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Research article

Mapping waste generation and supporting the green transition: A waste input-output model for Italy's circular economy

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Abstract: Achieving circularity in economic processes is a key challenge for modern economies, requiring a clear understanding of how economic activities generate waste. Improving resource efficiency, preventing waste generation, and reusing materials are central goals of the circular economy, helping reduce environmental pressures. Secondary waste—from recycling, incineration, and composting—plays a crucial role in assessing the effectiveness of waste management strategies. This paper addresses gaps related to reliance on imported resources and access to critical raw materials by constructing a waste input-output (WIO) table for Italy, linking waste generation data with macro- and regional-level accounts. Using the WIO framework, we explored direct and indirect industrial waste flows, calculated waste-output multipliers, and assessed supply chain impacts. Our findings highlight that secondary waste is key to understanding material circularity, with sectors showing particularly high waste multipliers. These insights offer useful guidance for policymakers aiming to promote resource recovery, reducing reliance on imported raw materials, and strengthen the national circular economy.

Keywords: input-output analysis; circular economy; secondary waste; national accounts; official statistics

JEL Codes: C67, Q53, Q01

1. Introduction

1.1. Circular economy and waste management

Circular economy (CE) is a concept officially adopted and promoted by the EU through the two Circular Economy Action Plans (CEAPs) from 2015 and 2020 (European Commission, 2015, 2020). Other developed and developing countries, as well as international institutions, have also embraced CE as a framework to address critical challenges, such as resource scarcity, climate change, and socio-economic issues, related to achieving the United Nations (UN) Sustainable Development Goals (SDGs). The traditional linear "take-make-dispose" model (Kirchherr et al, 2023) has contributed to economic growth and improved living standards. However, its environmental, social, and economic drawbacks have become increasingly evident, therefore calling for the need for a transition toward more sustainable economic processes.

CE proposes an alternative economic model emphasizing material re-circulation including reuse, remanufacturing, refurbishment, repair, cascading, and upgrading of materials (Korhonen et al, 2018) in the formats of products, components, and raw materials. Nonetheless, achieving circularity in economic processes is a complicated and challenging task. Scholars have also identified some challenges and limits in the practical application of the concept (Korhonen et al., 2018), which include spatial and temporal system boundaries as well as governmental and management challenges concerning inter-sectoral and inter-organizational material and energy flows. On the other hand, there are other examples of achieving environmental and social results in local and regional economies which have led, directly or indirectly through supply chains, value chains, or product life cycles, to other problems in other locations (Korhonen et al., 2004).

Waste management is a key aspect of CE and exemplifies the difficulties in fully implementing circular principles. According to the European Commission, approximately 5 tons of waste is generated per capita in Europe annually, with only 38% being recycled. Additionally, landfill disposal still accounts for over 60% of household waste in some European countries. In the EU27, the rate of waste recycling progress has been slowing down since 2017 (D'Adamo et al., 2022); regarding municipal solid waste (MSW), the recycling rate is less than half the total waste generated in 2022 (Lubello et al., 2025). In Italy, a recent disturbing news about waste made it to the worldwide headlines, with pictures of street-dumping and drainage-channel-clogging by uncollected waste in Campania (Ram et al., 2025). In response, the second CEAP, adopted in 2020, prioritizes improving waste management and recycling processes (European Commission, 2020). A CE framework emphasizes recapturing "waste" as a resource to produce new materials and products, closing material loops (Vines et al., 2023). Furthermore, effective CE implementation can recover the value among the captured and repurposed materials, hence demonstrating its capability to reduce waste generation and promote resource efficiency, which benefits the stakeholders with this new business model (D'Adamo et al., 2022). Quantifying and understanding waste generation across different sectors is an essential step. It sheds a light on the waste hotspots of the whole value chain and lays a solid base for measuring the effectiveness of waste management practices (D'Adamo et al., 2022).

However, quantifying waste generation and its distribution across supply chains remains challenging in today's highly interconnected global economy (Salemdeeb et al., 2016). Given that final products result from multiple industrial sectors, mapping waste generation and treatment processes is essential. However, quantification of waste in the supply chain is a compelling challenge due to our highly globalized and modern world. Products nowadays are highly interconnected, and a final product results from different industrial sectors. To achieve a successful transition from a linear model to a circular model, a mapping of waste generation and treatment is essential also in terms of disentangling the direct and indirect waste sources for each economic activity. Ripa et al. (2016) pointed out that the improvement of one sector might lead to some negative results in other sectors, on the opposite direction for an economy to achieve CE goals. To the best of our knowledge, inclusive analysis on the direct and indirect waste sources across various sectors of an economy—a macro approach—is much less prevalent in the literature compared to micro-level studies such as analysis of a particular case, industry, or waste. A macro-level and integrated framework is urgently on demand to trace waste generation and spot the weaknesses of waste management linking to economic activities of all sectors at a national or regional level. input-output (IO) analysis provides a valuable tool for assessing the potential of CE strategies and quantifying their impacts on waste generation and resource consumption by integrating all economic sectors of an economy.

