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Tracing the drivers of waste generation in Poland (2010–2018): a structural decomposition and input–output approach

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Abstract. The paper discusses the application of Structural Decomposition Analysis (SDA) in an extended input-output model to trace main sources of waste generation in Poland between 2010 and 2018. Poland is a country that has experienced significant economic growth in recent years, yet few studies discuss the costs of this miracle, including the generation of waste. The economy relies on sectors and their production, generating waste in quantities that depend on various factors. SDA is a quantitative method that can be used to examine the drivers of this waste generation. It provides insights into how changes in final demand and technology have affected the amount of waste generated by sectors over the analysed period of time. Analysing the results of the proposed model allows policymakers to develop targeted interventions to reduce waste and promote sustainable development. The paper concludes that this technique can be a valuable tool for environmental analysis, providing a comprehensive view of the connections between economic activity, environmental impacts, and waste generation.

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1. Introduction

Over the years, Poland's consistent economic growth (World Bank Group, 2023) has yielded numerous advantages for both individuals and businesses. The technological race that has been ongoing for many years and the increasing market demands are associated with the heightened activity of economic sectors, which strive to meet the needs of consumers on both local and global scales. An integral part of the functioning of these economic sectors is the generation of waste [1], the amount of which depends, among other factors, on changes in technology and production volumes. Examining Poland's economic growth and total waste production from 2010 to 2018, it is evident that the rise in GDP coincides with a rise in waste production, irrespective of population growth (European Environment Agency, 2023). The waste generated has a negative impact on the environment, which manifests itself in air, water, and soil pollution (Madaleno, 2018). Such contamination leads to a reduction in species biodiversity (Adeyemo, 2003), instigates climate change through harmful gas emissions (Yusuf et al., 2012), and triggers diseases that affect animals, plants and humans (Abubakar et al., 2022).

The increasing quantity of waste generated globally has emerged as a significant environmental challenge. The *What a Waste 2.0* report (Kaza et.al., 2018) highlights that the world produces 2.01 billion tons of municipal waste annually, with at least 33% not being adequately managed in an environmentally safe manner. The *per capita* average ranges from 0.11 kg to 4.54 kg, and predictions for the year 2050 estimate an annual waste generation of 3.4 billion tons, representing a 69% increase compared to the current state. In contrast to municipal waste, the amount of industrial waste generated is 18 times higher. Shifting the focus to the situation in Poland, according to a report from the central statistical office (*Statistics Poland*, 2022), 121 million tons of waste were produced in 2021, of which 107.7 million tons constituted industrial waste. Within the industrial waste category, waste from floatation dressing of non-ferrous metal ores (27.2%) and waste from washing and cleaning minerals (25.0%) dominate. To maintain sustainable economic growth, five waste management approaches have been implemented. Waste prevention is regarded as the best solution, followed by reuse, recycling, other forms of recovery and, finally, waste disposal.

The objective of this study is twofold. Firstly, it aims to show a comprehensive analysis of waste generation trends across various sectors in Poland over an eight-year period, with data collected every two years from 2010 to 2018, in order to examine the trends in waste generation within different sectors. By looking closely at this timeframe, we can get a clear picture of the changes in waste generation and identify key patterns and changes. Secondly, this study explores the role of various factors, such as technological change and final demand change, in the context of waste generation. By utilising input-output tables and SDA technique for Poland during the studied time period from 2010 to 2018, we can conduct an analysis that will provide valuable insights into the specific contributions of technological changes and of changes in final demand to waste generation within each sector group. By combining the analysis of the long-term trends in waste generation and examining the factors influencing it, this study aims to shed light on the dynamics of waste generation in the Polish economy. The findings presented in this paper provide valuable and original insights into the field of waste management, significantly contributing to the existing body of literature. Moreover, this study fills a gap in the literature by applying the integration of input-output tables and the SDA technique to analyse waste generation in the context of Poland. The results not only enhance knowledge in this area but also serve as a foundation for future studies seeking to explore and address waste management challenges.

