy and the waste management system is obvious — in the EU circular economy monitoring system[1], 2 out of 10 indicators are related to waste management (MSW recycling rate and the level of MSW generation per capita). Most likely, this issue was widely discussed after the publication of the review. Currently, various works rely on the principles of the circular economy when considering the performance indicators of the MSW management system.

For example, in their empirical study, Lombardi et. al (2021) studied the effectiveness of the urban MSW management system for 78 large cities in Italy in 2014–2018, considering the goals of reducing the generation of MSW per capita and the level of MSW recycling, which were contained in the EU Circular Economy Strategy. The authors used the following as performance indicators: location, population density, population age index, tariff for MSW collection services for the population, and method of MSW collection.

The paper by Tomić and Schneider (2020) evaluated the socio-economic impact of changes in the waste management system in the transition to a circular economy. Revenue and expenditure estimates (investment and operating costs) have been made for the processes of materials recovery and waste-to-energy production. These calculations allowed the authors to determine a variable fee (depending on time) and an average fee (per tonne of incoming MSW), which are to be charged to users of the waste management system.

Wiesmeth and Starodubets (2020) consider the role of the circular economy in the formation of an efficient MSW management system, including an assessment of business models of the circular economy and their applicability for the MSW sector.

It should be noted that even though the MCDM method has advantages (the ability to consider a large number of factors, a comprehensive assessment of the effectiveness of the waste management system), it also has disadvantages: the labour intensity associated with the collection of initial data and the implementation of an integral assessment, as well as subjectivity — a set of criteria and indicators is at the discretion of the authors.

The Life Cycle Assessment method (LCA) is another way to assess the effectiveness of various MSW management scenarios. This method is based on ISO 14040/44, which contains its basic principles and components: the choice of system boundaries and units of measurement; assessment approaches, including uncertainty assessment. The main idea of the LCA is the assessment of the cumulative impact on the environment throughout the life cycle of a product (service). For the purposes of this study, it is important to track exactly how the environmental impact assessment was carried out for various MSW management strategies. In this regard, the authors refer to the review by Zhang et. al (2021). The review analysed 45 studies where the effectiveness of the MSW management system was assessed using the LCA method.

According to this review, all 45 studies used such an indicator as the carbon footprint of the MSW management sector, which the authors called "global warming potential (GWP)", or "climate change impact". The use of specific GHG emissions as an indicator of the efficiency and sustainability of a waste management system can be explained by growing concerns about climate change and the contribution of the waste management sector to anthropogenic GHG emissions. According to the review (Zhang et. al, 2021), other criteria of efficiency included acidification potential (occurred in 27 of 45 studies) and potential toxicity to humans (occurred in 22 of 45 studies).

The clear advantage of the LCA approach is the existence of a single recognised methodology and principles of evaluation. However, despite its prevalence in the assessment of the effectiveness of the waste management system, the significant disadvantages of the LCA approach are the large number of initial data and the availability of special software for processing the results.

The use of only specific GHG emissions as a criterion for assessing the effectiveness of the MSW management system can be considered a special case of the LCA. There is a large number of studies based on this particular approach for different cities and regions (Kristanto, Koven, 2019; Yaman, 2020; Babel, Vilaysouk, 2016; Yu, Zhang, 2016; Liamsanguan, Gheewala, 2008, etc.). All of them are based on the Methodology of the Intergovernmental Panel on Climate Change

[1] European Commission. Commission of European Communities. Communication No. 29, 2018. Monitoring Framework for the Circular Economy; COM no. 29; European Commission: Brussels, Belgium, 2018.

(IPCC) for estimating GHG emissions by sector[1]. According to the authors, the prevalence of this approach can be explained, on the one hand, by the unified and globally recognised methodological approach of the IPCC, on the other hand, by an understandable integral indicator — specific GHG emissions per tonne of MSW (or GHG emissions attributable to the entire sector of the MSW management), which is an accessible screening indicator that characterises the MSW management system as a whole, although it does not take into account all types of environmental impacts.

Speaking of the existing approaches to assessing the effectiveness of the MSW management system for the regions and cities of Russia, the authors mainly use the approach based on the LCA for these purposes.

Thus, Tulokhonova and Ulanova (2013) developed four scenarios for the development of the MSW management system for Irkutsk and assessed them by considering environmental, economic, and social aspects based on the LCA model. The authors used the following types of impacts: resource depletion; climate change; toxicity to humans; formation of photo-oxidants; acidification and eutrophication.

A similar study using the LCA was carried out by Kaazke et. al (2013) for Khanty-Mansiysk and Surgut. Plastinina et. al (2019), who also used the LCA method, assessed the economic efficiency of activities at various stages of the MSW (paper waste) processing in the Sverdlovsk region. Vinitskaia et. al (2021) compared 6 scenarios for the development of the MSW sector in Moscow based on the LCA method, taking into account the following indicators: global warming potential, acidification potential, and eutrophication potential. Abu-Qdais and Kurbatova (2022) also used the LCA method to assess the environmental impact of eco-technoparks in Russia in comparison with the traditional waste management model.

There are also works that choose the territory of the Russian Federation as the object of study and suggest using GHG emissions as a criterion for the effectiveness of the waste management system. Rodionov and Nakata (2011) propose to evaluate the effectiveness of the MSW management system of the city of St. Petersburg by considering economic, energy, and environmental impacts, namely: expenses, annual energy production from waste, and total carbon footprint.

Bozhko et.al (2021) propose to use the indicator of specific GHG emissions when developing a strategy for the management of MSW within the green clusters of Russia and Kazakhstan. Wünsch and Tsybina (2022) assessed GHG emissions from the Russian MSW management sector under three sector development scenarios: the most sustainable scenario is the scenario with the lowest specific GHG emissions.

