Opportunities for greenhouse gases emissions reduction in the biodegradable industrial waste management processes

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Abstract. The article assesses opportunities for mitigating greenhouse gas (GHG) emissions in the waste treatment sector concerning biodegradable industrial waste. Authors describe GHG emissions sources and ways of their reduction, paying the specific attention to the stages of the life cycle, where, according to the official data, the most significant GHG flows are formed. Methods of systematization and statistical generalization are applied for analysis. The specified work is based on the data from various sources, including National Reference Documents on the Best Available Techniques, statistical and scientific publications. Russian Reference Documents are known in the Eurasian Economic Union and often discussed as a possible background for the future research in the field on Best Available Techniques and resource efficiency enhancement. The main GHG emission sources during the waste generation, neutralization, utilization, recycling and storage are roughly described. Authors suggest relevant approaches to GHG emissions reduction available from the economic and environmental points of view.

1 Introduction

All Parties of the United Nations Framework Convention on Climate Change and Parties of the Kyoto Protocol annually prepare and submit their National Inventories to the United Nations authorities. These National Inventories contain official (state) data on the emissions and absorption of greenhouse gases. Special attention is paid both to such evident sources as energy generation, industry and agriculture, as well as to the waste management sector, which vary a lot of origin and country wise [1]. National Inventories submitted by Parties in 2023, contain estimates of anthropogenic GHG emissions and absorptions for the period 1990-2021. Emissions in the Waste sector include methane (CH_4) from solid waste disposal in landfills and municipal and industrial wastewater treatment (including emissions from sludge desiccation), nitrogen hemioxide (N_2O) from biological waste treatment and when

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discharging municipal wastewater into water bodies and carbon dioxide (CO_2) from incineration.

In Russia, total calculated GHG emissions from the Waste sector in 2021 amount to 96,706,000 t of carbon dioxide equivalents (CO_2-eq). The significant steady growth of such emissions since 1999 is associated with an increase in the municipal solid waste landfilling as well as (partially) to expanded output in certain industries, which leads to a surge in wastewater treatment. From 1990 to 2021, emissions in the Waste sector witnessed an 85.2% upwards.

Municipal solid waste in 2021 have contributed 72.5% share of the GHG emissions from the Waste sector, amounting to 70,072,000 t CO_2-eq, 65.1% of it belongs to CH_4 alone. The rest share came from the industrial waste. Total Waste sector in 2021 shared 3.3% of national GHG emissions excluding Land Use, Land-Use Change and Forestry or 4.6% including this aspect, meanwhile the proportion for CH_4 alone is more noticeable (23% and 21%, respectively).

GHG emissions rate had been grown between 1990 and 2021 at 161.9% despite population decline, the result is attributed to an augmentation in waste generation per capita together with an influence of modern techniques of waste management [2], while the impact of the biological treatment of municipal solid waste had never exceeded the maximum of 160,000 t CO_2-eq (2021) and is considered negligible so far, variations in their volume are definitely linked to the operational start of several composting and waste recycling facilities.

This research work is aimed at the relevant assessment of main processes of waste generation from the point of view of their contribution to the GHG emissions in this sector and reviewing key strategies for their reduction.

2 Materials and methods

A compilation of regional inventories of GHG emissions and absorptions is one of the methods of their assessment. Several approaches can be used to estimate anthropogenic greenhouse impact on climate changes in certain objectives:

- GHG emissions originating directly from waste by itself and waste management techniques.
- Combination of both direct and indirect GHG emissions from the following sources of waste management technological process (based on ISO 14064–1:2018 "Greenhouse gases. Part 1. Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals"): waste management, electricity and heat generation (both on- and off-grid), waste transportation, daily activities, recycled waste and wastewater treatment.
- Total balance of GHG emissions during the entire life cycle of the customer product, which is generating the waste (based on ISO 14067:2018 "Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification"), which includes: carbon footprint of components, that had formed the customer product, carbon footprint of specific customer product manufacturing, carbon footprint of customer product distribution, carbon footprint of recycling and end-of-life use of customer materials and products, that were derived from waste (including fuel).

GHG emissions originating directly from waste management can be lessened by combination of both direct (aimed at reducing existing emissions) and indirect (focused on minimizing the possibility of their generation) approaches at various stages of the life cycle.

There are widely used GHG mitigation strategies, which include converting of evolved CH_4 into biogenic CO_2 achieved through oxidation (combustion), reducing the share of carbon-containing substances in the generated biodegradable or fossil-based waste, and that of fluorocarbons. It can be performed through recycling and resource conservation, using the lower-emission waste management techniques, such as composting organics instead of disposal at landfills, integrating waste and biogas into the circular economy as recycled materials and products, e.g., as energy sources.

