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Review

Life Cycle Sustainability Assessment of municipal solid waste management systems: a review

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ABSTRACT

In the context of Circular Economy, the significance of municipal solid waste management systems (MSWMSs) has increased, as well as the need for comprehensive assessment tools of their sustainability. In the Life Cycle Thinking (LCT) framework, the Life Cycle Sustainability Assessment (LCSA), which is a methodology aiming to evaluate the environmental, economic, and social burdens throughout the various phases of waste management, has raised great interest. The paper describes the state-of-the-art of the implementation of LCT tools, with high regard to LCSA, for the evaluation of MSWMSs through their life cycle, with a deep focus on the use of both midpoint and endpoint categories. Drawing insights from an analysis of 69 case studies, the paper identifies the most frequently applied midpoint and endpoint categories for the sustainability assessment of MSWMSs. These categories are exposed in terms of their significance and applicability to specific waste management scenarios, providing valuable guidance for experts and researchers seeking to employ LCSA in MSWMSs assessments. Additionally, the paper outlines the limits associated with the implementation of LCSA, thereby highlighting areas for further research and improvement. In contrast to other reviews in this field, this paper uniquely focuses on the implementation of LCSA in the specific context provided by MSWMSs. By disseminating such insights, the paper aspires to foster the widespread adoption of LCSA by experts and researchers, ultimately advancing the sustainability discourse in municipal solid waste management.

1. Introduction

During the last century, demographical growth, together with the improvement of economic conditions and urban migrations, has led to a worldwide increase in the generation of waste, including municipal solid waste (MSW). This is generally assumed to consist of household waste (organic waste, paper, plastic, etc.) and similar waste generated by small businesses and institutions (Wilson et al., 2015).

According to the World Bank, around 2.1 billion tons/year of MSW were produced in 2016 and, in a business-as-usual scenario, this value could be over 3.4 billion tons/year in 2050. The proximity of the urban population to this increasing amount of MSW, throughout its life cycle, calls for the identification of sustainable handling strategies, as improper management can lead to pollution, health and safety issues, and longer-term issues, such as climate change (Al-Maaded et al., 2012; Maalouf and El-Fadel, 2019).

Multiple solutions have been thus developed to promote the sustainability of municipal solid waste management systems (MSWMSs), such as the Waste Hierarchy system, which has encouraged local authorities to prioritize waste prevention, reuse, and recycling over energy recovery and disposal since the 1980s. This system was later conveyed into the larger frame of circular economy (CE), an economic system that was popularized at the beginning of the 1990s (Winans et al., 2017). CE is opposed to linear economy, a model that characterizes modern society globally and in which resources are manufactured into valuables that are disposed of at the end of their life cycle. Instead, CE aims at drastically reducing the depletion of natural resources by reusing and recycling materials that are already part of the value chain and that otherwise would be discarded as waste. Indeed, one of the main aims of CE is to treat waste as a valuable resource, instead of unwanted material (Awino and Apitz, 2023).

The implementation of CE practices in MSWM could potentially lead to environmental and socio-economic benefits, as it would protect the economy from the scarcity of resources and maximise the value of products by extending their lives, generating new jobs for different skill levels, and reduce the impact on the environment, while also promoting social inclusion (European Commission, 2015), thus helping institutions meet sustainability goals. Different CE strategies can be applied to MSWM. Nonetheless, the identification of the optimal one - as that pursuing the highest degree of sustainability – may be challenging. An environmentally friendly solution may turn out to be either not economically competitive or socially acceptable; moreover, its effects on the environment and the society, as well as on the economy, would be site-specific, making it not valid in different geographical areas and contexts. To evaluate the impacts of possible MSWM options targeting CE principles on the environment, the economy, as well as the society, researchers and policymakers have developed different sustainability

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List of abbreviations

AoP	Area of Protection
CAPEX	capital expenditures
CE	circular economy
eLCA	environmental life cycle assessment
eLCC	environmental life cycle cost
fLCC	financial life cycle cost
LCC	life cycle cost
LCOE	levelized cost of energy
LCSA	life cycle sustainability assessment
LCT	life cycle thinking
MCDM	multicriteria decision method
MSW	municipal solid waste
MSWMS	municipal solid waste management system
NATO	National Atlantic Treaty Organisation
NIMBY	not in my backyard
OELEX	end of life expenditures
OPEX	operational expenditures
RC	reducing cost
sLCA	social life cycle assessment
sLCC	social life cycle cost
UNEP	United Nations Environment Programme
WMS	waste management system
WtE	Waste-to-Energy

assessment frameworks and tools following the definition of sustainability provided by the World Commission on Environment and Development (Keeble, 1988) The most interesting approaches are framed in the Life Cycle Thinking (LCT) and rely on science-based tools meant to provide a holistic view of the potential impacts on the three pillars of sustainability, that could occur throughout the life cycle of products, processes, or waste. In the latter case, the life cycle normally includes collection, transportation, temporary storage, potential energy or material recovery, and landfill disposal (Taelman et al., 2020), which are the main stages of a WMS.