In this study, the authors propose to use the total GHG emissions of the waste management sector as a criterion for the effectiveness of the MSW management strategy. This criterion seems suitable for evaluation for several reasons. Firstly, the threat of climate change is one of the most pressing today, and, according to the latest report on climate change by the IPCC (Allan et. al, 2021), the “Waste” sector accounts for 18 % of global anthropogenic emissions of methane, one of the main GHGs. For large cities, this sector is one of the most significant sources of GHG emissions (Kennedy et. al, 2010). Secondly, the specific GHG emissions for each waste management method correlate with the hierarchy of waste management methods, according to which prevention and reuse of waste take precedence over incineration and landfill. Each of the waste management methods is a source of GHG emissions, but such methods as landfill and energy utilisation of waste have the maximum of specific emissions.

The purpose of this article is to determine the total carbon footprint of the regional waste management system, which allows us to take into account the “contribution” of each of the waste management methods, and makes the studied criterion suitable for assessing the environmental friendliness and sustainability of the regional waste management system as a whole in various scenarios of its development.

To achieve this goal, the following tasks were set and solved, which was reflected in the structure of the article:

— the current situation in the field of MSW management in the Sverdlovsk region was assessed;

— based on the available documents for the development of the sphere of MSW management in the Sverdlovsk Region, conditions for three development scenarios of the industry — basic, inertial, innovative — were developed;

— the factors of direct and prevented GHG emissions were substantiated;

— calculations of GHG emissions from the MSW management sector for the period 2023–2030 were made for each of the three scenarios, conclusions were drawn.

[1] 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 5 Waste; 2019. Retrieved from: https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html (Date of access: 22.06.2022).

It should be noted that such work is carried out for the first time for the Russian region.

3. Materials and Methods

3.1. Object of the Study

The Sverdlovsk region is one of the industrial regions of Russia, located in the centre of Eurasia. As of 2021, the gross regional product (GRP) of the region amounted to 36.7 billion roubles (0.6 billion Euro), the population is 4.29 million people. The city of Ekaterinburg is the capital of the region. This city, together with the adjacent cities that make up the Ekaterinburg agglomeration, is home to 2.3 million people.

Currently, about 1.5 million tonnes of MSW are generated in the region. The data on the formation of MSW and the dynamics of its management are presented in Table 1 (according to the Federal Service for Supervision of Natural Resources, based on the form “2-TP Waste”).

Thus, as of 2021, each inhabitant of the Sverdlovsk region generates 340 kg of MSW per year. Less than 1 % of the total amount of generated MSW is recycled. The rest goes to MSW landfills, the capacity of which is close to exhaustion.

The morphological structure of MSW for the Sverdlovsk region, according to the Territorial waste management scheme of the Sverdlovsk region, is presented in Table 2. The potentially recyclable part (food waste, paper, cardboard, wood, metals, textiles, glass, rubber, PET) amounts to 80 % of the total MSW.

Target indicators of the MSW management reform for the Sverdlovsk region are determined in accordance with the National Project Ecology[1]; Strategy for the development of the industry for the processing, recycling and neutralisation of production and consumption waste for the period up to 2030[2]; Regional project “Integrated system of municipal solid waste management (Sverdlovsk region)”[3], Territorial waste management scheme. According to these documents, 100 % of all MSW should be processed (sorted), 50 % of the generated MSW should be recycled by 2026 (Table 3).

According to the Federal Law N 89-FZ “On Production and Consumption Waste”, recycling is defined as both the production of new goods from waste and the use of waste for energy production. The Russian environmental operator has raised the issue of equating composting to recy-

Table 1

The current situation with MSW in the Sverdlovsk region

Indicator, thousand tonnes	2019	2020	2021
MSW generated	1513.4	1470.6	1459.5
Sent for processing	166.5	155.9	141.5
Sent for recycling	7.0	22.1	8.8
Placed at the landfill, including temporarily stored MSW	1274.0	1371.0	1436.2

Source: Federal Service for Supervision of Natural Resources. Retrieved from: https://rpn.gov.ru/open-service/analytic-data/statistic-reports/production-consumption-waste/ (Date of access: 25.06.2022).

Table 2

Morphological structure of MSW, Sverdlovsk region

MSW component	Share, %
Food waste **	17.2
Paper, cardboard*	23.26
Wood*	1.35
Ferrous metal *	0.85
Non-ferrous metal *	1.28
Textile*	3.94
Glass*	9.48
Leather, rubber *	1.89
Stone **	2.17
Plastic, incl.	14.89
- polyethylene terephthalate (PET)*	3.06
- composite packaging ***	2.03
- other ***	9.8
Other MSW	9.10
Screenings (less than 15 mm) **	14.56
Total	100
including processed fractions (secondary material resources), marked *	45.10
fractions supplied for composting and technosoil production, marked **	33.93
fractions supplied for the RDF production, marked ***	11.83

Source: Territorial waste management scheme for production and consumption in the territory of the Sverdlovsk region, approved by order of the Ministry of Energy and Housing and Public Utilities of the Sverdlovsk Region on 31.03.2020 No. 185. Retrieved from: https://energy.midural.ru/wp-content/uploads/2021/11/p_15.11.2021_499_ts.pdf (Date of access: 30.06.2022).

[1] Passport of the federal project “Formation of an integrated system for handling municipal solid waste” of the national project Ecology. Retrieved from: http://energy.midural.ru/wp-content/uploads/2020/08/PAS_TKO_21.12.2018_3.pdf (Date of access: 28.06.2022).

[2] Strategy for the development of the industry for the processing, recycling and neutralization of production and consumption waste for the period up to 2030. Retrieved from: http://www.consultant.ru/document/cons_doc_LAW_289114/549eef11ae953dc6e4261b88ed6d14f776df3203/ (Date of access: 28.06.2022).

[3] Regional project “Integrated system of municipal solid waste management (Sverdlovsk region)”. Retrieved from: https://energy.midural.ru/wp-content/uploads/2019/09/Reg_pro_tko2019.pdf (Date of access: 28.06.2022).

Table 3

Target indicators of the MSW management reform for the Sverdlovsk region

№	Indicator, thousand tonnes	2023	2024	2025	2026–2030
1	MSW generated	1500	1500	1500	1500
2	MSW processed	250	617	932	1500
3	MSW recycled	180	450	675	725
4	MSW placed at the landfill	1320	1050	825	775

Source: Territorial waste management scheme for production and consumption in the territory of the Sverdlovsk region, approved by order of the Ministry of Energy and Housing and Public Utilities of the Sverdlovsk Region on 31.03.2020 No. 185. Retrieved from: https://energy.midural.ru/wp-content/uploads/2021/11/p_15.11.2021_499_ts.pdf (Date of access: 30.06.2022).

cling[1]. In this study, the authors define recycling as reuse of waste, use of waste for energy, as well as composting.