1.2. Input-output approach for waste management and CE

Within the CE framework, the input-output (IO) model has gained importance, particularly when integrated with life cycle assessment (LCA) and environmental statistics, leading to the environmental extended IO analysis (Çetinay et al., 2020). The waste input-output (WIO) model is a specific application of this approach that has been employed in various national and regional studies. Nakamura and Kondo (2002), who first introduced waste treatment in WIO analysis, highlighted the important contribution of WIO analysis to the CE framework. The application of WIO analysis follows in the UK (Salemdeeb et al., 2016), Wales (Jensen et al., 2013), the National Accounting Matrix including Environmental Account (NAMEA) approach for the Netherlands (De Haan and Keuning, 1996), Germany (Radermacher and Stahmer, 1998), Japan (Nakamura and Kondo, 2002b), Australia (Reynolds, 2013), Taiwan (Liao et al., 2015), and Poland (Gacek, 2025). More research has been done by extending WIO analysis in particular topics. For example, Barata (2002) explored the environmental load related to the waste generation driven by the landfill consumption demand, and Reynolds et al. (2015) applied it on the study of organic waste by treating the charity donation food waste as a waste source.

One of the principles of IO analysis method is to track the material flows of the whole economy and capture patterns of some sectors or industries according to the design of the research target. Therefore, in the sense of waste, researchers can understand waste generation and flows among various sectors in a country by using the WIO method, and the effectiveness of CE development could be compared and measured potentially. This is crucial for improving the circularity of a country (Towa et al., 2020; Vines et al., 2023).

An important aspect often overlooked in waste management studies is the role of secondary waste, which results from intermediate treatments in recycling processes, which include recycling, incinerations, and composting. Secondary waste can be seen as a positive indicator of a high recycling rate, as it represents the byproduct of extensive material recovery efforts. Italy, for example, ranks among the leading European countries in recycling performance. However, an increase in secondary waste could also indicate the existence of some inefficiencies, such as the lack of infrastructure for energy recovery, underdeveloped markets for secondary raw materials, or regulatory constraints like the End-of-Waste (E-o-W) framework. Understanding secondary waste generation and disentangling it for the various sectors is important to assess the effectiveness of circular strategies while improving resource recovery pathways. Another strength of IO analysis method is to capture the direct and indirect contribution to the research target. Hence, the WIO approach is a powerful tool to assess not only the direct but also intermediate attributes to waste generation including secondary waste, and to assess their effects of consumption and production in an economic system (Nakamura et al., 2002a, 2002b; Liao et al., 2015).

The aim of this paper is to construct and analyze the WIO table for the Italian economy, linking data from waste generation data to national economic accounts within the methodological framework initially formulated by Leontief (Leontief, 1936, 1972a, 1972b) and presented for waste management issues by Nakamura and Kondo (1999, 2002a). By referring to harmonized data sources, this study examines various aspects of waste accountability, including the extent to which supply chain length influences waste generation, the movement of resources across different economic activities, and the estimation of industry-specific waste coefficients and multipliers. This will be the first attempt to apply the WIO analysis method to the Italian economy, which fills a gap in the current literature and initiates an analysis on waste management with a macro-approach at the Italian national level. This study also serves as an inspiring step to stimulate more waste data collection from disaggregated industries, so that more in-depth analysis with the WIO method could be carried out in the future. Last but not the least, it sheds the light on the strengths and weaknesses of waste management practices to the stakeholders of different Italian economic sectors and policymakers, who are working to advance the circular transition in Italy.

The remainder of this paper is structured as follows: Section 2 provides a state-of-the-art of the existing literature on IO and WIO analysis methods, outlining the theoretical framework and key empirical findings. The same section describes the data sources and the methodological approach adopted in constructing the WIO table. Section 3 presents the obtained results, highlighting the role of direct and indirect waste as well as the occurrence of secondary waste in the Italian economy. Section 4 concludes by assessing the implications of the findings for policy and research purposes, highlighting the potential of this analysis tool and identifying areas for further investigation.

2. Materials and methods

2.1. State of the art: IO and WIO analysis methods

The CE framework emphasizes the importance of closing material loops, reducing waste generation, and promoting resource efficiency. IO analysis is a valuable tool for assessing the potential of CE strategies and quantifying their impacts on waste generation and resource consumption. Nakamura and Kondo (2002), who first introduced waste treatment in WIO analysis, highlighted the important contribution of WIO analysis to the CE framework. Since then, more research has been done by extending WIO analysis in various topics. For example, Barata (2002) explored the environmental load related to waste generation driven by the landfill consumption demand, and Reynolds et al. (2015) applied it on the study of organic waste by treating the charity donation food waste as a waste source.

