Waste Footprint And Accounting Methods

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Abstract. A comprehensive accounting of waste generation is the basis for the development of an effective waste management policy and makes it possible to identify the sources of waste generation. Identifying the major waste-producing sectors allows the waste policy to be targeted and measures to be taken with high efficiency. The aim of this study is to expand the environmental footprint of waste under an interdisciplinary perspective and propose a methodological approach to account for waste production pathways. The study used an interdisciplinary approach based on the integration of different methods for estimating waste accumulation and its qualitative characteristics using bibliometrics and different databases. Waste production can be viewed from the perspectives of both producers and consumers (perspectives based on production and consumption). Differences in the interpretation of the term "waste footprint" on the principles of circular economy were identified. At the same time, it is close to the water footprint principles, where the amount of fresh water used is included in the water footprint indicator, but only the amount that is consumed and cannot be reused. Similarly, the principle can be established that the waste footprint indicator should include only the amount of waste that is released into the environment and is no longer used as input in another production chain. Thus, the total waste production in a country is not in itself a valid measure of the burden on the environment. A formalization of the waste footprint approach is proposed, taking into account the possibility of waste recycling, using food waste as an example.

1 Introduction

The problem of waste generation and recycling remains a major issue worldwide. Nakamura and Kondo determined waste production for individual industrial sectors in Japan using Input-Output tables and marked the quantified waste production as a waste footprint [1]. At the same time, it is close to the principles of the water footprint, where the amount of freshwater used is included in the water footprint indicator, but only the amount that is consumed and cannot be reused. Similarly, the principle can be established that only the volume of waste that is emitted into the environment and is no longer used as an input in another product chain should be included in the waste footprint. Thus, the overall production of waste within a country is not in itself the right measure of the burden on the environment [2].

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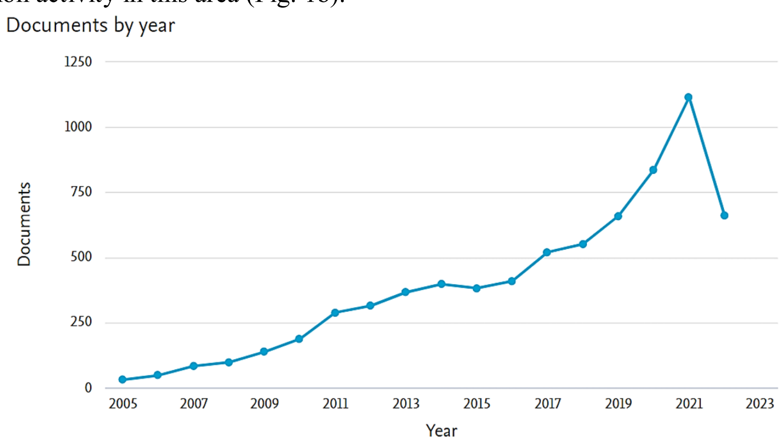
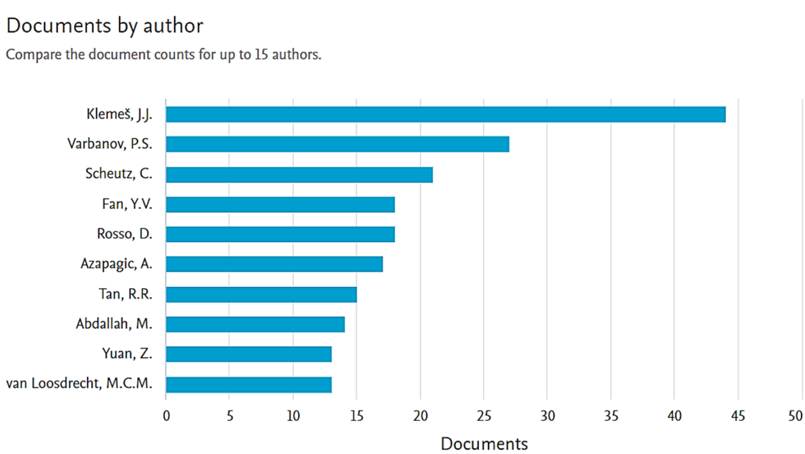
A total of 7,237 documents (in the Scopus database) were found in the analysis of publications on the waste footprint. As can be seen in Figure 1a, publication activity is increasing, with a peak of interest in the development of the waste footprint concept in 2019-2022. One of the most researched areas of application of the footprint concept to a particular type of waste is the application to plastic waste. For example, one concept related to footprint estimation using plastic waste as an example was developed by [3], [4]. The concept of Plastic Waste Footprint (PWF) is defined as the total mass of plastic waste used in a process, product, or minus the amount of plastic that is not used, reused, recycled, and recycled. Plastic recycling is an alternative, but has some drawbacks. Some recycling technologies are very sensitive to purity. Plastics have characteristics that are important for COVID-19 management applications. However, prior to this crisis, public perception and government regulations sought to minimize the use of plastics. use. It is important to note that many of their environmental consequences (e.g., microplastic contamination) are not inherent properties of the materials but are consequences of consumer behavioral patterns (e.g., improper disposal). It should be noted that the Klemeš and Fan researchers have significant publication activity in this area (Fig. 1b).