To achieve these goals within the framework of the territorial scheme, it is proposed to do the following:

— introduce separate collection of MSW and develop infrastructure in the field of MSW management;

— extract biodegradable waste during MSW processing at aerobic composting complexes;

— produce refuse-derived fuel (RDF) from non-recyclable waste.

3.2. Scenario Conditions

In this study, we consider three scenarios for the development of the waste management sector from 2023 to 2030 (Table 4). Scenarios 2 and 3 are compiled in accordance with the Territorial waste management scheme (section 9). It should be noted that the volume of generated MSW and the morphological composition of MSW do not change, only the ratios between the MSW treatment methods change.

Scenario 1 (basic, business-as-usual). The activities envisaged by the Territorial scheme are not being implemented. The situation in the field of MSW management remains unchanged: 0.6 % of MSW is recycled; there are no sites for composting and production of technosoil, RDF production. The rest of the waste goes to the MSW landfill.

Scenario 2 (inertial). The minimum standard for the system of separate MSW collection has been implemented — dual (two-container) system. All MSW at the collection stage are divided into two streams: the first stream contains MSW suitable for reuse (polymer waste, paper and cardboard, metal, glass, etc.), the second stream contains non-recyclable waste (organic waste, screenings, stones, non-recyclable plastic).

The advantage of the dual scheme, in addition to its organisational simplicity, is the fact that the sorted waste is not contaminated with organic matter, which increases the recovery rate. However, the authors believe that the recovery rate surely cannot reach 100 % in the dual system and propose to use a correction factor of 0.6 to the amount of potentially recyclable waste (first stream) for further calculations.

Scenario 3 (innovative). Organising a full-fledged separate waste collection in the form of a multi-container system, using various containers for the separate collection of glass, plastic, paper, and other fractions; informing households about the new system; stimulating separate collection by differentiating the tariff for MSW removal depending on the degree of household participation in the MSW sorting. In addition to the reduction of the cost of MSW recycling, the advantage of separate collection is an increase in the recovery rate. We propose to use a correction factor of 0.8 to the amount of potentially recyclable waste for further calculations.

According to scenarios 2 and 3, after separate collection, MSW goes to processing facilities — waste processing complexes (WPC), where it is further sorted. At WPC, useful fractions are extracted from the incoming waste: metal, paper, cardboard, plastic, film, glass (recovered materials), and organic fraction.

After that, recovered materials go to enterprises that process them. The organic fraction, along with screenings, enters the aerobic composting area. The end product of the composting process is, among other things, technosoil — an inert non-combustible organo-mineral fraction, which is supposed to be used for pouring waste layers at MSW landfills.

Moreover, the Territorial waste management scheme provides for the production of RDF for that part of MSW that has not been disposed of in any other way. It is planned to send a part of MSW, which is unsuitable for recycling after processing, to the production of RDF (40 % of all potentially recyclable MSW under Scenario 2 and 20 % under Scenario 3, as well as other plastics, see Table 2). The scheme does not define how and where RDF will be used. In this study, we propose to consider the option of using RDF in the kilns of a cement plant located 140 km from Ekaterinburg.

[1] https://www.vedomosti.ru/ecology/regulation/news/2022/02/04/907937-kompostirovanie-othodov-predlagayut-otnesti-k-utilizatsii (Date of access: 28.06.2022).

MSW that remained after processing will be sent to the MSW landfill.

The material balance of MSW for each scenario for 2023–2030 is presented in Table 4. The following assumptions were used when constructing material flows:

— the volume of generated waste is assumed unchanged for the period under review, that is, the Territorial waste management scheme does not take into account the factors of potential reduction in consumption and prevention of MSW generation;

Table 4

Material balance of MSW for each scenario for 2023–2030 for the Sverdlovsk region

№	Indicator, thousand tonnes	2023	2024	2025	2026-2030
	Scenario 1				
1	MSW generated (See Table 3, line 1)	1500	1500	1500	1500
2	MSW processed	145.5	145.5	145.5	145.5
3	MSW recycle, including	9	9	9	9
	— mixed glass 9.48 %	0.85	0.85	0.85	0.85
	— paper, cardboard 23.26 %	2.07	2.07	2.07	2.07
	— mixed metal, scrap metal 2.13 %	0.1404	0.1404	0.1404	0.1404
	— PET 3.06 %	0.2754	0.2754	0.2754	0.2754
	— wood 1.35 %	0.1215	0.1215	0.1215	0.1215
	— textile 3.94 %	0.3546	0.3546	0.3546	0.3546
4	MSW landfill (line 1 — line 3)	1491	1491	1491	1491
	Scenario 2				
5	MSW generated (See Table 3, line 1)	1500.0	1500.0	1500.0	1500.0
6	Processed MSW collected under the dual collection system (See Table 3, line 2)	250.0	617.0	932.0	1500.0
7	MSW recycled (45.1 % · 0.6 of line 6), including	67.7	167.0	252.3	406.0
	— mixed glass 9.48 %	6.4	15.8	23.9	38.5
	— paper, cardboard 23.26 %	15.7	38.8	58.7	94.4
	— mixed metal, scrap metal 2.13 %	1.4	3.6	5.4	8.6
	— PET 3.06 %	2.1	5.1	7.7	12.4
	— wood 1.35 %	0.9	2.3	3.4	5.5
	— textile 3.94 %	2.7	6.6	9.9	16.0
8	Composting (33.9 % of line 6)	84.8	209.4	316.3	509.0
9	RDF production. including:	74.7	184.3	278.4	448.1
	— composite packaging, other plastic (11.8 % of line 6)	29.5	72.8	110.0	177.0
	— the rest of the processed fractions unsuitable for recycling (45.1 % · 0.4 of line 6)	45.2	111.5	168.4	271.1
10	MSW landfill (line 5— line 7 — line 8 — line 9)	1272.8	939.3	653.1	136.9
	Scenario 3				
11	MSW generated (See Table 3. line 1)	1500.0	1500.0	1500.0	1500.0
12	Processed MSW collected under separate collection system (See Table 3, line 2)	250.0	617.0	932.0	1500.0
13	MSW recycled (45.1 %*0.8 of line 12), including	90.2	222.7	336.3	541.3
	— mixed glass 9.48 %	8.6	21.1	31.9	51.3
	— paper, cardboard 23.26 %	21.0	51.8	78.2	125.9
	— mixed metal. scrap metal 2.13 %	1.9	4.7	7.2	11.5
	— PET 3.06 %	2.8	6.8	10.3	16.6
	— wood 1.35 %	1.2	3.0	4.5	7.3
	— textile 3.94 %	3.6	8.8	13.3	21.3
14	Composting (33.9 % of line 12)	84.8	209.4	316.3	509.0
15	RDF production, including	52.1	128.7	194.4	312.8
	— composite packaging, other plastic (11.8 % of line 12)	29.5	72.8	110.0	177.0
	— the rest of the processed fractions unsuitable for recycling (45.1 % · 0.2 of line 12)	22.6	55.9	84.4	135.8
16	MSW landfill (line 11 — line 13 — line 14 — line 15)	1272.8	939.3	653.1	136.9