2. Brief literature review

The topic related to the utilisation of input-output tables and the SDA method for analysing greenhouse gas emissions in Poland has been often addressed by researchers. Using nonlinear programming, Lach (2022) presented a novel tool for quantitative investigations, enabling the identification of coefficients in the input-output model where even slight changes can lead to significant reductions in greenhouse gas emissions. In turn, the SDA technique's application to energy usage issues in Poland has been addressed in the study by Stachura (2018). As a result, such an approach allowed for identifying factors influencing energy consumption growth not only at the national level but also within the analysed sectors during the specified time period. In general, the subject of input-output applications is not commonly discussed in relation to data from the Polish economy. Putting aside environmental concerns, the input-output tables were used to determine regional dependencies and linkages between provinces, focusing mainly on the Research and Development (R&D) sector (Rok & Zawalińska, 2017). In the field of R&D, Świeczewska (2014) also employs Input-Output analysis to examine the influence of final demand on the enterprises' R&D activity.

Input-output tables and the SDA method can also be applied in the field of international trade theory. In his research, Przybyliński (2012) uses input-output tables to compute trade intensity indices, import dependency, and intra-industry trade intensity. Additionally, conducting multiplier analysis enabled the estimation of labour inputs in Polish exports and imports, in comparison to labour input assosiated with other categories of final demand. Subsequently, the author applied this method to determine emissions of air pollutants linked to foreign trade. Another application of IO multipliers is the estimation of labour content in exported goods and services, which enables a comparison with the labour content in domestically produced items. As a result, the study indicated that production for domestic final demand was more labour-intensive than exports in 1990 and 2000 (Przybyliński, 2006).

From a global perspective, there have been papers that integrate waste generation issues using IO tables for further analysis. The main goal of these studies is to identify determinants in waste generation by sectors. In the work focusing on Australia (He et al., 2019), the authors analyse the period from 2007 to 2014 to determine the primary factor responsible for the increase in waste production, considering technological effects and the breakdown of final demand into smaller components. A similar approach is employed by the authors in the case of China (Zhang et al., 2021) to analyse the influence of socio-economic drivers on common industrial solid waste and hazardous waste generation. Subsequently, through the application of Structural Path Decomposition, it became possible to delve deeper into the impact of drivers at the supply chain level, resulting in more meaningful outcomes for policy formulation. In another article also focused on China (Huang et al., 2020), the authors analyse the period from 2005 to 2017 to identify the socio-economic drivers of solid waste recycling. The selected articles above represent only a portion of the current research on the issue of waste generation utilising Input-Output tables and SDA method. For more insights into the expansion of methods and potential applications in the field of waste management within industrial ecology, the author refers to the book by Nakamura and Kondo (2009).

Furthermore, environmental analysis issues are gaining popularity, and more individuals are interested in expanded input-output (IO) models. Between 2005 and 2009, nearly three times as many articles related to this topic were published compared to the period between 1968 and 1994 (Hoekstra, 2010). These studies exhibit a diversity of employed methods (e.g., SDA, dynamic I-O models) and cover a wide range of research areas (e.g., greenhouse emissions, energy usage). For instance, in a comprehensive study, Guan et al. (2010) used SDA and IO analysis to assess the significant drivers behind the anticipated tripling of China's CO2 emissions from 1980 to 2030. As a further illustration, an analysis of energy consumption and CO2 emissions in Korea's industrial sectors from 1990 to 2003 was undertaken using input-output structural decomposition to consider eight influential factors, such as emission coefficient changes, economic growth and structural changes (Lim et al., 2009). Research using IO tables and the SDA method can also relate to energy-related topics, such as changes in renewable energy consumption in China (Lin et al., 2022) and shifts in energy use and CO2 emissions in Japan (Ueda, 2022).

To the best of the author's knowledge, linking IO tables with the SDA technique to the waste generation issue has not been applied in the context of Poland. Therefore, the results presented in this article offer novel insights and lay the groundwork for future research. The insights gained from this study can inform the development and implementation of effective waste reduction strategies, resource optimisation techniques and circular economy initiatives. By highlighting the specific factors and trends influencing waste generation in the context of Poland, this research contributes to the broader discourse on sustainable development and environmental stewardship.

3. Methodology

The starting point for the deliberations is the introduction of the input-output (IO) model, which was originally developed by Wassily Leontief, the Nobel laureate in Economics in 1973. The model was initially designed to study the economy's production and consumption flows (Leontief, 1936). Over the years, this method has undergone significant development and is now widely used, including in environmental analysis. The following section provides a concise introduction to the Leontief model, the methodology of sector aggregation, and the application of Structural Decomposition Analysis in the extended IO model. More detailed descriptions and fundamental applications of IO models can be found in Miller & Blair (2009), while recent extensions in this field are outlined in Lach (2020, 2022).