Focusing specifically on the analysis of waste arising in industrial sectors, Nakamura et al. (2002a, 2002b) pioneered the introduction of the WIO approach to the flows of goods and waste and waste treatments. The WIO model was first introduced by Nakamura and colleagues when they developed this new model on the extended LCA and a previous study by Leontief (1972a). Nakamura's study on the WIO table for Japan aggregated 13 industrial sectors, 3 treatment methods, and 13 types of waste; therefore, the mapping of waste groups to waste treatment methods was realized, and the corresponding change of economic impacts could be observed by a given change in the input coefficients (Nakamura et al., 2002b). Barata (2002) explored the solid waste generation by economic sectors and final consumption demand in Portugal. He pointed out that the IO approach was able to merge the different economic and environmental dimensions as well as to integrate the structure of different industrial sectors and levels of final demand with total waste generation, hazardous waste generation, and landfill consumption; therefore, he revealed the direct and indirect interactions of waste in the national economy. Inspired by Nakamura's study, Barata not only tried to quantify waste generation by economic sectors and final consumption demand but also explored the environmental load associated with the waste generation exclusively driven by the landfill consumption demand. Similarly, in 2015, Liao and colleagues drew the Taiwan WIO table and tried to highlight the drivers of direct and indirect waste generation from the perspective of the final consumption demand. However, the approach to incorporating the economic sector, waste type, and waste treatment methods or waste species associated with the final demand requires a good amount of quality data; indeed, many studies took one step backward to lay down the initial WIO table of a region or country with the production accounting principle (or "top-down" approach), as seen in Table 1. As Jensen et al. (2013) explained, the single-region WIO model is a useful starting point for direct and indirect waste accounting from industries and consumption behaviors.

The study by Salemdeeb et al. (2016), on which most of the analysis of this paper has been inspired, captured direct and indirect waste arising throughout the supply chain in the UK. It was demonstrated how sectors with a long supply chain with more indirect waste arisings, such as manufacturing and services industries, tended to have higher indirect waste generation compared with primary industrial sectors with a shorter supply chain, which had more direct waste arisings, such as mining, industry, and construction. Similar research has been done in Australia (Reynolds et al., 2016), Spain (Ruiz-Peñalver et al., 2019), South Korea (Lee et al., 2022), and Poland (Gacek, 2025). Most works implemented a top-down approach (waste generation by economic sectors and waste types) in a single-region domestic scope. The WIO table developed for Spain shared high similarity to that of the UK, which estimated waste generation by mapping economic sectors and waste categories. In Reynolds' version, the research focus was placed on MSW and industrial solid waste in Australia. In the version for South Korea, the research target was limited to industrial hazardous waste instead of all waste types, but the authors considered both production and demand perspectives. The latest WIO analysis of the Polish economy in relation to waste generation focused on examining the sectoral independency. The author utilized forward and backward linkages and identified key sectors for waste generation.

Jensen et al. (2013) pointed out that the simple approach of WIO model with economic sectors and waste types could lay down a good base; however, the domestic technology assumption approach could highlight waste generation from imported goods and services. Meanwhile, the consumption accounting principle might give more insights on not only a single region or country, but a multiregional overview. This approach was employed in a study in Australia (Fry et al., 2015) and France (Beylot et al., 2016). Beylot and colleagues extended their table with a more disaggregated framework on products (mainly from French household consumption) and activities (including waste treatment activities) with the consumption accounting principle. Furthermore, their study included a sensitivity analysis with the distinction of waste produced domestically and abroad; in other words, a multiregional approach by including waste generation driven by foreign demand. Fry et al. (2015) quantified the direct and indirect waste footprint instead of waste volume from a consumption accounting perspective across multiple regions in Australia. They displayed the reallocation of the waste footprint from the primary and manufacturing sectors to the trade (retail and wholesale) and service sectors; a similar reallocation was captured from domestic consumers to international consumers. Even within one single country, Australia, the household waste footprint of smaller and less populated regions displayed a higher contribution of waste footprint in other regions.

Some scholars got inspiration from Nakamura's WIO approach and continued in other directions by focusing on the selected waste type. Reynolds et al. (2015) first introduced the material flows of charity within an IO framework. In their study, the Australian food rescue operation by charities was evaluated. They concluded that the food rescue operation was more economical to feed the food insecure than direct purchasing, even though it cost more than landfill or composting by defining charity donations as a waste product. Meyer et al. (2020) developed the United States environmental-extended input-output (USEEIO) model. The model was used to craft only the commercial waste generation table and indicators for specific waste types: hazardous, municipal solid, construction, and demolition debris waste. Table 2 summarizes the different approaches to IO analysis.