Source: Compiled by the authors.

— data on the morphological structure of MSW from the Territorial waste management scheme are used to determine the volumes of recyclable / non–recyclable fractions (see Table 2), calculations are carried out in proportion to the volume of processed waste by year;

— we consider the following types of waste to be recyclable fractions: paper, cardboard, wood, ferrous metal, non-ferrous metal, textiles, glass, leather, rubber, PET (see Table 2), in total, they account for 45.1 % of all processed MSW;

— according to the authors, the following types of waste are sent for composting and technosoil production: food waste, stones, screenings (see Table 2), in total they account for 33.9 % of all processed MSW;

— a correction factor of 0.6 is applied to the recyclable fractions to determine the amount of secondary material resources suitable for reuse, for dual collection (scenario 2);

— a correction factor of 0.8 is applied to the recyclable fractions to determine the amount of secondary material resources suitable for reuse, for full-fledged separate collection (scenario 3);

— correction factors are not applied to the waste sent for composting and techno-soil production;

— according to scenarios 2 and 3, RDF production receives composite packaging, other plastics (see Table 2, in total they account for 11.8 % for all processed MSW), and the processed fractions which turned out to be unsuitable for recycling;

— the volume of potentially recyclable waste for scenarios 2 and 3 varies in proportion to the volume of waste received for processing;

— under all scenarios, the remaining waste (“tailings”) is sent to the MSW landfill.

3.3. Determining the Factors of Emissions and Prevented Greenhouse Gas Emissions

MSW management is one of the significant sources of GHG emissions. According to the National Inventory Report 2022, in Russia, this source of emissions is the fourth after energy, industry and agriculture sectors[1].

MSW management leads to the release of such GHGs as methane, nitrogen oxide, carbon dioxide into the environment. In further calculations, all types of GHGs will be converted into CO_2-eq. using conversion factors from the IPCC Methodology[2].

On the other hand, waste management activities prevent GHG emissions in some cases. Thus, RDF produced under scenarios 2 and 3 is planned to be used at the cement plant, where it will partially replace natural gas, which is currently used at the plant for the cement production.

Recovered materials processing activities, on the one hand, are a source of GHG emissions (fuel and energy resources are needed to produce goods from recovered materials), but on the other hand, they certainly prevent GHG emissions that occur during the production of goods from natural resources. Thus, a methodological issue arises: the determination of specific GHG emissions per 1 tonne of MSW treated in one way or another (factors of direct emissions), and specific prevented emissions (factors of prevented emissions). Since calculations for the conditions of the Sverdlovsk region were not carried out, the authors determined the factors of direct and prevented emissions using the data from the National Inventory Report 2022 for “Waste” and “Energy” sectors, as well as the information contained in studies that can be applied to the conditions of the Sverdlovsk region. This methodological approach is acceptable, it corresponds to Tier 1 and partially Tier 2 of the IPCC Methodology. Factors of direct and prevented emissions are presented in Table 5.

The following assumptions were used:

— The average transport distance for MSW transportation to the landfill, composting site, and waste sorting complexes is 20 km.

— GHG emission from the combustion of $1 m^3$ of natural gas is 1.8 kg of CO_2-eq. In terms of calorific value, 1 kg of RDF replaces 0.55 m^3 of natural gas. Thus, incinerating 1 kg of RDF will prevent 1 kg of CO_2-eq emissions associated with burning natural gas.

— For the conditions of Russia, there are no calculations of prevented GHG emissions associated with the use of the recovered materials for the production of goods. In this regard, the authors suggest relying on data from the study by Turner, Williams and Kemp (2015), which uses the LCA approach to calculate prevented GHG emissions for different types of recovered materials.

According to the IPCC Methodology, direct GHG emissions from processes related directly to the MSW management sector (landfill, transportation, composting, RDF incineration) are considered to be calculation boundaries. For processes that are not directly related to the MSW management sector, prevented GHG emissions (from par-

[1] National report on the inventory of anthropogenic emissions by sources and removals by sinks of GHGs, not controlled by the Montreal Protocol. Retrieved from: http://downloads.igce.ru/kadastr/RUS_NIR-2022.zip (Date of access: 01.07.2022).

[2] 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 5 Waste; 2019. Retrieved from: https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html (Date of access: 22.06.2022).