LCT-based tools as the environmental Life Cycle Assessment (eLCA), the Life Cycle Costing (LCC), or the social Life Cycle Assessment (sLCA) have been developed to assess the impact on single pillars of sustainability. The application of such tools to MSWMSs, which has been detailed further in this work, results in partial assessments of their effects on the different aspects of sustainability, limiting their effectiveness as decision-supporting tools. Thus, the Life Cycle Sustainability Assessment (LCSA) has been proposed as well, with the aim of following all the phases of the waste life cycle, quantifying, and describing its impacts on the environment, economy, and society collectively.

Presently, there are two main ways of conducting an LCSA: either leading separate impact studies, each one addressing one of the three sustainability pillars, or conducting a single cohesive study on all these aspects (Kloepffer, 2008). In both cases, it is possible to follow the procedure defined in the ISO 14040 and ISO 14044 standards for eLCA (Liu et al., 2013; Valdivia et al., 2021) and consisting of four phases: goal and scope definition, inventory analysis, impact assessment, and result interpretation.

The first phase, the goal definition, identifies the main reasons for the study, as well as its final beneficiaries, while the scope definition entails the proper selection of the so-called functional unit, which describes the quantity of product or service to which all the impact flows will be referenced and reconducted to. Then, it is necessary to establish what production processes of the life cycle should be involved in the assessment, drawing the geographical, temporal, and technological boundaries of the analysis: in this way, the foreground system is figured out. Based on the set goal and scope, the inventory analysis consists of collecting data and information, from multiple sources, about the physical input and output flows (resources, material, emissions, waste, products, by-products, etc.) that are relevant to the life cycle phases previously included in the foreground system. All these streams are scaled in regard to the functional unit and can be used to quantify the impact on several categories. In fact, during the following step of the impact assessment, it is possible to convert the physical flows and interventions of the life cycle into impacts, by assigning them to the impact categories, which are classes representing issues of concern for the environment (e.g. global warming), the economy (e.g. economic revenues), or the society (e.g. equity) (Oliveira and Souza, 2023). These are divided into midpoint and endpoint categories, respectively characterised by a higher and lower data accuracy (Huijbregts et al., 2017), which can be used complementarily, as they represent different phases of the impact pathway: midpoint categories refer to the effects caused by the inventory flows that produce aggregated impacts, while endpoint categories represent the Areas of Protection (AoP), i.e. areas of concern affected by midpoint impacts, individually or in combination (ISO, 2006; McClelland et al., 2018).

According to the ISO 14044, the choice of the impact categories needs to ensure - among other requirements - that they: i) are not redundant and do not lead to double-counting, ii) do not disguise significant impacts, iii) are complete, and iv) allow traceability. To meet these requirements, several methods have been developed over time, but still some overlapping in the use of indicators and impact categories can be recognized, especially when LCSA is applied (Liu et al., 2013). This condition may represent a constraint when the overall sustainability of MSWMSs needs to be assessed as a strategy to support the transition from linear to CE. In this regard, the application of selected LCT tools may provide incomplete indications, whereas the use of the same indicators or parameters to evaluate the impacts belonging to different categories (namely environment, society, and economy) may result in undesired double-counting effects, making the impact assessment less reliable (Reich, 2005; Woon and Lo, 2016).

In this context, there is a need for a consistent and integrated approach to LCSA, able to meet the complexity of comprehensive impact assessment. To the best of the author's knowledge, few attempts in integrating environmental, economic, and social impact categories into a LCSA method, i.e., a set of impact categories and well-defined characterisation models, have been proposed for MSWMSs, but none of them is mainstream neither in research nor in practice. To promote LCSA as a LCT tool to evaluate the extent to which CE is applied at MSWMSs, this work proposes, for the first time, an extensive review of the efforts provided in this direction. Studies reporting the application of either single or combined LCT tools to both MSWMSs and their relevant phases were collected and used to draw the key elements driving the impact assessment. The results of this analysis served the identification of the main advantages and drawbacks of the different impact categories and laid the basis for a critical discussion of the current scientific gaps that need to be filled for the definition of a comprehensive and effective LCSA tool for MSWMS.

2. Methodology

2.1. The approach

This review is based on an extensive literature search, leading to the selection and analysis of 69 case studies. The research of the most suitable scientific papers was conducted through Google Scholar, Scopus, and Web of Science and it included the following terms, as well as their variations and acronyms, as keywords: “Life Cycle Sustainability

Assessment", "Life Cycle Cost", "Social Life Cycle Assessment", and "Sustainability Assessment", in combination with the terms "Municipal Solid Waste", "Urban Waste", "Municipal Solid Waste Management".

As the first scientific reports about LCSA date back to the early 2000s (Costa et al., 2019), papers published between 2005 and 2023 were selected.

All these papers share common features.

1) they compare different options for the management of MSW, or its fractions (i.e., food waste, plastic, etc.).
2) all case studies claim to assess the sustainability of MSWMSs, even though not all of them are proper LCSA studies. Indeed, some reports focus on all pillars of sustainability by applying multicriteria decision methods (MCDM), while others focus on one or two pillars of sustainability, implementing multiple LCT tools separately or in combination.