3.1. Formulation of the mathematical model and aggregation method

In the subsequent part of the article, the following notations concerning symbols are adopted – bold capital letters will be used to represent matrices, bold lowercase letter for vectors, and italicised capital and lowercase letters for scalars. The capital letter T will signify transposition, and a circumflex will indicate a diagonal matrix. Having introduced the notations mentioned above, let us assume that the economy consists of n sectors, and the allocation of the total production of sector i is expressed by the equation: $x_i = z_{i1} + ... + z_{in} + f_i$, where z_{ij} represents the sales from sector i to sector j ($i,j \in 1,\ldots,n$) and f_i represents the final demand. After introducing the technical coefficient in the form of $a_{ij} = z_{ij}x_j^{-1}$ and depicting the results in the matrix **A**, with the assumption that a matrix $(\mathbf{I} - \mathbf{A})^{-1}$ exists, the representation of the output **x** is as follows:

$$x = (I - A)^{-1} f = Lf, \quad (1)$$

where **I** is the $n \times n$ identity matrix and the matrix $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is referred to as the Leontief inverse.

The next step is to propose a method for sector aggregation into groups. Let 'us introduce the matrix **S**, which has dimensions $k \times n$, where k represents the number of groups formed from n sectors. The matrix **S** is filled with "0" and contains "1" at positions in the matrix rows that correspond to the sectors being aggregated into groups. Using the previously introduced notations, one can determine the aggregated vector of final demand and the matrix of interindustry flows, denoted as $\mathbf{f}^* = \mathbf{Sf}$ and $\mathbf{Z}^* = \mathbf{SZS}^T$, respectively. By substituting the vector $\mathbf{f}^*$ and $\mathbf{Z}^*$ into the model formulation, the aggregated vector of total production $\mathbf{x}^*$ can be obtained, along with the matrix of technical coefficients $\mathbf{A}^*$ and the Leontief inverse $\mathbf{L}^*$ for the aggregated sectors.

3.2. SDA method derivation

The last element involves extending the classical IO model with information regarding waste generation by relevant sectors and applying the Structural Decomposition Analysis (SDA) method. This will allow us to analyse the structure of the studied economy and, by including an environmental variable, identify the impact of different sector groups on waste generation.

Let **w** be a vertical vector of dimension $n \times 1$ in the form $\mathbf{w}^T = [w_1,\ldots,w_n]$ which describes waste per unit of output. Additionally, let superscripts 0 and 1 denote two periods of time expressed in such a way that 0 represents a period (for example, a year) that occurs earlier than 1. Hence, the vector of changes in the amount of waste generated between period 0 and 1 is in the form:

$$\Delta w = w^1 - w^0 = \hat{w}^1 L^1 f^1 - \hat{w}^0 L^0 f^0 \quad (2)$$

To determine the factor responsible for the change in waste generation, along with its contribution to this change, one needs to decompose the above equation in a way that encompasses changes occurring in **w**, **L** and **f**. Considering that there are three decomposition factors, the number of equivalent decompositions of $\mathbf{\Delta w}$ is six. In the general case, where the number of factors is k, the number of possible breakdowns is ($k!$). Consequently, the results of the analysis may vary, depending on the chosen decomposition. In this paper, a method of taking the average of two polar decompositions will be used. The conducted research (Dietzenbacher & Los, 1998) shows that this approach closely approximates the results obtained by averaging all ($k!$) possibilities.