(a)



(b)

Fig. 1. Publication activity in the world by subject: (a) number of publications by year (until July 2022), (b) authors with the largest number of publications

The scope of application to the assessment of the waste accumulation process in the world covers various research directions, presented in a number of works [5]–[10]. It should be noted that the composition of municipal solid waste differs significantly depending on the level of development of the countries and, accordingly, the level of well-being of the population living in this territory.

In addition to the increase in the volume of solid waste for developing countries with low-income populations, a very typical problem is the controllability by the local administration of the very process of removal and disposal of garbage generated in cities.

Over the past two decades, EC countries have increasingly shifted their focus on municipal waste from disposal methods to prevention and recycling. This policy of municipal waste management has the importance of extracting more value from resources while reducing the burden on the environment and creating jobs. Although municipal waste is only about 10% of the total waste generated in the EU, this value is visible to the public[11]. Preventing this waste contains significant potential to reduce its environmental impact, not only at the waste generation stages, but also throughout the entire life cycle of products from their manufacture to the disposal of residues. Figure 2 shows the dominant countries in the group of studies on the development of the waste footprint concept in the world according to the Scopus database.

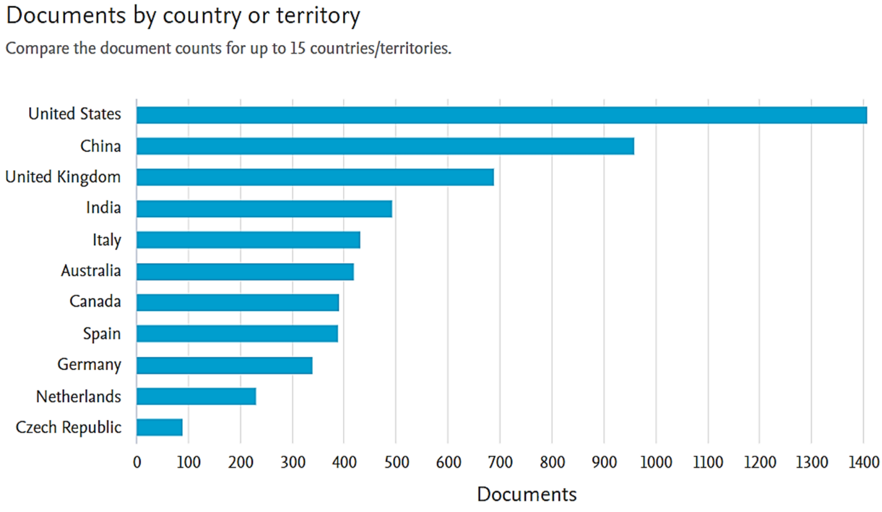


Fig. 2. Dominant countries in terms of publication activity related to the topic of the waste footprint

The aim of the work is to extend the framework of the environmental footprint of waste in an interdisciplinary way and to offer a methodological approach for accounting for waste pathways.