Table 5

Factors of direct and prevented emissions

MSW treatment operation / type of recovered material	Emission factor (EF)/ prevented emission (PE) (neg. values), unit		Source
Controlled disposal at MSW landfills (*EF*)	1.046	kg CO_2-eq./kg MSW	Data from Russian National Inventory Reports (National Inventory Report …, 2020, 2021, 2022)
Biological treatment of MSW (composting) (*EF*)	0.172	kg CO_2-eq./kg MSW	2019 Refinement to the 2006 IPCC Guidelines …, 2019 (“Waste” sector)
Incinerating RDF in cement kilns (EF_{RDF})	1.1	kg CO_2-eq./kg RDF	Reza et. al (2013)
Transportation (EF_{trans})	$0.06 \cdot 10^{-3}$	kg CO_2–eq./kg MSW/km	2019 Refinement to the 2006 IPCC Guidelines …, 2019 (“Energy” sector)
Replacing natural gas with RDF in cement kilns (PE_{RDF})	–1.0	kg CO_2-eq./kg RDF	The authors’ calculations and data from 2019 Refinement to the 2006 IPCC Guidelines …, 2019 (“Energy” sector)
Glass (PE_G)	–0.314	kg CO_2-eq./kg MSW	Turner, Williams and Kemp (2015), taking into account GHG emissions from MSW recycling and production of materials from SMR
Paper, cardboard (PE_{PC})	–0.120	kg CO_2-eq./kg MSW	
Ferrous, non-ferrous metal (PE_M)	–3.577	kg CO_2-eq./kg MSW	
PET (PE_P)	–2.192	kg CO_2-eq./kg MSW	
Wood (PE_W)	–0.444	kg CO_2-eq./kg MSW	
Textile (PE_T)	–3.376	kg CO_2-eq./kg MSW	

Source: Compiled by the authors.

tial replacement of natural gas in cement kilns with RDF; from replacement of natural resources by the recovered materials) are also calculated.

To determine direct GHG emissions for such operations as landfill and composting, the expression (1) was used:

$$E_{waste} = m \cdot EF, \quad (1)$$

where E_{waste} — direct GHG emissions associated with a specific waste management operation, kg CO_2-eq.; *m* — mass of MSW processed in one way or another, kg; *EF* — GHG emission factor depending on the method of waste management, kg CO_2-eq./kg MSW (see Table 5).

To determine direct GHG emissions from RDF incineration in cement kilns, the expression (2) was used:

$$E_{RDF} = m \cdot EF, \quad (2)$$

where E_{RDF} — direct GHG emissions associated with RDF incineration, kg CO_2-eq.; *m* — RDF mass sent to the cement plant, kg; EF_{RDF} — GHG emission factor from RDF incineration in a cement plant kiln, kg CO_2-eq./kg RDF (see Table 5).

To determine direct GHG emissions from waste transportation, the expression (3) was used:

$$E_{trans} = d \cdot m \cdot EF_{trans}, \quad (3)$$

where E_{trans} — direct GHG emissions associated with waste transportation, kg CO_2-eq.; *m* — mass of transported MSW, kg; *d* — the distance over which the waste is transported, km; EF_{trans} — GHG emission factor associated with waste transportation, kg CO_2-eq./kg MSW/km (see Table 5).

To determine the amount of prevented GHG emissions from RDF incineration in cement kilns, the expression (4) was used:

$$PE_{RDF} = m \cdot PE_{RDF}, \quad (4)$$

where PE_{RDF} — prevented GHG emissions associated with the replacement of natural gas in cement kilns with RDF, kg CO_2-eq.; *m* — RDF mass sent to the cement plant, kg; PE_{RDF} — prevented GHG emission factor from RDF use, kg CO_2-eq./kg RDF (see Table 5).

To determine the amount of prevented GHG emissions from the use of the recovered materials for the production of goods, the expression (5) was used:

$$PE_R = m \cdot PE_{G, PC, M, P, W, T}, \quad (5)$$

where PE_R — prevented GHG emissions associated with the use of recovered materials, kg CO_2-eq.; *m* — mass of recovered materials of the corresponding type, directed to processing, kg; PE_{RDF} — prevented GHG emission factor from the use of recovered materials, kg CO_2-eq./kg MSW (see Table 5).

4. Results

Based on the material balance of MSW movement under different scenarios from 2023 to 2030 (see Table 4) and the factors of direct and prevented emissions (see Table 5), using formulas (1–5), the authors obtained the following results for GHG emissions for the Sverdlovsk region (Table 6).

The results are presented graphically in Figure.

Calculations show that Scenario 1 (basic, business-as-usual) is the least favourable scenario in terms of GHG emissions associated with the MSW management, which is due to the preservation of the "landfill" model of the MSW management with high specific GHG emissions, as well as a small share of MSW sent for processing (9.7 % of all MSW) and recycling (0.6 % of all MSW).

Scenarios 2 and 3 are characterised by a gradual decrease in net GHG emissions. By 2030, they will amount to 143.3 thousand tonnes of CO_2-eq for scenario 2, and 82.6 thousand tonnes of CO_2-eq for scenario 3, which is 9 and 16 times less, respectively, than the initial level of GHG emissions in 2023. The positive dynamics for scenarios 2 and 3 is due to the following factors: building capac-

Table 6

Net GHG emissions under different development scenarios for the MSW management sector of the Sverdlovsk Region