The last of these methods has an additional potential for GHG emissions reduction due to several factors: biogas and natural organic fuel serve as carbon-neutral biofuels, offering a sustainable alternative to fossil fuel. GHG emissions from recycling of materials may be significantly lower than those from primary production of the corresponding products. Reducing deforestation preserves ability of forests to act as carbon sinks (capturing and fixing carbon from the atmosphere), the application of organic fertilizers promotes long-term carbon storage in a soil.

In addition to approved emission reduction methods, directly related to waste management, various approaches had been employed to minimize GHG emissions associated with supporting activities, as transportation, energy production, management. Among these methods one can consider: replacement of traditional motor fuels with lower-emission alternatives like biofuel or hydrogen, minimization of the shipping distances, energy efficiency promotions for the enterprise and separate waste management processes, focusing on incorporating of renewable sources, environmental protection business activities and the engagement of the employees, implementation of the Best Available Techniques.

During the process of selection and evaluation of the effectiveness of GHG emission reduction methods, it is essential to consider the following: by focusing solely on climate impacts, there is a risk of increasing environmental damage in another area. Transformation of waste management systems should be carried out in accordance with the strategic goals and approaches adopted by the native country in this field; the economic efficiency of the chosen methods for reducing GHG emissions is of the greatest importance in the final decision-making.

For each type of waste, the management options were reviewed, the key stages of GHG generation were identified, and the ways of GHG emissions mitigation were formulated. The compiled list of biodegradable types of waste includes the following categories: crop and forestry waste, animal breeding (livestock) waste, timber harvesting waste, wood and other products (e.g., paper), that had lost their consumer properties (excluding those contaminated with specific substances), digested sewage sludge from domestic and combined biological treatment systems, waste from food production and food products, industrial and non-industrial waste, municipal solid waste.

3 Results

The following waste transformation processes were identified as the key GHG emissions sources: anaerobic decomposition of plant- and animal-based organic substances, combustion of fossil organic matter and products of their processing, denitrification of substances. At the initial stage of analysis, the certain composition of groups of waste capable to emit GHGs was identified, both currently existing and prospective (Table 1).

Table 1. Waste groups and associated types of waste with GHG emissions.

Waste groups	Types of waste
Group 1. Waste containing biodegradable carbon	1.1. Food production waste 1.2. Food products that had come to waste somehow 1.3. Kitchen and catering waste
	1.4. Crop waste 1.5. Forestry waste 1.6. Timber harvesting waste
	1.7. Waste from biological water treatment facilities 1.8. Waste from animal breeding
	1.9. Municipal solid waste
Group 2. Waste containing fossil carbon	2.1. Waste oil-based products, mineral waste contaminated with oil-based products, etc.
	2.2. Waste tires and tubes, shoes, rubber products
	2.3. Polymer products that have lost their consumer properties
	2.4. Organic solvents
	2.5. Biological waste

Though the analysis of open data [3], we aggregated the sources of biodegradable types of waste serving as potential GHG sources. In our opinion, municipal solid waste should be considered as a special part of waste management system, that has been entrusted in 2019 to the Russian Environmental Operator. Figure 1 illustrates the primary strategies for biodegradable waste management.

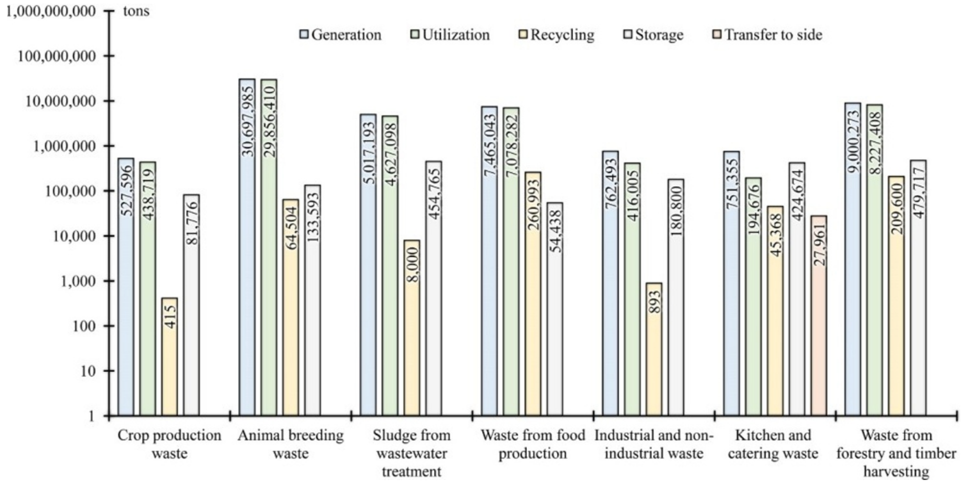

Fig. 1. Sources of and biodegradable waste management, 2022 (Source: composed by authors based on [3]).