In Italy, the implementation of the IO approach to waste management at a national level does not exist. Indeed, Ali et al. (2018) discovered some potential relationships between economic activities and carbon-and-water footprint in Italy with the IO approach. They demonstrated that a huge amount of carbon emissions was related to international trade, and the fastest growth in water use was related to imports in Italy. As for the waste management issue, Ripa et al (2016), using the life cycle assessment approach, explored the solid waste management system and its impacts on the environment in the Metropolitan City of Naples. Their work allowed the identification of critical driving factors of waste and potential improvement strategies. Moreover, the authors reminded that an improvement in a single sector would not be enough to contribute to all impact categories but might shift the burden from one to the other; in other words, waste management must be integrated with all material flows in the society.

Our goal is to propose the first WIO table for the Italian economy, inspired by Salemdeeb's work (2016), with a focus on waste accounting along the Italian supply chain, which serves as the base of the extended work by introducing other disaggregation perspectives or multiregional approaches in the future.

Table 1. IO analysis of waste accounting across countries.

Author(s) and country	Model and methodology	Data sources	Research target
Barata (2002) Portugal	Environmental input-output model - Top-down & bottom-up - Single region - Domestic scope - Selected focus, e.g., hazardous waste, landfill consumption	- Portugal National Institute of Statistics (INE) - Eurostat - Portuguese Environment Department - National Waste Institute (INR) - European Topic Centre on Waste and Material Flows (ETC/WMF)	- Quantification of solid waste by economic sectors and final consumption demand - Quantification of hazardous solid waste within the waste generation - Environmental load associated with the waste generation driven by landfill consumption demand
Liao et al. (2015) Taiwan	Waste input-output model - Top-down & bottom-up - Single region - Domestic scope	- Taiwan IO Table by Industrial Waste Control Center (IWCC) - Ministry of Finance	Assessment of the drivers among the final demand categories on the direct and indirect generation of specific waste spices
Salemdeeb et al. (2016) UK	Waste input-output table - Top-down - Single region - Domestic scope	- 2010 UK input–output analytical tables (Office for National Statistics, 2014) - Environment Data Waste Centre (Eurostat) - EWC-Stat (Eurostat) - UK's Standard Industrial Classification 2007 (ONS, 2007) - Department for Environment, Food and Rural Affair	Quantification of waste arising throughout the supply chain and capturing both direct and indirect arisings
Reynolds et al. (2016) Australia	Input-output table - Top-down - Single region - Domestic scope	- Eora World MRIO database - Department of sustainability, environment, water, population and communities, waste and recycling in Australia 2011 - Environment Protection and Heritage Council and the Department of Environment, Water, heritage and the arts, national waste report 2010 - Inside Waste Industry Report 2011–2012 - Sustainable Resource Use Pty Ltd (SRU)	Estimated quantification of municipal solid waste and industrial solid waste for Australia with disaggregation of economic sectors and waste types
Ruiz-Peñalver et al. (2019) Spain	IO-based hybrid LCA model - Top-down - Single region - Domestic scope	- Eurostat - Spanish National Statistics Institute (INE) - Statistical Classification of Economic Activities in the European Community (NACE Rev. 2) - EWC-Stat (Eurostat)	Estimation of waste generation by economic sectors and waste categories in Spain
Lee et al. (2022) South Korea	Waste-extended input-output model - Top-down & bottom-up (highly aggregated) - Single region - Domestic scope	- Korea Ministry of Environment - Korea Input-Output Table (Bank of Korea)	Coefficients of direct, indirect, and total industrial hazardous waste generation from a production perspective and inducement coefficients from a demand perspective
Gacek (2025)	Waste-extended input-output model (WEIO) - Top-down - Backward & forward linkages - Single region - Domestic scope	- Poland Input-output tables (2010-2018) - OECD (waste generation by individual sectors)	- Key sectors in the Polish economy in terms of waste generation - Waste generation change patterns of the sectors over the investigation period due to policies and implications

Table 2. Extended IO analysis of the waste accountings across the countries.