2 Methods For Waste Quality Assessment

The methodology [12] describes what is needed to develop a standard common EU methodology for quantifying food waste - this is part of the EU circular economy action plan. Food waste has been defined as: "food and inedible food parts removed from the food supply chain" for recovery or disposal (including composting, ploughed/unploughed crops, anaerobic digestion, bioenergy production, cogeneration, incineration, dumping in sewers, landfills or discharge to sea). The amount of food waste is calculated at different stages of the food chain, i.e., primary production, manufacturing, retailing and distribution, and

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consumption (including food services and households), and is reported in wet weight. The model uses a territorial approach in which food waste included in net imports of raw and industrial products is not counted. Several official statistical resources can be identified to estimate food waste generation in the world [13][14][15] (fig. 3).

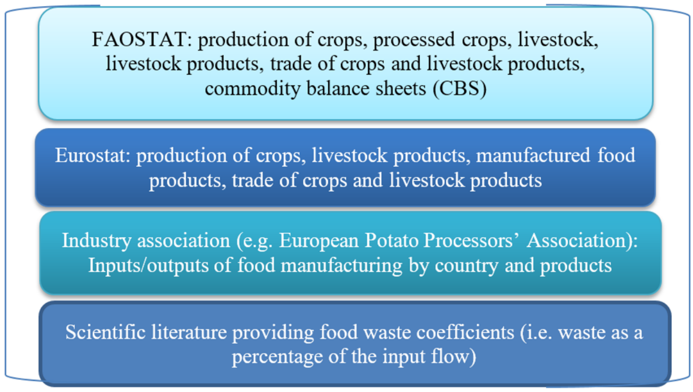

Fig. 3 Main databases for assessment of food waste generation

The main underlying data source used is the EU waste statistics, reported by each MS and collected by Eurostat based on EU Commission regulation on waste statistics (No. 2150/2002) [2], [16]

There are mainly two studies dealing with pan-European data on food waste: the study carried out by the Bio Intelligence Service (BIOIS) on behalf of the European Commission [17] and the study carried out by the Swedish Institute for Food and Biotechnology (SIK) on behalf of FAO. The general outline is shown in Figure 3. In this case, an important challenge is to develop an applied direction for the use of a waste footprint methodology to effectively evaluate the co-treatment of sectoral application.

Public data collection. A search of open databases on food waste statistics was conducted. Below is a scheme of working with the Food Waste - OECD Statistics[18] (Fig. 4). The Food Loss and Waste database is the largest online collection of data on both food loss and food waste and causes reported in scientific journals, academic publications, grey literature, countries among others. Its use will make it possible to cover different regions of the world, not only EU countries. The database contains data and information from openly accessible databases, reports, and studies measuring food loss and waste across food products, stages of the value chain, and geographical areas.

To select the necessary bibliometric data on the subject of research, the Scopus database was taken. The methodology of bibliometric network analysis implies the analysis of a large volume of data from the citation database. This methodology involves the construction of networks linking different bibliometric objects (publications, authors, journals, keywords, etc.) by relations of various types (co-presence, citation, co-citation, bibliographic combination, etc.). The analysis of such networks provides opportunities to study the development of different scientific fields and disciplines, their thematic structure, and scientific teams. During the bibliometric analysis, searches were used for the keywords "environmental footprint", "waste footprint", "waste generation", "municipal solid waste", "agricultural waste", "construction waste", "food waste", and "recycling methods".