Let us denote $\hat{\mathbf{w}}^1 = \hat{\mathbf{w}}^0 + \mathbf{\Delta w}$, $\mathbf{L}^1 = \mathbf{L}^0 + \mathbf{\Delta L}$ and $\mathbf{f}^1 = \mathbf{f}^0 + \mathbf{\Delta f}$. Once $\hat{\mathbf{w}}^1$, $\mathbf{L}^1$ and $\mathbf{f}^1$ are substituted into equation (2), and the expressions are simplified, the result is:

$$\Delta w = (\Delta \hat{w}) L^0 f^0 + w^1 (\Delta L) f^0 + w^1 L^1 (\Delta f) \quad (3)$$

On the other hand, after substituting $\hat{\mathbf{w}}^0 = \hat{\mathbf{w}}^1 - \mathbf{\Delta w}$, $\mathbf{L}^0 = \mathbf{L}^1 - \mathbf{\Delta L}$ and $\mathbf{f}^0 = \mathbf{f}^1 - \mathbf{\Delta f}$ also into equation (2), the following result is derived:

$$\Delta w = (\Delta \hat{w}) L^1 f^1 + w^0 (\Delta L) f^1 + w^0 L^0 (\Delta f) \quad (4)$$

Ultimately, with equations (3) and (4) added together and $\mathbf{\Delta w}$ calculated, the equation decomposed by the SDA technique emerges as:

$$\mathbf{\Delta w} = \frac{1}{2}\underbrace{(\Delta\hat{\mathbf{w}})(\mathbf{L}^0\mathbf{f}^0 + \mathbf{L}^1\mathbf{f}^1)}_{\text{Waste coefficient change}} + \frac{1}{2}\underbrace{(\hat{\mathbf{w}}^0(\Delta\mathbf{L})\mathbf{f}^1 + \hat{\mathbf{w}}^1(\Delta\mathbf{L})\mathbf{f}^0)}_{\text{Technology change}} + \frac{1}{2}\underbrace{(\hat{\mathbf{w}}^0\mathbf{L}^0 + \hat{\mathbf{w}}^1\mathbf{L}^1)(\Delta\mathbf{f})}_{\text{Final demand change}} \quad (5)$$

The first term represents the change in the waste generation coefficient, the second term refers to technological changes, and the last term accounts for changes in final demand.

3.3. Dataset and sector classification

The IO data (OECD, 2021a) presents cross-sectoral exchanges of goods and services that were produced both domestically and imported for an extensive time period, ranging from 1995 to 2018. As a result, the paper considers an open economy model. Meanwhile, data concerning the amount of waste generated by sectors in Poland is accessible (with minimal data omissions) at biennial intervals between the years 2010 and 2020 (OECD, 2021b). The analysis was conducted in the R environment [2] for the period from 2010 to 2018 at two-year intervals, as it ensures the availability of both sources of data. The IO tables are expressed in current prices in millions dollars, so the data has been converted to the local currency (PLN) and adjusted for inflation. Both the average annual exchange rates and inflation data were obtained from the OECD database (OECD, 2023a; 2023b). Furthermore, data regarding the amount of waste generation is expressed in thousands of tons.

The initial dataset encompassed 45 sectors, which, due to limitations in the availability of data on the amount of waste generated by the respective sectors, were grouped into seven categories. Additionally, due to a lack of complete data, two waste generation amounts in 2018 in a group of sectors: Energy Production (electricity, gas, steam and air conditioning supply) and Other Sectors were estimated using linear regression based on the amount of waste generated in previous years. The classification of sectors into groups, as detailed in Table 1.

The sector numbers in the above table correspond to the economic classification introduced by the *International Standard Industrial Classification* (ISIC). A detailed list of sectors belonging to the above categories according to specific abbreviations can be found in the *International Standard Industrial Classification of All Economic Activities* (United Nations Statistical Division, 2008).

4. Results and implications

This section focuses on presenting and interpreting the results obtained using the SDA method outlined in Section 3. Table 2 is presented as a direct result coming from equation (5), with data corresponding to the years 2016 and 2018. It provides the most up-to-date data that connects the output of sector groups with the quantity of waste generated. For more details, please refer to Table 2.

The numerical values in the Table 2, Table 3, Table 4 and Table 5 are expressed in thousands of tons. The results presented in parentheses correspond to the percentage share in the change in the amount of waste generated by the respective sector located in the row. As there is a large amount of data, the final analysis result will be presented through a graphical summary covering the period from 2010 to 2018. The stacked bar charts ilustrate the amount of changes contributing to waste generation in the specified group of sectors, except for the "Other sectors" category due to its high level of aggregation. The data in the form of tables for the remaining years are included in Table 3, Table 4 and Table 5.