In this context, the following groups are prioritized due to their place on the scale of waste generation: wood products no longer fit for consumer use (excluding those contaminated with specific substances), animal breeding (livestock) waste, waste from food production and food products, digested sewage sludge from domestic and combined biological treatment systems.

Methods of recycling biodegradable waste could be separated into two groups (Figure 2).

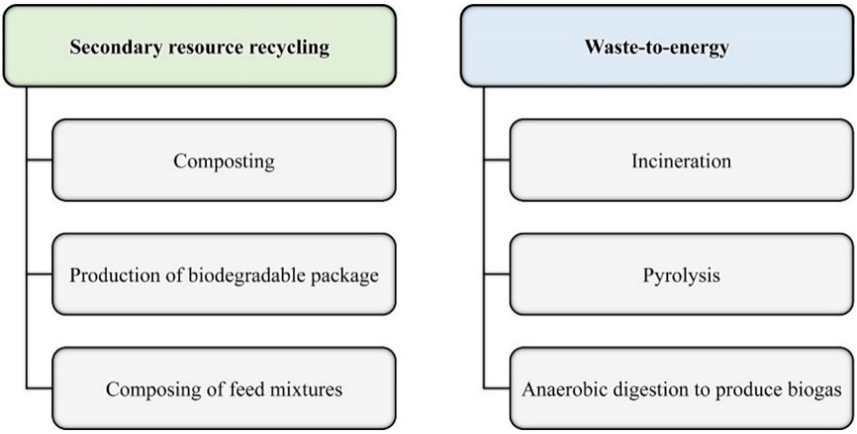

Fig. 2. Biodegradable waste recycling methods [4] (Source: composed by authors based on [4]).

Figure 3 illustrates the primary approaches for biodegradable waste management in the largest waste groups by mass; we note a small share of the waste disposal, ranging from 0.44% for animal breeding waste to 8% for digested sewage sludge from domestic and combined biological treatment systems.

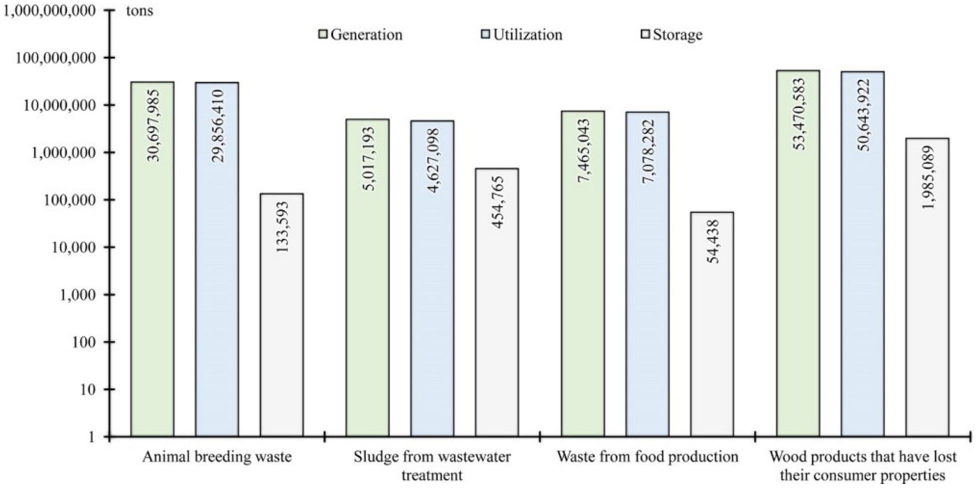

Fig. 3. Waste management of biodegradable waste by mass, 2022 (Source: composed by authors based on [3]).

Below is the review of the main ways of biological waste management for some substances.

3.1 Sewage Sludge

According to the statistics on sludge treatment at biological wastewater treatment facilities serving domestic and combined sewage systems, only 8% of the sludge mass produced by those installations in 2022 was sent for landfills, while 92% were neutralized and utilized.