Author(s) and country	Model and methodology	Data sources	Research target
Fry et al. (2015) Australia	Input-output table with multi-regional waste supply-use framework (MRWSU) - Bottom-up - Multiple region - Domestic and international scope - Selected quantification focus: waste footprint	- Australian Bureau of Statistics (ABS) - Blue Environment and Randell Environmental Consulting (BE) - Hyder Consulting - Sustainable Resource Use Pty Ltd (SRU) - Total Environment Centre (TEC) - Encycle Pty. Ltd	Direct and indirect waste footprint calculation from a consumption-based accounting perspective across multiple regions
Beylot et al. (2015) France	Waste input-output table - Top-down & bottom-up - Multiple region - Domestic and international scope (neighbor countries)	- Eurostat - INSEE - ADEME - WIOD	Assessment of waste generation and treatment induced by French household consumption
Reynolds et al. (2015) Australia	Australian WSUT model, WIO - Top-down - Single region - Domestic scope - Selected focus on food waste accounting in the food supply chain and taking food donation waste as one of the food waste treatments	- Database and IO table (Reynolds et al., 2014) - Foodbank Australia - FAOSTAT database - Wolfram Alpha database - Eora database	- Comprehend the psychical flows of charity within an input-output framework, treating the charity donations as a waste product - Quantify the environmental and economic impacts of food rescue operations in Australia
Meyer et al. (2020) US	Environmental-extended Input-output model - Top-down - Single region - Domestic scope - Selected focus on three solid waste streams	- USEPA - 2014 Generator-Based Characterization of Commercial Sector Disposal and Diversion in California (CalRecycle, 2015) - Quarterly Census of Employment and Wages (QCEW) (Bureau of Labor Statistics) - Census Bureau Value-inPlace (ViP) survey activity classifications (U.S. Census Bureau) - US Bureau of Economic Analysis (BEA)	Waste generation table and indicators to address the commercial waste streams of hazardous, municipal solid, construction, and demolition debris

2.2. Data sources and elaboration

With the aim of obtaining the WIO table for Italy, we referred to two sources of data. First, financial data (in million Euros) were obtained from the Italian IO symmetric table constructed by the Italian National Statistical Office (ISTAT), while waste data were obtained from the Environment Data Waste Centre produced by Eurostat. The IO tables for Italy are available up to the year 2019, while data on waste are available every two years from 2004 up to 2020. As a result, to select the same period of time for both financial and waste data, we referred to the year 2018 as the latest published table and statistics, showing on the one hand the composition of uses and resources across institutional sectors and the inter-dependence of industries within the Italian national economy, and on the other hand waste statistics and composition distinguished by economic activities, classified according to the European Classification of Economic Activities (NACE rev.2) and data collected under the Waste Statistics Regulation.

The 2018 IO table for Italy was disaggregated into 63 industries (branches) according to the NACE classification. However, due to the unavailability of the same high-resolution waste arisings data, these industrial sectors were aggregated into 17 sectors as detailed in Table 2. On the other hand, waste categories for each economic activity are shown in Table 3.

Table 2. Sector classification considered for the analysis (NACE classification, rev 2).

	Sector
(I)	Agriculture forestry and fishing
(II)	Mining and quarrying
(III)	Manufacture of food products, beverages, and tobacco products
(IV)	Manufacture of textiles and related products
(V)	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
(VI)	Manufacture of paper and paper products; printing and reproduction of recorded media
(VII)	Manufacture of coke and refined petroleum products
(VIII)	Manufacture of chemical, pharmaceutical, rubber, and plastic products
(IX)	Manufacture of other non-metallic mineral products
(X)	Manufacture of basic metals and fabricated metal products
(XI)	Manufacture of computers, electronic and optical products, electrical equipment, motor vehicles, and other transport equipment
(XII)	Manufacture of furniture; jewelry, musical instruments, toys; repair and installation of machinery and equipment
(XIII)	Electricity, gas, steam, and air conditioning supply
(XIV)	Water collection, treatment, and supply
(XV)	Waste collection, treatment, and disposal activities; materials recovery; sewerage management, sanitation, and other waste management services
(XVI)	Construction
(XVII)	Services

Table 3. Waste categories for each economic activity (according to the European Waste Classification for statistical purposes).

	Category of waste
1	Acid, alkaline, or saline wastes
2	Animal and mixed food waste
3	Animal feces, urine, and manure
4	Batteries and accumulator wastes
5	Chemical wastes
6	Combustion wastes
7	Common wastes
8	Discarded equipment (except discarded vehicles and batteries and accumulators waste) (W08 except W081, W0841)
9	Discarded vehicles
10	Dredging spoils
11	Glass wastes
12	Healthcare and biological wastes
13	Household and similar wastes
14	Industrial effluent sludges
15	Metal wastes, ferrous
16	Metal wastes, mixed ferrous and non-ferrous
17	Metal wastes, non-ferrous
18	Mineral and solidified wastes (subtotal)
19	Mineral waste from construction and demolition
20	Mineral waste from waste treatment and stabilized wastes
21	Mixed and undifferentiated materials
22	Paper and carboard wastes
23	Plastic wastes
24	Rubber wastes
25	Sludges and liquid wastes from waste treatment
26	Soils
27	Sorting residues
28	Spent solvents
29	Textile wastes
30	Used oils
31	Vegetal wastes
32	Waste containing PCB
33	Wood wastes

In the analysis presented in this paper, we have considered a waste treatment sector (Branch XV in Table 3), whose level of activity depends on the amount of waste treated. Furthermore, it is worth noting that the WIO model introduced is a single-region model with a domestic technology assumption in which the impact of import and export flows on waste is not considered.