Type of emissions/prevented emissions, thousand tonnes	2023	2024	2025	2026-2030
Scenario 1				
Direct GHG emissions from landfill disposal	1559.6	1559.6	1559.6	1559.6
Direct GHG emissions from MSW transportation, 20 km	1.8	1.8	1.8	1.8
Prevented GHG emissions due to recycling, incl.	–2.9	–2.9	–2.9	–2.9
— mixed glass	–0.3	–0.3	–0.3	–0.3
— paper, cardboard	–0.2	–0.2	–0.2	–0.2
— mixed metal, scrap metal	–0.5	–0.5	–0.5	–0.5
— PET	–0.6	–0.6	–0.6	–0.6
— wood	–0.1	–0.1	–0.1	–0.1
— textile	–1.2	–1.2	–1.2	–1.2
Net GHG emissions	1558.5	1558.5	1558.5	1558.5
Scenario 2				
Direct GHG emissions from landfill disposal	1331.3	982.5	683.1	143.2
Direct GHG emissions from MSW transportation, 20 km	1.8	1.8	1.8	1.8
Direct emissions from transporting RDF to the cement plant, 140 km	0.6	1.5	2.3	3.8
Direct GHG emissions from composting	14.6	36.0	54.4	87.5
Direct GHG emissions from RDF incineration	82.2	202.7	306.2	492.9
Prevented GHG emissions from natural gas replacement	–74.7	–184.3	–278.4	–448.1
Prevented GHG emissions due to recycling, incl.	–23.0	–57.0	–85.7	–137.8
— mixed glass	–2.0	–5.0	–7.5	–12.1
— paper, cardboard	–1.9	–4.7	–7.0	–11.3
— mixed metal, scrap metal	–5.0	–12.9	–19.3	–30.8
— PET	–4.6	–11.2	–16.9	–27.2
— wood	–0.4	–1.0	–1.5	–2.4
— textile	–9.1	–22.3	–33.4	–54.0
Net GHG emissions	1332.8	983.3	683.8	143.3
Scenario 3				
Direct GHG emissions from landfill disposal	1331.3	982.5	683.1	143.2
Direct GHG emissions from MSW transportation, 20 km	1.8	1.8	1.8	1.8
Direct emissions from transporting RDF to the cement plant, 140 km	0.4	1.1	1.6	2.6
Direct GHG emissions from composting	14.6	36.0	54.4	87.5
Direct GHG emissions from RDF incineration	57.3	141.6	213.8	344.1
Prevented GHG emissions from natural gas replacement	–52.1	–128.7	–194.4	–312.8
Prevented GHG emissions due to recycling, incl.	–30.8	–75.6	–114.6	–183.9
— mixed glass	–2.7	–6.6	–10.0	–16.1
— paper, cardboard	–2.5	–6.2	–9.4	–15.1
— mixed metal, scrap metal	–6.8	–16.8	–25.8	–41.1
— PET	–6.1	–14.9	–22.6	–36.4
— wood	–0.5	–1.3	–2.0	–3.2
— textile	–12.2	–29.7	–44.9	–71.9
Net GHG emissions	1322.5	958.7	645.8	82.6

Source: Compiled by the authors.

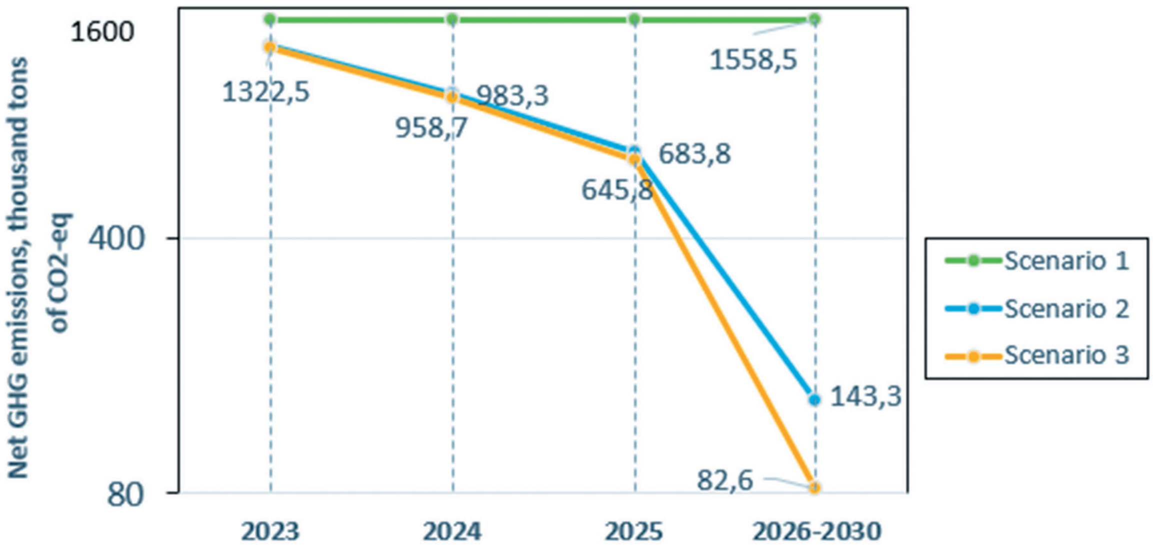

Fig. *Net GHG emissions from MSW management in the Sverdlovsk Region under scenario 1,2,3 for 2023–2030*

ity for waste treatment and recycling; introduction of separate collection at the household level; waste recycling; construction of sites for composting and production of RDF fuel. These factors will reduce landfill disposal significantly: 85 % of all MSW goes to the MSW landfill in 2023, but this figure will be reduced to 9.1 % by 2030.

The difference between scenarios 2 and 3 is largely due to the different share of recycled waste: in scenario 2, dual collection is organised, and 27 % of the sorted waste is recycled; this indicator reaches 36 % in scenario 3 due to the organisation of a full-fledged multi-container separate collection, which increases the amount of prevented GHG emissions associated with recycling. Due to the greater extraction of useful SMRs in Scenario 3, less waste goes to RDF production, which also contributes to lower net GHG emissions compared to Scenario 2.

As for RDF, calculations have shown that using RDF in cement plant kilns instead of natural gas can reduce the net GHG emissions associated with RDF incineration to almost zero. At the same time, it is undeniable that the use of RDF leads to additional environmental risks, as this fuel is a source of emissions of dioxins, cadmium, mercury, and lead, which can enter the environment due to imperfect purification (Genon, Brizio, 2008). Moreover, the very fact of energy recycling is contrary to the principles of the circular economy, does not contribute to the reduction of waste and the transition to 100 % recyclable packaging, which is confirmed by an analysis of the situation in the EU countries, where the practice of waste incineration is widespread (Starodubets et. al, 2022). For these reasons, the authors do not support energy recycling and hope that the launch of the Extended Producer Responsibility (EPR) institution in Russia will encourage manufacturers to use recyclable packaging and reduce its volume, and the funds received as a result of the EPR will go to the development of the waste recycling sector.

5. Discussion

The analysed scenarios for the development of the MSW management in the Sverdlovsk region until 2030 in terms of their carbon footprint showed that the most sustainable scenario is scenario 3 — an innovative scenario with full-fledged separate collection and large-scale waste recycling.