These figures cannot be considered as accurate. To ensure reliable data, it is necessary to obtain waste inventory.

3.1.1 Utilization

Waste-contaminated activated sludge, when not mixed with other sewage sludge, can be utilized depending on its concentration of toxic impurities. It may be added to fertilizers, protein and vitamin concentrates, building materials [5].

3.1.2 Recycling

National BREF for municipal wastewater treatment ITS 10-2019 (which does not have international analogues) describes methods for the liquid sludge recycling. For example, it can be stabilized under anaerobic conditions. A mixture of sediments from primary settling tanks and waste activated sludge is fed into stirring reactors, or digesters, where an oxygen-free process of decomposition for the organic part of the sediment occurs with the formation of CH_4 and CO_2. The biogas released during the fermentation process potentially is a valuable fuel source [6]. Its effective utilization (along with other engineering solutions) makes it possible not only to maintain the required temperature in the digesters, but to produce an energy and partially cover the costs for wastewater treatment. This method is one of the most environmentally friendly for municipal wastewater management. However, the formation of CH4 can lead to the risk of an occasional explosion.

Another method of liquid sludge recycling is the energy-intensive process of aerobic stabilization; however, this method does not provide the required degree of disinfection to use this sludge as a fertilizer [7].

The composting method [8] can also be used for the purposes of utilization of desiccated sludge. Aerobic biothermal process of the decomposition of organic matter provides disinfection, reduction of humidity, and improvement of the physical and mechanical properties of the composted mass. Mechanically dewatered sludge, as a rule, do not meet specific requirements, it have to be mixed with filler to reduce its humidity, to enrich it with carbon, and to increase its porosity. Sawdust, peat, plant waste, etc., can be used as fillers. In Russian conditions, on-site composting requires significant time because of poor climatic conditions – both temperature and precipitation.

3.1.3 Waste-to-energy

There is another hopeful method of incineration of dewatered or dried sludge [9]. The precursory desiccation requires significant consumption of energy and reagents (alkaline). When the facility provides its own power generation, the output of electricity or heat covers treatment demands and allows to supply excess energy for customers. The main disadvantage of this method is the expenses for equipment. There are only three sludge incineration plants at the wastewater treatment facilities in St. Petersburg, so far more than 5,000,000 m^3 of dewatered sludge were utilized during their work [10].

3.2 Wood waste from forestry, timber harvesting the manufacturing of wood products

It is important supporting climate change mitigation policy for forestry to increase carbon sequestration by forest ecosystems, to raise the consumption of biofuels, wood construction materials and other bio-products, that could replace fossil fuels and carbon-intensive products and store the carbon contained in them for a long time. The main areas of wood waste use are technical and energy purposes.

3.2.1 Recycling

Bulky waste from timber harvesting and wood processing enterprises, such as flitches, is generally used in mines, as fuel, and for the design of panels, parquet, box containers, and barrels. Other parts of wood are used in pulp and paper industry; furniture manufacturing, construction (roofing and thermal insulation); making of particleboard, fibre-board, plywood, etc.; purifying wastewater from oil by filtration through wood chips; manufacturing of toys, pyrotechnics, as underlying material in animal breeding, as fertilizer in agriculture; together with production of basic chemicals (oxalic acid, ethyl alcohol, yeast, lignosulfonates) from sawmill waste [11]. Cork is a valuable raw material for the production of tanning extracts and can be used as a filler for the insulating boards, chipboards, and wood plastic composites.

3.2.2 Waste-to-energy

Wood waste serves as a source of generating thermal and electrical energy through combustion, or pyrolysis, or gasification. National BREF for thermal waste treatment ITS 9-2020 (European BREF for Waste Incineration is its analogue) presents a method for its utilization (in the absence of other available methods) by burning it in a layered furnace or in a fluidized bed with usable energy output. According to Russian Reference Document on Best Available Techniques for Pulp and Paper Manufacturing ITS 1-2022 (similar to the European sectoral Reference Document), wood processing waste is also proposed to be used in bark boilers or as a component of fuel mixtures.

The expansion of use of wood materials, for example in power engineering, construction, textile manufacturing could bring significant climate change mitigation benefits when replacing concrete, steel, and polymers due to the reduction of carbon footprint of used materials. The longer wood products are used, the longer their carbon storage function lasts. Net reduction in carbon emissions can be achieved on the side by replacing fossil materials with renewable ones [12].

3.3 Animal breeding waste

An industrial programme entitled "The Use of Secondary Resources and Secondary Raw Materials from Agricultural Waste for 2022–2030" has been developed already. This programme focuses on agricultural waste, including livestock and biological, with the purpose to share it into the circular economy.