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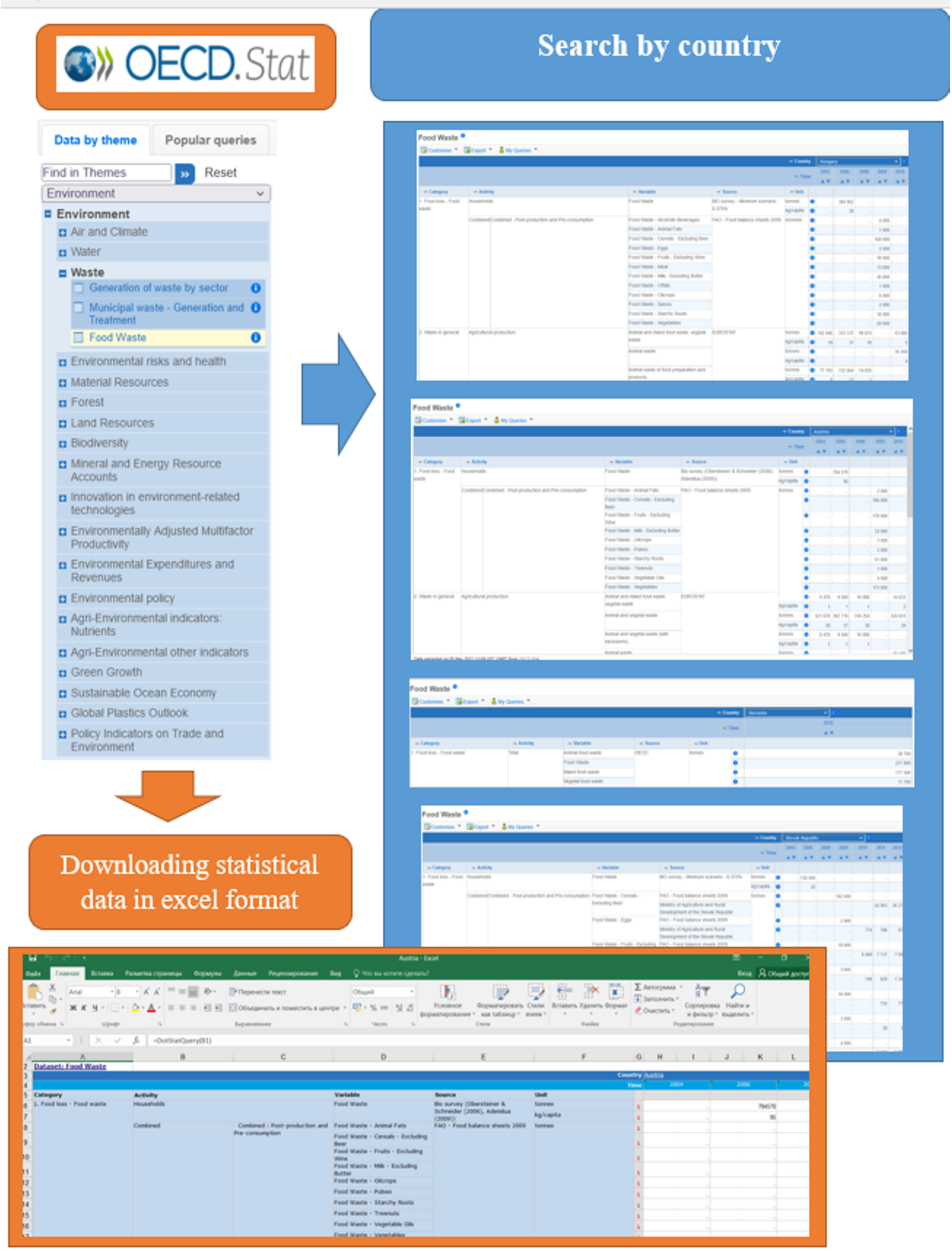

Fig. 4. Search options in the OECD Statistics database

3 Results And Discussion: Conceptualizing The Use Of A Footprint Approach For Waste Processing

Based on the amount of waste generated, its composition and ways of handling it, an estimated 1.6 billion tons of carbon dioxide (CO_2) equivalent greenhouse gas emissions have been generated by solid waste treatment and disposal, which is 5% of global emissions. This is mainly due to the disposal of waste in open dumps and landfills without landfill gas collection systems. Almost 50% of emissions come from food waste. By 2050, emissions associated with solid waste are expected to increase to 2.38 billion tons of CO_2-equivalent per year if no improvements are made in the sector [19].