Changes in waste generation are influenced by technological advancements and shifts in final demand, impacting both the quantity and waste intensity. Across the entire economy, no clear trend points to a dominant factor during the analysed period. In 2010–2012 and 2016–2018, technological effect was the primary drivers of waste generation growth, coinciding with a decrease in waste generated per total output unit. Conversely, from 2012 to 2016, the factor driving increased waste production was final demand. Analysing data within specific sectors, the mining sector exhibited the largest positive impact on waste intensity (Fig. 1b), reaching 19.3 thousand tons during 2012–2014. In contrast, during 2016–2018, this sector showed the biggest change in waste intensity, achieving the

Table 1. Classification of sectors into groups

Category name	Number of sectors belonging to the category
Agriculture, forestry and fishing	S01–03
Mining and quarrying	S05–09
Manufacturing industries	S10–33
Electricity, gas, steam and air conditioning supply	S35
Water supply, sewerage, waste management and remediation activities	S36–39
Construction	S41–43
Other sectors	S45–96

Source: Own elaboration

Table 2. Change in waste generation, waste intensity, technology contribution and final demand contribution by a group of sectors in 2016–2018

	Waste Generation Change	Waste Intensity	Technology Change Contribution	Final Demand Change Contribution
Agriculture, forestry and fishing	-108.5	-131.2 (120.9%)	8.2 (-7.6%)	14.5 (-20.0%)
Mining and quarrying	-6,348.8	-15,998.4 (252.0%)	24,192.4 (-381.1%)	-14,542.9 (229.1%)
Manufacturing industries	-556.4	-4,257.4 (765.2%)	559.9 (-100.6%)	3,141.1 (-564.5%)
Energy production	941.2	297.9 (31.7%)	-670.9 (-71.3%)	1,314.2 (139.6%)
Water supply, sewerage, waste management	85.8	-44.3 (-51.6%)	3.2 (3.7%)	127.0 (148.0%)
Construction	-2,028.8	-4,703.3 (95.0%)	523.4 (-25.8%)	2,151.1 (-106.0%)
Other sectors	1,082.3	-1,503.9 (-139.0%)	369.2 (34.1%)	2,217.0 (204.8%)
Total	**-6,933.2**	**-26,340.6 (379.9%)**	**24,985.4 (-360.4%)**	**-5,578.0 (80.5%)**

Source: own elaboration

Table 3. Change in waste generation, waste intensity, technology contribution and final demand contribution by a group of sectors in 2014-2016

	Waste Generation Change	Waste Intensity	Technology Change Contribution	Final Demand Change Contribution
Agriculture, forestry and fishing	42.1	175.2 (416.2%)	-38.8 (-92.2%)	-94.3 (-224.0%)
Mining and Quarrying	-5069.9	15759.6 (-310.8%)	-45810.8 (903.6%)	24981.3 (-492.7%)
Manufacturing industries	-1424.4	2765.9 (-194.2%)	228.3 (-16.0%)	-4418.5 (310.2%)
Energy Production	-1385.3	3991.3 (-288.1%)	-1004.9 (72.5%)	-4371.7 (315.6%)
Water supply, sewerage, waste management	220.2	351.2 (159.5%)	29.4 (13.4%)	-160.4 (-72.8%)
Construction	1884.1	5126 (272.1%)	838.5 (44.5%)	-4080.4 (-216.6%)
Other sectors	3950.4	5962.3 (150.9%)	303.3 (7.7%)	-2315.3 (-58.6%)
Total	**-1782.8**	**34131.5 (-1914.5%)**	**-45455 (2549.6%)**	**9540.7 (-535.2%)**

Source: own elaboration

Table 4. Change in waste generation, waste intensity, technology contribution and final demand contribution by a group of sectors in 2012-2014

	Waste Generation Change	Waste Intensity	Technology Change Contribution	Final Demand Change Contribution
Agriculture, forestry and fishing	-318.5	-358 (112.4%)	-21.1 (6.6%)	60.6 (-19.0%)
Mining and Quarrying	7698.4	19690.9 (255.8%)	-31533.1 (-409.6%)	19540.6 (253.8%)
Manufacturing industries	320.9	-1982.6 (-617.8%)	-141.7 (-44.2%)	2445.3 (762.0%)
Energy Production	1216.6	1627.3 (133.8%)	-1462.6 (-120.2%)	1052 (86.5%)
Water supply, sewerage, waste management	-91.5	-246.4 (269.3%)	27 (-29.5%)	128 (-139.9%)
Construction	1598.7	1596.2 (99.8%)	-482.8 (-30.2%)	485.2 (30.3%)
Other sectors	1072	-238.9 (-22.3%)	12.7 (1.2%)	1298.2 (121.1%)
Total	**11496.6**	**20088.5 (174.7%)**	**-33601.6 (-292.3%)**	**25009.9 (217.5%)**