2.3. Methodology

The derivation of the WIO table for Italy and the related statistical analysis are carried out following the approach proposed by Salemdeeb et al. (2016) and the mathematical structure based on the principles of the IO analysis (Miller and Blair, 2009). This approach has the potential, according to Salemdeeb et al. (2016, page 1090), "to capture both direct and indirect waste arising across the supply chains", by means of the following Equations:

$$V = LY \tag{1}$$

$$L = W(I - A)^{-1} \tag{2}$$

$$L_{direct} = W(I + A) \tag{3}$$

$$L_{indirect} = W[(I - A)^{-1} - (I + A)] \tag{4}$$

where V represents a vector registering waste arisings (measured in tons) generated as a result of final demand represented by the vector V (million Euros), while L is the vector containing the waste arisings associated with the supply chain. In Equation (2), W is the coefficient matrix describing waste arisings at each stage per monetary unit of output, A is the matrix of technical coefficients, and $(I - A)^{-1}$ is the Leontief inverse coefficient matrix resulting from the Italian 2018 IO table.

It is worth noting that the L_{direct} matrix, which details 33 waste categories (in rows) for each industry, represents the waste generated by suppliers that directly provide inputs to the industry under consideration. According to Salemdeeb et al. (2016), direct suppliers can be defined as those providing inputs that originate from other industries and are necessary for the production process of the investigated industry (e.g., steel sheet coils for manufacturing final products, stainless steel trays).

On the other hand, the matrix $L_{indirect}$ with the same level of detail refers to the indirect suppliers, i.e., suppliers that do not directly supply the industry under consideration but are suppliers to the industry's suppliers (suppliers of the suppliers).

3. Results and discussion

Based on the L-matrix obtained according to Equation (2), the sector generating the highest waste rate is construction with 458.3 tons of waste per million Euros of final demand. Similar evidence was found at a global EU level, with construction contributing 38.4% of the total waste generated in 2022.

Two other sectors contribute to the production of waste; construction is followed by the manufacturing of other non-metallic mineral products (137.18 tons per million Euros of final demand) and manufacturing of basic metals and fabricated metal products (133.8 tons per million Euros).

The economic activity sectors that, on the other hand, generate the least amount of waste in total are the services industry, with an amount of 34 tons of total waste per million Euro of final demand, the mining and quarrying industry (with 39.6 tons of waste per million of final output), and agriculture, forestry, and fishing, with 45.1 tons of waste per million Euros of final output.

By considering the distinction between direct and indirect waste, it is interesting to observe whether and to what extent there is a high level of heterogeneity between sectors and between different production sectors. With reference to indirect waste, it ranges from an amount close to 1% within the water collection, treatment, and supply industry to the highest value recorded for the manufacture of computers, electronics, and optical products, electrical equipment, motor vehicles, and other transport equipment (53%). Within this range, the trend already emerged for the British economy (Salemdeeb et al., 2016) is partially confirmed for the Italian economy, in which sectors with a longer production chain record higher percentages of indirect waste. This is the case, for example, of the manufacture of electronic products and textiles but also foodstuffs and services, while the generation of indirect waste for the primary industrial sector (mining and quarrying), as well as for construction, is relatively smaller (Table 4).

Table 4. Breakdown of total waste into direct and indirect sources: share (% values) per economy activity.

Sector	Direct waste (%)	Indirect waste (%)
Agriculture forestry and fishing	64.10	35.90
Mining and quarrying	89.03	10.97
Manufacture of food products, beverages, and tobacco products	58.39	41.61
Manufacture of textiles and related products	57.17	42.83
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	79.67	20.33
Manufacture of paper and paper products; printing and reproduction of recorded media	72.77	27.23
Manufacture of coke and refined petroleum products	59.88	40.12
Manufacture of chemical, pharmaceutical, rubber, and plastic products	62.87	37.13
Manufacture of other non-metallic mineral products	80.36	19.64
Manufacture of basic metals and fabricated metal products	72.07	27.93
Manufacture of computer, electronic and optical products, electrical equipment, motor vehicles, and other transport equipment.	46.99	53.01
Manufacture of furniture; jewelry, musical instruments, toys; repair and installation of machinery and equipment	55.95	44.05
Electricity, gas, steam, and air conditioning supply	60.09	39.91
Water collection, treatment, and supply	99.18	0.82
Construction	89.63	10.37
Services	55.87	44.13

The granularity of the available data about types of waste enabled us to classify economic sectors based on their contribution to secondary waste generation. According to the EU regulation and taxonomy, secondary waste refers to waste generated from various sources and of different nature, i.e., waste generated in a process that is known as a waste treatment operation. This category includes residual materials originating from recovery and disposal operations, such as incineration and composting by-products. Based on the EU classification reported in Table 3 and according to the EU glossary[1], waste categories that consist entirely of secondary waste are:

- sorting residues, which include waste from mechanical sorting processes, refuse-derived fuels, non-composted residues from composting, etc.;
- mineral wastes from waste treatment, which cover mainly wastes from waste incineration (bottom ash, slag, fly ash, etc.), mineral fractions from mechanical treatment, and solidified, stabilized or vitrified wastes; wastes from co-incineration are not included here but covered by the category combustion waste;
- sludges and liquid wastes from waste treatment comprises wastes from chemical-physical treatment of hazardous waste, liquids and sludges from anaerobic waste treatment, landfill leachates, etc.

Using this classification, we ranked the economic sectors of the Italian economy based on their contribution to secondary waste generation. Overall, aggregated data from Eurostat indicates that of the total tons of waste generated, approximately 69% consists of primary waste, whereas the remaining part is secondary waste. Indeed, the proportion of secondary waste can represent a proxy for assessing the efficiency of the overall waste management cycle, encompassing industrial, institutional, and regulatory-administrative aspects[2].

A high-level degree of heterogeneity is observed across sectors. When analyzing total waste generation per capita, it was found that the highest percentage of secondary waste, after the water collection, treatment, and supply sector, is recorded in agriculture and services, where 36% of total waste originated from secondary (waste) sources. Conversely, the construction sector exhibits the lowest share, only 5% (Table 5).

Table 5. Generation of secondary waste (EU classification): percentage over the total amount of waste generated per sector.

Sector	% (out of the total waste)
Agriculture forestry and fishing	35.58
Mining and quarrying	21.83
Manufacture of food products, beverages, and tobacco products	27.56
Manufacture of textiles and related products	33.33
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	13.88
Manufacture of paper and paper products; printing and reproduction of recorded media	20.48
Manufacture of coke and refined petroleum products	26.77
Manufacture of chemical, pharmaceutical, rubber, and plastic products	26.14
Manufacture of other non-metallic mineral products	14.30
Manufacture of basic metals and fabricated metal products	24.22

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[1] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Secondary_waste.

[2] https://www.sipotra.it/wp-content/uploads/2025/01/Rifiuti-e-pil-perche-litalia-produce-piu-rifiuti-tra-i-grandi-paesi-ue.pdf.

Sector	% (out of the total waste)
Manufacture of computer, electronic and optical products, electrical equipment, motor vehicles, and other transport equipment.	27.95
Manufacture of furniture; jewelry, musical instruments, toys; repair and installation of machinery and equipment	24.13
Electricity, gas, steam, and air conditioning supply	30.55
Water collection, treatment, and supply	52.47
Construction	5.14
Services	36.20

Furthermore, we distinguished between secondary waste originating from a sector's activities and that generated indirectly through intersectoral linkages (Table 6). The use of these classifications aligns with key CE metrics, as they reflect material flows relevant to recycling targets established under the EU's Waste Framework Directive. Analyzing the share of secondary waste produced directly by each sector further provides insights into the effectiveness of recycling practices, resource circularity, and progress toward EU recycling benchmarks.

Table 6. Generation of secondary waste (EU classification): percentage from direct and indirect waste.

Sector	Direct waste (%)	Indirect waste (%)
Agriculture forestry and fishing	62.64	37.36
Mining and quarrying	78.16	21.84
Manufacture of food products, beverages, and tobacco products	41.88	58.12
Manufacture of textiles and related products	48.73	51.27
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	48.79	51.21
Manufacture of paper and paper products; printing and reproduction of recorded media	50.37	49.63
Manufacture of coke and refined petroleum products	38.02	61.98
Manufacture of chemical, pharmaceutical, rubber, and plastic products	47.26	52.74
Manufacture of other non-metallic mineral products	50.97	49.03
Manufacture of basic metals and fabricated metal products	54.37	45.63
Manufacture of computer, electronic and optical products, electrical equipment, motor vehicles, and other transport equipment.	31.52	68.48
Manufacture of furniture; jewelry, musical instruments, toys; repair and installation of machinery and equipment	35.18	64.82
Electricity, gas, steam, and air conditioning supply	50.33	49.67
Water collection, treatment, and supply	99.31	0.69
Construction	48.37	51.63
Services	54.00	46.00

From the analysis, high levels of secondary waste from direct activities are observed in mining and quarrying, agriculture, and services. On the other hand, lower levels are recorded in the manufacture of furniture, jewelry, musical instruments, and toys, and repair and installation of machinery and equipment. The latter categories are major contributors to waste electrical and electronic equipment (WEEE), which require specialized treatment centers capable of adopting the best available techniques for waste treatment, recovery, and recycling.