It is possible to present the general classification of waste as an integrated system that characterizes the properties of waste, taking into account the different sources of its formation (fig.5). Hazardous properties of waste are established in accordance with the requirements of Annex III to the Basel Convention or the relevant national standards of the EU countries. Toxicity is defined as the ability to cause serious, prolonged, or chronic human illness, including cancer, when ingested through the respiratory, digestive, or skin. Chemicals can have harmful effects on the human body in different ways. Acute toxicity occurs when a single exposure to a chemical, usually in large doses, leads to harmful effects on the body immediately or in a short period of time. Chronic or delayed toxicity occurs when there is long-term exposure to lower doses in which harmful effects do not occur at the time of initial exposure, but occur later in the exposure period. However, in addition to the environmental effects of waste and the impact on human health, it is important to determine the feasibility of recycling certain wastes of different origins. The composition of waste significantly affects the possibility of recycling and, accordingly, the reduction of the trace of waste [4]. Thus, secondary material resources are wastes of production and consumption, which can currently be used in the national economy. Types of production and consumption waste used directly, as well as those for which there are or are planned economically feasible technological methods of processing, are secondary material resources. The rest of the waste forms non-recoverable losses.

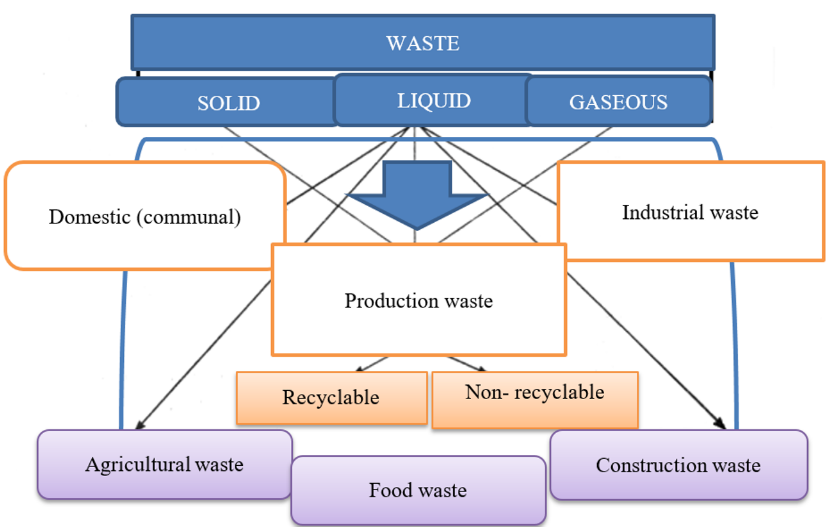

Fig. 5. Integrated classification of waste, taking into account the possibility of recycling

The most common methods of food waste processing are presented in Fig.6. The general European trend for a significant reduction in the share of solid waste disposal.

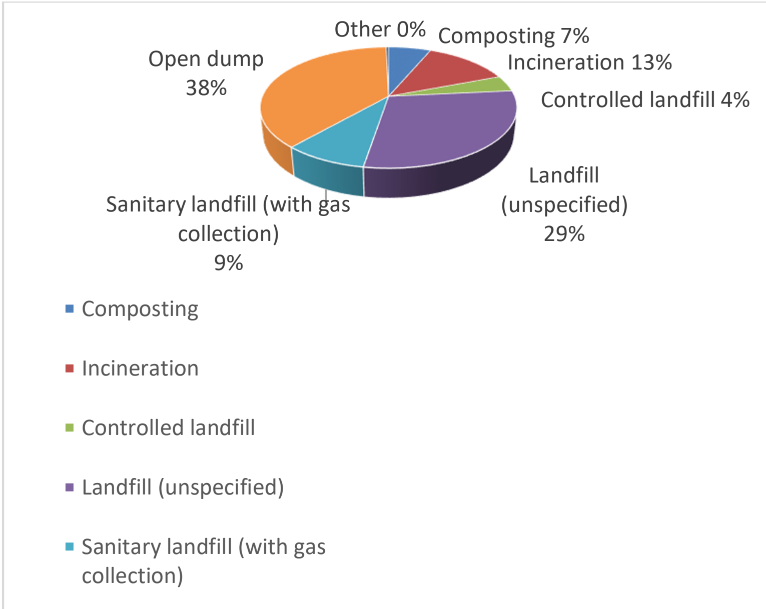

Fig. 6. Global treatment and disposal of waste according to [19]

Changing the properties of solid municipal waste makes incineration technologies more preferable (without taking into account the environmental consequences) for waste collected in bulk [20], [21]. The use of biological methods of processing municipal waste requires the introduction of sorting lines in the technological scheme to increase the proportion of the compostable fraction. The metal fraction can be disregarded when calculating the economic efficiency of waste processing enterprises. When developing technological processes of waste recycling, it is necessary to take into account the fact that part of food waste will be in the packaging and it will be necessary to disintegrate them to involve them in the process of biological processing [22], [23]. Thus, when implementing technological solutions for the utilization of different types of waste, it is advisable to apply the concept of waste trail.