Moreover, this scenario aims for carbon neutrality — landfill decreases as the share of potentially recyclable MSW increases, suggesting that carbon neutrality of the MSW management sector in the Sverdlovsk Region is achievable in the future. This, in turn, can justify the financial support of the innovative scenario for the development of this sector.

It should be noted that a study with a similar design was carried out by Wünsch and Tsybina (2022) on scenarios for the development of the Russian MSW management sector. The authors of that study also took prevented emissions into account and, according to the calculations, net GHG emissions also approach zero in the most sustainable innovation scenario.

We believe that MSW management activities can be an effective way to reduce GHG emissions, and carbon neutrality of the sector can become one of the goals of the National Project Ecology, along with the goal of the increased share of processed and recycled waste.

We assume that the use of correction factors of 0.6 and 0.8 in scenarios 2 and 3, which characterise the extraction of potentially recyclable materials from pre-sorted waste, is debatable. These coefficients depend on many factors: on the composition of MSW, the season, the thoroughness of MSW sorting by households, the technical and economic feasibility of extracting and processing individual fractions, the technical characteristics of waste processing complexes, etc. Moreover, these coefficients must be calculated for the individual waste processing plant. It should be noted, since in the Russian Federation we are talking only about individual experiments on organising dual and separate collection with subsequent processing on high-tech waste processing complexes (see e.g. Kaplina et al., 2018, for Dubna), there are currently no empirical data based on which country (regional) specific values for the recovery rates could be given. In this regard, the authors suggest relying on the other countries' experience: the article by Cimpan et al. (2015) presents data from four studies that considered the share of potentially recyclable materials extraction from pre-sorted waste (collection of mixed recyclables "all-in-one bin") for 19 waste processing complexes in the USA and the UK. The given values range from 42.6 % for cardboard to 100 % for aluminium cans, aluminium foil.

In any case, the methodical toolkit proposed in this paper makes it possible to change the correction factors characterising the recyclable materials extraction and to perform a more accurate assessment of the carbon footprint of the MSW management sector using the parameters of the operating waste processing complexes, when empirical data will be available. The study of the MSW composition after the processing and the recovery rate for the regions with organised dual and separate MSW collection may be the direction of further research.

Another limitation of the methodological approach of this article is the use of direct and prevented emission factors, which are calculated for the conditions of Russia and other comparable countries without considering the existing regional specifics. To improve the accuracy of calculations, it is necessary to conduct an inventory of GHG emissions for the Sverdlovsk region, including the "Waste" sector, by calculating factors of direct and prevented emissions and creating a monitoring system for GHG emissions from sources associated with the treatment of MSW, which also may be the direction of further research.

References

Abu-Qdais, H. A. & Kurbatova, A. I. (2022). The Role of Eco-Industrial Parks in Promoting Circular Economy in Russia: A Life Cycle Approach. *Sustainability, 14,* 3893. DOI: https://doi.org/10.3390/ su14073893.

Allan, R. P., Hawkins, E., Bellouin, N. & Collins, B. (2021). *IPCC, 2021: summary for Policymakers*. Cambridge: Cambridge University Press, 32. DOI: 1017/9781009157896.001.

Babel, S. & Vilaysouk, X. (2016). Greenhouse gas emissions from municipal solid waste management in Vientiane, Lao PDR. *Waste Management & Research, 34(1),* 30-37. DOI: https://doi.org/10.1177/0734242X15615425.

Bozhko, L., Starodubets, N., Turgel, I. & Naizabekov, A. (2021). GHG Emissions Assessment as Part of MSW Green Cluster Design: Case of Large Cities in Russia and Kazakhstan. *Environmental and Climate Technologies, 25(1),* 1165-1178. DOI: 10.2478/rtuect-2021-0088.

Cimpan, C., Maul, A., Jansen, M., Pretz, T. & Wenzel, H. (2015). Central sorting and recovery of MSW recyclable materials: A review of technological state-of-the-art, cases, practice and implications for materials recycling. *Journal of Environmental Management, 156,* 181-199. DOI: 10.1016/j.jenvman.2015.03.025.

Coban, A., Ertis, I. F. & Cavdaroglu, N. A. (2018). Municipal solid waste management via multi-criteria decision making methods: A case study in Istanbul, Turkey. *Journal of cleaner production, 180,* 159-167. DOI: 10.1016/j.jclepro.2018.01.130.

Das, S., Lee, S. H., Kumar, P., Kim, K. H., Lee, S. S. & Bhattacharya, S. S. (2019). Solid waste management: Scope and the challenge of sustainability. *Journal of cleaner production, 228,* 658-678. DOI: https://doi.org/10.1016/j.jclepro.2019.04.323.

García-Pérez, J., Fernández-Navarro, P., Castelló, A., López-Cima, M. F., Ramis, R., Boldo, E. & Lopez-Abente, G. (2013). Cancer mortality in towns in the vicinity of incinerators and installations for the recovery or disposal of hazardous waste. *Environment international, 51,* 31-44. DOI: https://doi.org/10.1016/j.envint.2012.10.003.

Generowicz, A., Kowalski, Z. & Kulczycka, J. (2011). Planning of waste management systems in urban area using multi-criteria analysis. *Journal of Environmental Protection, 2(06),* 736. DOI: 10.4236/jep.2011.26085.

Genon, G. & Brizio, E. (2008). Perspectives and limits for cement kilns as a destination for RDF. *Waste management, 28(11),* 2375-2385. DOI: https://doi.org/10.1016/j.wasman.2007.10.022.

Goulart Coelho, L. M., Lange, L. C. & Coelho, H. M. (2017). Multi-criteria decision making to support waste management: A critical review of current practices and methods. *Waste Management & Research, 35(1),* 3-28. DOI: https://doi.org/10.1177/0734242X16664024.

Herva, M. & Roca, E. (2013). Ranking municipal solid waste treatment alternatives based on ecological footprint and multi-criteria analysis. *Ecological Indicators, 25,* 77-84. DOI: 10.1016/j.ecolind.2012.09.005.