Source: own elaboration

Table 5. Change in waste generation, waste intensity, technology contribution and final demand contribution by a group of sectors in 2010-2012

	Waste Generation Change	Waste Intensity	Technology Change Contribution	Final Demand Change Contribution
Agriculture, forestry and fishing	255.8	170.6 (66.7%)	45.7 (17.9%)	39.6 (15.5%)
Mining and Quarrying	6484.1	-2009.5 (-31.0%)	19878.4 (306.6%)	-11384.8 (-175.6%)
Manufacturing industries	2394.4	-1087 (-45.4%)	459.6 (19.2%)	3021.8 (126.2%)
Energy Production	452.7	-322.8 (-71.3%)	-738.3 (-163.1%)	1513.8 (334.4%)
Water supply, sewerage, waste management	-552.3	-601.9 (109.0%)	-31.5 (5.7%)	81.2 (-14.7%)
Construction	-5466	-5388.5 (98.6%)	-249.4 (4.6%)	171.8 (-3.1%
Other sectors	1154.6	892.5 (77.3%)	-194.8 (-16.9%)	456.9 (39.6%)
Total	**4723.3**	**-8346.6 (-176.7%)**	**19169.7 (405.9%)**	**-6099.7 (-129.1%)**

Source: own elaboration

Fig. 1. Waste generation determinants. (a) Agriculture, forestry and fishing; (b) Mining and quarrying; (c) Manufacturing industries; (d) Energy production; (e) Water supply, sewerage, waste management; (f) Construction; (g) Poland's overall economy, measured in thousands of tons
Source: own elaboration

lowest value of all sectors, nearing −16 thousand tons. Domains such as manufacturing (Fig. 1c) and construction (Fig. 1e), displayed decreasing or low waste generation per output unit, despite a small positive value during 2014–16. Other sectors did not exhibit clear trends or distinctive characteristics; waste intensity fluctuated during the analysed period.

Technological effect had the most significant impact in the mining sector, contributing to waste generation growth during 2010–2012 and 2016–

2018. In the later period, a rapid growth in the economy, lack of modernisation and maintenance of infrastructure, but also rapid expansion without appropriate investment in waste reduction technology, led to an increase in the amount of waste generated. From 2012 to 2016, technological effect had the most significant negative effect on waste generation. Stable and non-volatile economic growth, combined with the introduction of environmental policies and a slow transition away from fossil fuels, has led to a decrease in waste generated by technological change. Additionally, the negative technological effect persisted in the energy sector (Fig. 1d) throughout the entire period, while the manufacturing sector displayed a rising trend.

Final demand effect remained consistent throughout the analysed period, driving an increase in waste generation in the agriculture, manufacturing, energy, water supply, and construction sectors. The dominance of this factor causing increased waste generation is especially visible in the manufacturing and energy sectors. In the manufacturing industries, this shift can be attributed to a rise in demand for low-quality products. However, over time, as society matured, this transformed into an increased demand for more durable, eco-friendly products and those made from recycled materials, consequently reducing waste intensity. In the energy production sector, an increase in final demand may be caused by constant GDP growth, leading to a greater demand for energy. In the case of Poland, the main source of energy is fossil fuels (coal), contributing to the increase in waste generated by this sector. Furthermore, final demand had the most significant positive impact in the mining sector during 2012–2016, whereas, in other periods in this sector, it contributed to a decrease in waste generation.