Environmental impact assessment has become as important as economics in the processing industry. Various techniques are widely used for impact assessment, namely life cycle assessment (LCA), emergent analysis (EA), and environmental footprint analysis (EF).

Over the past 20 years, scientific research on the topic of environmental footprint has become increasingly interdisciplinary [1], [3], [4], [24]–[32]. Based on the key formula of Wackernagel and Rees [31], [32], along with some refinements to standardize calculations, ecological footprint research has been applied to the study of the ecological security of socio-economic systems of various levels, from the global to the individual. Of course, the environmental footprint concept has both strengths and weaknesses, which is why in the scientific literature for more than 20 years, attempts to improve it have not stopped (Table 1). Of course, there have been many attempts to modernize the concept of the ecological footprint, many more than we indicated in Table 1. However, it is the models listed above that are currently used the most frequently.

Table 1. Different approaches to calculating the environmental footprint.

Approach/Calculation method	**Peculiarities of the calculation method**	**Note**
$ef = \sum_{j=1}^{i} w_j \times A_i = \sum_{j=1}^{i} \left(w_j \sum \frac{c_j}{p_j} \times y_j \right)$ EF = N × *ef* where ef is the ecological footprint per capita; j is type of land productivity; I is category of the object of consumption; w_j is equivalence coefficient; y_j is income coefficient; A_i is area of the object of consumption; c_j is per capita consumption of the i-th item; p_j is local unit of the output area of the item consumption; EF is the total value of the environmental footprint; N is population of the region.	The traditional method of measuring the Environmental Footprint estimates how much biologically productive land and water an individual, population or activity requires to produce all the resources it consumes and *absorb the waste it produces, using the prevailing technology and resource management practices*, but does not account for biodiversity loss, the extent of soil and water pollution, etc. In essence, measuring the environmental footprint is simply the result of translating carbon dioxide emissions into virtual hectares.	[31], [32]
$T = \frac{EF}{GDP\ at\ PPP}$; where T is the intensity of the impact per unit of production; $T_{ei} = \frac{T}{Md_t}$, where T_{ei} is the coefficient of exposure intensity; Md_t is the cross-national median T, equal to 4.86 m^2 per a dollar of gross domestic product (GDP)	Estimates the change in the intensity of the environmental impact of national economies, i.e. *resource consumption and waste generation per unit economic output*. T is also a measure of eco-efficiency: the lower its value, the lower the output per unit of economic activity (i.e., the higher the efficiency).	[28]
Modified Environmental Footprint Models (disturbed land model, EF-NPP model (human appropriation of net primary productivity), emergent model, etc.)	These models, while not providing a fundamental shift in favor of the utility of Environmental Footprint for policy measures, can help address specific research questions and help smooth out some of the inconsistencies of the traditional approach.	[26], [33]
Dynamic environmental footprint models (DEF) Identify causal relationships between human consumption and biocapacity and rely on ecology by incorporating variables of biodiversity	Using the method allows for temporal analysis of consumption, production, land use, greenhouse gas emissions, species diversity, and biocapacity at the country level over the long term.	[34]
Methods for estimating the environmental footprint based on input-output tables: - Single-region input-output models (SRIO); - Multi-regional input-output models (MRIO).	Applying the input-output method to the ecological footprint involves filling in the matrix of use of biological resources and coefficients for each sector of the economy.	[24], [25]

The general outline is shown in Figure 7. In this case, an important challenge is to develop an applied direction for the use of a waste footprint methodology to effectively evaluate the co-treatment of sectoral application.