Jovanovic, S., Savic, S., Jovicic, N., Boskovic, G. & Djordjevic, Z. (2016). Using multi-criteria decision making for selection of the optimal strategy for municipal solid waste management. *Waste Management & Research, 34(9),* 884-895. DOI: https://doi.org/10.1177/0734242X16654753.

Kaazke, J., Meneses, M., Wilke, B. M. & Rotter, V. S. (2013). Environmental evaluation of waste treatment scenarios for the towns Khanty-Mansiysk and Surgut, Russia. *Waste management & research, 31(3),* 315-326. DOI: https://doi.org/10.1177/0734242X12473792.

Kaplina, S. P., Semenova, M. V., Dzyuba, K. S., Andronov, S. V., Kamanina, I. Z. & Starostina, I. A. (2018). Municipal solid waste as secondary raw material (exemplified by Dubna, Moscow region). *Uspekhi sovremennogo estestvoznaniya [Advances in current natural sciences], 2,* 93-98. (In Russ.)

Kaza, S., Yao, L., Bhada-Tata, P. & Van Woerden, F. (2018). *What a waste 2.0: a global snapshot of solid waste management to 2050.* Washington, DC: World Bank, 274. DOI: 10.1596/978-1-4648-1329-0.

Kennedy, C., Steinberger, J., Gasson, B., Hansen, Y., Hillman, T., Havránek, M., ... Mendez, G. V. (2010). Methodology for inventorying greenhouse gas emissions from global cities. *Energy policy, 38(9),* 4828-4837. DOI: https://doi.org/10.1016/j.enpol.2009.08.050.

Kristanto, G. A. & Koven, W. (2019). Estimating greenhouse gas emissions from municipal solid waste management in Depok, Indonesia. *City and environment interactions, 4,* 100027. DOI: https://doi.org/10.1016/j.cacint.2020.100027.

Liamsanguan, C. & Gheewala, S. H. (2008). The holistic impact of integrated solid waste management on greenhouse gas emissions in Phuket. *Journal of Cleaner Production, 16(17),* 1865-1871. DOI: https://doi.org/10.1016/j.jclepro.2007.12.008.

Lombardi, G. V., Gastaldi, M., Rapposelli, A. & Romano, G. (2021). Assessing efficiency of urban waste services and the role of tariff in a circular economy perspective: An empirical application for Italian municipalities. *Journal of Cleaner Production, 323,* 129097. DOI: https://doi.org/10.1016/j.jclepro.2021.129097.

Plastinina, I., Teslyuk, L., Dukmasova, N. & Pikalova, E. (2019). Implementation of circular economy principles in regional solid municipal waste management: The case of Sverdlovskaya Oblast (Russian Federation). *Resources, 8(2),* 90. DOI: https://doi.org/10.3390/resources8020090.

Reza, B., Soltani, A., Ruparathna, R., Sadiq, R. & Hewage, K. (2013). Environmental and economic aspects of production and utilization of RDF as alternative fuel in cement plants: A case study of Metro Vancouver Waste Management. *Resources, Conservation and Recycling, 81,* 105-114. DOI: 10.1016/j.resconrec.2013.10.009.

Rodionov, M. & Nakata, T. (2011). Design of an optimal waste utilization system: a case study in St. Petersburg, Russia. *Sustainability, 3(9),* 1486-1509. DOI: https://doi.org/10.3390/su3091486.

Stahel, W. R. (2016). The circular economy. *Nature, 531(7595),* 435-438. DOI: https://doi.org/10.1038/531435a.

Starodubets, N. V., Belik, I. S. & Alikberova, T. T. (2022). Sustainability Assessment of the Municipal Solid Waste Management in Russia Using the Decoupling Index. *International Journal of Sustainable Development and Planning, 17(1),* 157-163. DOI: https://doi.org/10.18280/ijsdp.170115.

Tomić, T. & Schneider, D. R. (2020). Circular economy in waste management — Socio-economic effect of changes in waste management system structure. *Journal of environmental management, 267,* 110564. DOI: https://doi.org/10.1016/j.jenvman.2020.110564.

Tulokhonova, A. & Ulanova, O. (2013). Assessment of municipal solid waste management scenarios in Irkutsk (Russia) using a life cycle assessment-integrated waste management model. *Waste Management & Research, 31(5),* 475–484. DOI: 10.1177/0734242X13476745.

Turner, D. A., Williams, I. D. & Kemp, S. (2015). Greenhouse gas emission factors for recycling of source-segregated waste materials. *Resources, Conservation and Recycling, 105,* 186-197. DOI: https://doi.org/10.1016/j.resconrec.2015.10.026.

Vinitskaia, N., Zaikova, A., Deviatkin, I., Bachina, O. & Horttanainen, M. (2021). Life cycle assessment of the existing and proposed municipal solid waste management system in Moscow, Russia. *Journal of Cleaner Production, 328,* 129407. DOI: https://doi.org/10.1016/j.jclepro.2021.129407.

Wiesmeth, H. & Starodubets, N. V. (2020). The management of municipal solid waste in compliance with circular economy criteria: the case of Russia. *Ekonomika regiona [Economy of region], 16(3),* 725-738. DOI: https://doi.org/10.17059/ekon.reg.2020-3-4.

Wünsch, C. & Tsybina, A. (2022). Municipal solid waste management in Russia: potentials of climate change mitigation. *International Journal of Environmental Science and Technology, 19(1),* 27-42. DOI: https://doi.org/10.1007/s13762-021-03542-5.

Yaman, C. (2020). Investigation of greenhouse gas emissions and energy recovery potential from municipal solid waste management practices. *Environmental Development, 33,* 100484. DOI: https://doi.org/10.1016/j.envdev.2019.100484.

Yu, Y. & Zhang, W. (2016). Greenhouse gas emissions from solid waste in Beijing: The rising trend and the mitigation effects by management improvements. *Waste Management & Research, 34(4),* 368-377. DOI: https://doi.org/10.1177/0734242X16628982.

Zhang, J., Qin, Q., Li, G. & Tseng, C. H. (2021). Sustainable municipal waste management strategies through life cycle assessment method: A review. *Journal of Environmental Management, 287,* 112238. DOI: https://doi.org/10.1016/j.jenvman.2021.112238.

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