In most sectors, the sustained level of final demand indicates that consumers have a significant impact on waste generation during the analysed period. However, special attention should be paid to the role of technological changes in the amount of waste generated. This factor can influence, either deteriorating or improving, the issues related to waste generation in Poland. In the broader context of the entire article, these findings shed light on the multifaceted aspects of waste generation in Poland. They emphasise that changes in consumer behaviour, combined with shifts in technology and economic practices, can have a profound impact on the amount of waste generated. This recognition is crucial because it offers pathways for both short-term and long-term policy interventions. Policymakers can use these results to examine closely the individual sector groups and assess historically taken actions. Moreover, the findings can guide them in drawing conclusions about possible development paths and improvements that can be implemented, not only in technological aspects but also in educating citizens to increase their awareness. This dual approach, focusing on systemic change and individual responsibility, offers a more comprehensive strategy for waste reduction in Poland. Enhancing the public's understanding of waste generation and disposal can facilitate more sustainable consumption practices, contributing to the overall reduction of waste generation in the country.

5. Conclusions

The presented analysis has provided a comprehensive understanding of waste generation within seven economic groups of sectors in Poland during the years 2010–2018. These findings highlight the dynamic nature of waste generation patterns and the influence of both technological changes and shifts in final demand. Throughout the analysed period, it has been indicated that the mining and quarrying sector consistently generates the highest amount of waste. Furthermore, it is a sector that is highly vulnerable to both technological changes and shifts in consumer demand, as evidenced by the fluctuations in factors influencing the quantity of waste generated. Additionally, the consistently elevated proportion of the technological coefficient indicates the need to adopt new methods that will optimise production processes and have a less harmful impact on the environment. At the same time, a strong dependence of this sector on market conditions and demand is evident – a decrease in demand leads to significant changes in the quantity of waste generation. When analysing the economy of Poland on a global scale, the application of the IO model in conjunction with the SDA technique enables comparison of results with other economies that have large mining industries. For example, He et al. (2019) conducted a similar study for Australia. In the case of Poland, there is a significant impact of technological factors on the amount of waste generated, whereas in the case of Australia this stimulating factor is final demand. Moreover, there are large fluctuations in the amount of waste generated per million dollars of output, which is much less visible in the case of Australia. Understanding and addressing the factors behind these variations across all sectors is crucial for policymakers and stakeholders in formulating effective waste management strategies and promoting sustainable practices at an economy-wide level. One of the actions that can significantly improve the amount of generated waste and mitigate the negative impact on the environment is reducing Poland's dependence on fossil fuels and transitioning to, among others, renewable energy sources. Consequently, this would lead to a reduction in coal dependency, positively impacting the environment and the efficiency of the economy.

6. Study limitations

Considering that these are preliminary studies and findings in this field, further exploration in this domain could significantly enhance the depth of understanding, and guide sustainable economic planning in the future. With complete data on waste generation by sector from year to year, it would be possible to disaggregate these sector groups into smaller subgroups, or ideally into individual sectors, and apply a similar analysis. The conducted study faced several limitations due to e.g., the absence of inflation data for individual sectors according to the ISIC classification, leading to the consideration of only the annual inflation rate at the national level.

Furthermore, it was observed that certain sectors generate waste from imported products during their production processes. For instance, coal-fired power plants, which often depend on imported coal, generate waste through the process of burning coal, regardless of its origin. These include fly ash, FGD gypsum, catalysts, and hazardous trace elements, as noted by researchers such as Ye et al. (2019) and Vu Thi Ngoc Minh et al. (2023). Similarly, the pharmaceutical industry in Poland is another example where essential components (Stauffer et al., 2018) are imported from abroad for manufacturing processes, leading to the generation of manufacturing waste (Castensson, 2008; Okeke et al., 2022; Jaseem, Kumar, & John, 2017). In contrast to these sectors, there are other industries that do not rely heavily on imported materials and thus have a different waste generation profile. Due to the lack of data on waste generation from imports, and the absence of up-to-date Input-Output tables that distinguish imports per sector, the study adopted IO tables that include both domestic production and imports.

The parameters of technology and final demand change can be further broken down in greater detail. For instance, the change in final demand could be caused by a shift in the overall level of end demand, but also by a change in expenditure proportions on goods and services in the demand vector. Similarly, for the Leontief inverse matrix, which is created by matrix "A" , the possibility exists for further decomposition of technological changes into their various aspects (Miller & Blair, 2009).

In conclusion, the proposed recommendations for further research could augment the precision, relevance, and predictive power of the analysis. By integrating insights into policy formulation and implementation, we can strive towards a more sustainable and environmentally conscious future in Poland.

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