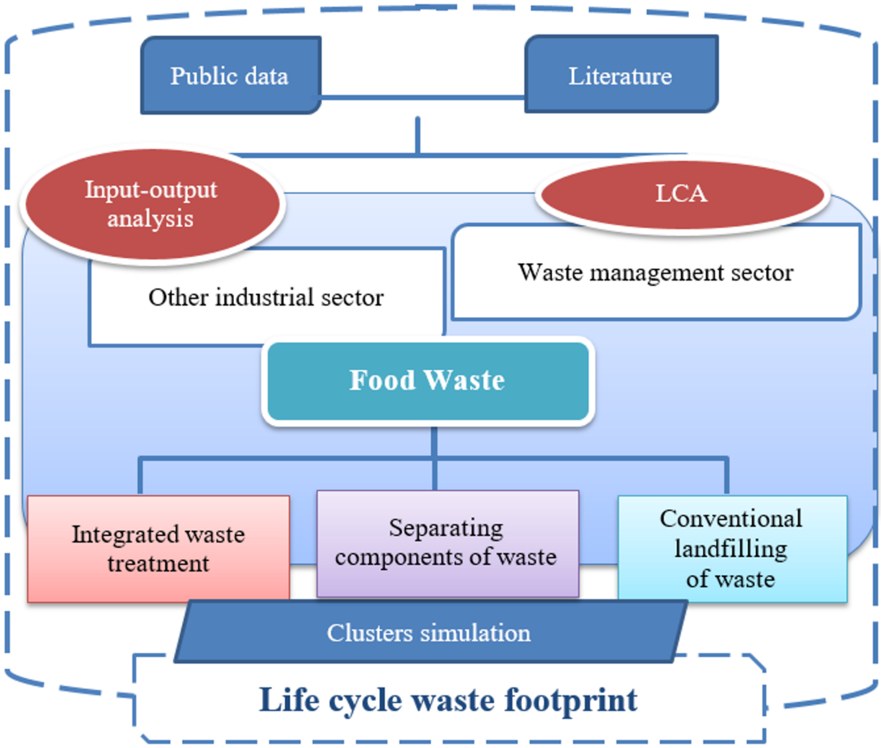

Fig. 7 Interaction of approaches to evaluating food waste generation and treatment

The resource supply footprint is calculated using regional renewable energy density, and the environmental footprint associated with emissions/waste assimilation is calculated using LCA results [35]**.**

In a study by [3] indicated that the energy and environmental footprint of food production systems has increased rapidly in response to the dramatic increase in cases of COVID-19 worldwide, while critical hazardous waste management issues raise hazardous waste management issues due to the need to ensure destruction residual pathogens in household and medical waste. The concept of the plastic waste footprint is proposed to reflect the ecological footprint of a plastic product throughout its life cycle. We propose to develop this concept for other waste generations and their types [3][4].

Thus, the idea of the "waste footprint" concept is as follows: the waste footprint is the amount of waste generated from production until the end of the product/service life, which is all the more difficult to recycle (when the technology is invented). We do not assess the impact of waste on the environment, but its loss as a raw material resource. That is, hazardous waste is contaminated with hazardous substances, limiting its reuse. Restoring such waste to a primary raw material should have a greater waste footprint than other - non-hazardous waste. The proposed approach is shown in Fig. 8.