The integration of IO analysis with the CE concept provides a robust framework to improve waste management practices. This methodological approach allows for a detailed assessment of material and energy flows enabling the identification of waste prevention opportunities and the evaluation of the environmental and economic performance of circular strategies. By quantifying direct and indirect waste generation across sectors, IO analysis supports researchers and policy makers in designing targeted interventions to enhance resource efficiency and sustainability.

The findings of this study highlight a dual interpretation of secondary waste generation in Italy. On the one hand, high levels of secondary waste production can be seen as an indicator of an effective waste recycling system: Italy ranks among the top European countries for recycling rates, and the significant volume of secondary waste is partly due to extensive pre-recycling treatment processes needed to facilitate material recovery. On the other hand, as noted in REF (2025) the reliance on intermediate treatment processes may also reflect structural changes, such as the lack of energy recovery facilities or the underdeveloped secondary raw material markets. However, there is a high level of heterogeneity among regional levels: for example, Lombardy in the Northern Italy represents a best-practice, with over 3,000 treatment and recovery plants ensuring almost complete regional self-sufficiency; less than 3.5% of municipal waste ends up in landfills, with over 84% recovered through material or energy processes (ISPRA, 2023). On the other hand, Sicily lacks energy recovery facilities entirely and still sends more than 51.5% of its municipal waste to landfills, despite recent improvements in recycling collection (ISPRA, 2023, REF, 2025). Similarly, Lazio and Campania face difficulties closing their waste cycles, exporting approximately 14–25% of their municipal waste to other regions for treatment (CDP, 2023). These examples highlight how a high level of secondary waste output can either indicate advanced recycling performance with appropriate infrastructure (as in Northern Italy) or signal critical infrastructural gaps (as seen in the Southern regions). Additionally, weak markets for secondary raw materials further contribute to transforming potentially reusable materials into residual waste (Circular Economy Network and Fondazione per lo Sviluppo Sostenibile, 2024). These combined factors underscore the need for effective waste management strategies that integrate infrastructure development with market and policy interventions.

4. Conclusions

This study highlights the potential of IO analysis as a strategic tool for advancing CE policies.

Adopting a systems perspective through IO analysis will offer valuable insights for policymakers and practitioners, enabling the development of waste management strategies that minimize environmental impacts while fostering resource circularity. The ability to capture inter-sector linkages and track waste flows provides a comprehensive understanding of waste generation patterns and their implications for the Italian economy. The use of IO analysis can also spot the strengths and weaknesses among various economic sectors in Italy, which can be referenced by the policymakers and industrial stakeholders to prioritize waste management practices under the guidelines of EU's CEAP.

Despite its strengths, this study also presents certain limitations. While secondary waste data are available, it could remain incomplete, as not all secondary sources waste streams are always recorded (Sileryte et al., 2022). This is not uncommon when researchers apply the IO framework on national economy studies or other particular topics. Data availability, data quality, and update frequency are the foundation of IO analysis methods, but also the key to CE actions (Vines et al., 2023). However, this analysis relies on the most comprehensive dataset currently available and accessible. Future research should further explore the balance between direct and indirect waste production within the same industry and across branches. Additionally, improved data availability in national accounts would enable researchers with a more detailed examination of resource flows along supply chains, thus enhancing the accuracy and applicability of IO-based waste assessments. This is also a meaningful intake for Italian policymakers who might consider improving the data availability and quality related to national accounts and encourage data collection among inter-sectoral and inter-organizational material and energy flows (Korhonen et a., 2018). As the first attempt to implement the WIO analysis method for Italian waste management, this paper is a preliminary effort. The research can be enriched by applying other extended IO models to the same dataset for a comparison study; furthermore, it will be interesting to carry out a comparative study by using the WIO approach and other mainstream analysis methods.

Based on the results of our analysis, further exploration should consider tailored measures for Italy, such as promoting the use of prefabricated and modular components in the construction sector (Tavares et al., 2025) or strengthening extended producer responsibility (EPR) schemes for electronic waste (WEEE), drawing on Germany's advanced recycling networks.

Further development and future research on this topic should address several important aspects. First, it will be crucial to explore the model assumptions underlying the WIO framework such as static intersectoral relationships, to better understand their influence on sectoral contributions and waste flow estimates. Additionally, expanding the geographical scope beyond Italy will help assess the generalizability of the findings to other countries with comparable waste management systems. By improving data collection and integrating waste management strategies within broader economic planning, Italy can further enhance its position as a leader in sustainable resource use and waste reduction. Indeed, incorporating a sensitivity or uncertainty analysis, following approaches such as those presented by Ferrari and Secondi (2017), would enhance the robustness of the results, allowing for a more comprehensive evaluation of the model's strengths and limitations.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

All authors declare no conflicts of interest in this paper.

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