3.3.1 Recycling

Promising directions for the utilization of agricultural livestock waste are involving the development of biotechnologies such as aerobic and anaerobic biothermal utilization (fast composting, vermicomposting, anaerobic digestion, thermophilic aerobic stabilization, etc.). These methods lead to the manufacturing of organic fertilizers (vermicompost, compost), biogas, and solid fuels [13].

Various manure's nature led to the development of technologies for its preparation. To set the bedding-free manure the technologies of composting semi-liquid substance, homogenizing semi-liquid and liquid fraction, and dividing liquid manure into fractions with full biological processing of waste liquids have been used [14]. National Russian Reference Document on Best Available Techniques for Intensive Rearing of Pigs ITS 41-2023 (similar to then European sectoral Reference Document) reveals methods for specific waste management, proposing a combination system of mechanical separation and biological treatment, whereby ammonia is removed and released as nitrogen.

3.3.2 Waste-to-energy

Manure serves as an alternative energy source through anaerobic digestion, producing biogas containing 60-80% CH_4 and CO_2. Processing of agricultural waste into biological fertilizers and energy is considered to be the top priority method for waste disposal [15].

Anaerobic digestion methods are more suitable from the environmental, technologic, and economic perspective while generating liquid biofertilizers and biogas for electric and thermal energy production. Manure is homogenized and subjected to anaerobic digestion [16]. Biogas is burned in an engine, the digested sludge is separated into solid and liquid fractions, which can be used as fertilizers. For the poultry manner, following methods of treatment are recommended: manure aging, passive and active composting, accelerated- and vermicomposting, bio fermentation in chamber and drum installations, thermal drying followed by granulation, burning [17].

3.4 Waste from the food products industry

Recycled materials from food processing are used in various areas: for the production of food products or as additional components, in animal breeding in the form of feed for livestock and poultry, in agriculture as fertilizers and biofuels, in other industries (chemical, pharmaceutical, microbiological, construction, etc.) as raw materials or components for the manufacturing of various products.

The predominant use of food industry waste is for feeding [18]. Technologies for recycling waste from food, beverages, and tobacco production can be supplemented with methods from the National Russian Reference Document on Best Available Techniques for food industries ITS 44-2023 (similar to the European sectoral Reference Document). For instance, apple pomace is used as a component of the nutrient medium for growing moulds in the production of pectolytic enzymes. An alternative approach could be based on the use extracted apple pomace as a substrate for growing the oyster mushrooms. Biofuel boilers use sunflower husks and fuel briquettes made from sunflower, soybean, or rapeseed stem biomass to increase energy and economic efficiency in the oil and fat industry.

4 Discussion

It can be considered obvious, that the greatest contributors for GHG emissions during the life cycle of sewage waste are the stages of its disposal and storage. So, the main task is to minimize the amount of waste treatment sediments stored in sludge drying beds.

The greatest contributor for GHG emissions during the life cycle of wood waste seems to be the waste-to-energy stage (thermal utilization). The task is to reduce them by optimizing combustion process and subsequent sorption of CO_2 from flue gases.

The greatest contributor for GHG emissions during the life cycle of manure apparently is the stage of its processing and utilization. The task is to reduce the amount of released GHG (production of biogas for energy use; composting).

The greatest contributor for GHG emissions during the life cycle of food waste presumably is the waste-to-energy stage. The task is to reduce GHG emissions during consumption of biofuels (recycled energy sources) by optimizing combustion processes and subsequent sorption of CO_2 from flue gases.

5 Conclusion

The fundamental principle of the waste management policy is comprehensive material processing using the Best Available Techniques to reduce waste generation and finding its serviceable place in the circular economy.

The strategic goal of the circular economy is to maximize waste recycling, it requires the considerable growth of the waste management industry.

The priority directions in national waste management policy include: waste prevention, reducing waste generation and hazard effects mitigation at the places of its origin and utilization.

Waste management has a couple of useful products at the output, e.g., recycled materials or energy resources.

Waste reduction often involves thermal utilization (incineration, pyrolysis, or gasification), that leads to the origin of a lot of GHG gases. The focus of technology should be concentrated on two directions: optimizing thermal processes and improve carbon capture in flue gases.

It should be noted that GHG emissions capturing sometimes can have economically justified subsequent use, for example, dry ice manufacturing is feasible at large industrial plants but is unreliable at small incinerators or pyrolysis facilities.

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