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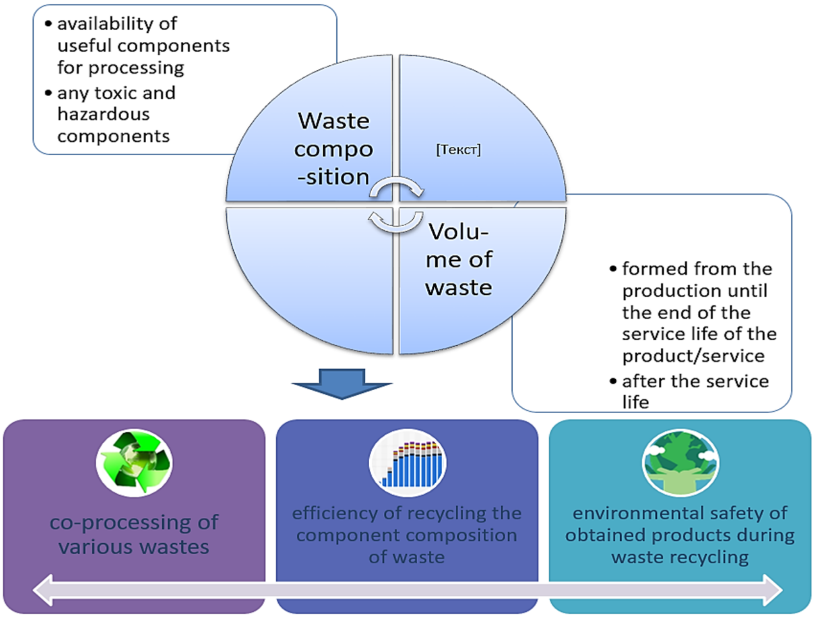

Fig. 8. The concept of the "waste footprint".

Accordingly, this concept can be applied to evaluate the co-digestion of waste. Figure 9 shows the conceptual model proposed to explain the relationship between the dependent variable and the independent variables are given our vision of the waste footprint concept. The priority is to determine whether and to what extent the dependent variable is affected by the independent variables. The dependent variable, in this case, is the "interest in choosing a zero-waste production system" with a combination of co-treatment of food waste and wastewater of a certain composition.

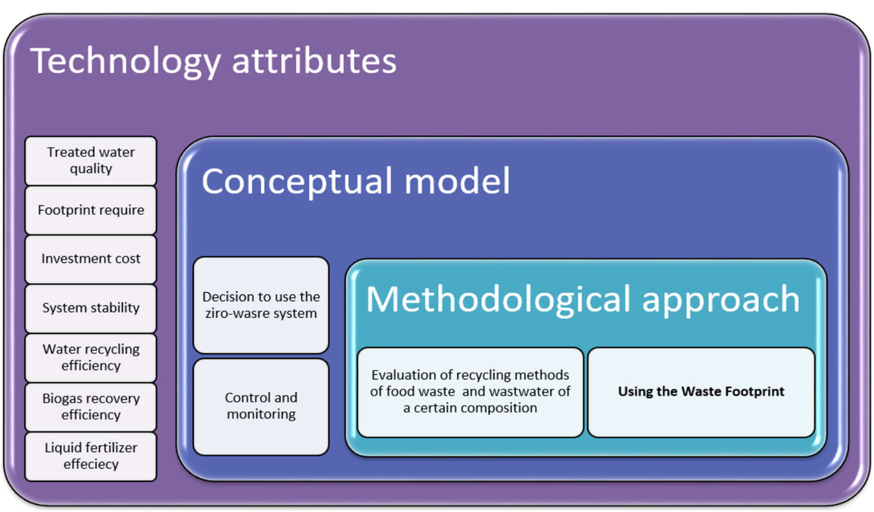

Fig. 9. The conceptual model for evaluating co-treatment scenarios for waste

Food waste is a renewable resource, and by valorizing it, wastewater treatment plants can be turned into small biorefineries capable of producing biogas and other new products. Thus, the amount of organic fraction of municipal solid waste fed to co-digestion varies over time due to the characteristics of the waste, the course of the anaerobic process, and the allowed annual recycling limit. Analysis of the mass balance of the collection system, taking into account the "waste footprint" approach, will allow an assessment of the efficiency of the selection and content of the rejected waste of the street separate collection system, which is consistent with previous studies [23].

4 Conclusion

Nowadays, there is no ideal solution for the elimination of production and consumption waste, which would allow cost-effective and maximum utilization of secondary raw materials or energy without creating new waste, pollutant emissions into the atmosphere, and wastewater discharges.

The existing waste management system should be aligned with the principles of sustainable economic development, taking into account the concept of the waste footprint. The waste management policy should be based on the priority of preservation of non-renewable natural resources. From this point of view, the proposed waste footprint concept may allow finding a more rational use of different types of waste, including food waste, taking into account the component composition to determine the technological and environmental, and economic feasibility of recovery of secondary resources, or the use of energy obtained from waste incineration.

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