Differences in the system boundaries were not used as an exclusion criterion, as all case studies focus on different phases of the MSW life cycle. More specifically, 24 papers deal with comprehensive MSW systems, including stages such as collection and transportation, prevention strategies, or the generation of products out of the recovery process (e.g. energy production); target treatment options (recycling, landfilling, etc.) and collection schemes were considered in 26 and 6 studies, respectively.

For the analysis of the case studies, these were divided into groups based on the MSW fraction that was considered, the width of the life cycle system boundaries, and the aspects of sustainability for which the impact was assessed. The years of publication and the geographical areas where the cases were located were also investigated, to identify trends in the implementation of sustainability assessment approaches.

From each scientific paper, the impact categories - midpoint and endpoint - were identified and classified in accordance with the environmental, economic, or social connotation attributed to them in the study, with the aim to identify the most used impact categories for MSWMSs worldwide for each pillar of sustainability. The corresponding indicators, or measures representing phenomena of interest (Heink and Kowarik, 2010), were also identified and further discussed in the Supplementary materials.

2.2. Publication trend

The distribution over time of the selected papers highlights that since 2005 there has been an increase in the number of publications dealing with the sustainability assessments applied to MSWMSs. This shows a growing interest in both sustainability and the implementation of LCT principles in MSWMSs, and it is reasonable to expect a rise in the number of papers and case studies on this topic (see Fig. 1).

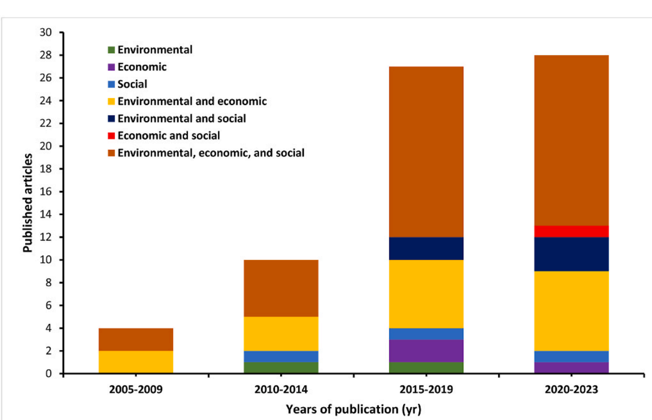

Fig. 1. Case studies distribution over the years 2005–2009, 2010–2014, 2015–2019, 2020–2023.

2.3. Geographical distribution of case studies

In accordance with the approach followed in LCT tools, each study is set in a well-defined geographical context, namely a specific city, region, or country, while some papers deal with the implementation of sustainability assessment methodologies in multiple places, as shown in Table 1.

Table 1
Distribution of case studies per country.

Country	Number of case studies	References
Italy	10	(Degli Esposti et al., 2023; Demichelis et al., 2022; Di Maria et al., 2020; Gadaleta et al., 2022; Magrini et al., 2021; Rigamonti et al., 2016, 2019)
China	7	(Dong et al., 2014; Li et al., 2015; Nie et al., 2018; Z. Wang et al., 2020; Yu and Li, 2020; Zhao et al., 2011; Z. Zhou et al., 2019)
Brazil	5	(Angelo et al., 2017; Ibáñez-Forés et al., 2019; Paes et al., 2020; Prateep Na Talang and Sirivithayapakorn, 2021; Santos et al., 2017)
Iran	4	(Mirdar Harijani et al., 2017; Mozaffari et al., 2023; Rahimi et al., 2021; Shahivand and Rouhani, 2020)
Spain	4	(den Boer et al., 2007; Fernández-González et al., 2017; Pons et al., 2018; Vinyes et al., 2013)
India	3	(Chhabra et al., 2021; Prateep Na Talang and Sirivithayapakorn, 2021; Sharma and Chandel, 2021)
Peru	3	Aparcana and Salhofer (2013)
Sweden	3	Reich (2005)
Nigeria	3	(Ayodele et al., 2018; Nubi et al., 2022b)
Greece	2	(den Boer et al., 2007; Tsilemou and Panagiotakopoulos, 2007)
Hong Kong	2	(Lam et al., 2018; Woon and Lo, 2016)
Indonesia	2	(J. Wang et al., 2018; Zurbrügg et al., 2012)
Mexico	2	(Botello-Álvarez et al., 2018; Tsydenova et al., 2018)
Serbia	2	(Milutinovic et al., 2016; Stefanović et al., 2016)
Thailand	2	(Menikpura et al., 2012a; Prateep Na Talang and Sirivithayapakorn, 2022)
USA	2	(Alamu et al., 2021; Berardocco et al., 2022)
Afghanistan	1	Azimi et al. (2020)
Argentina	1	López de Munain et al. (2021)
Australia	1	Edwards et al. (2018)
Belgium	1	Sanjuan-Delmás et al. (2021)
Bulgaria	1	Milutinovic et al. (2016)
Czech Republic	1	Zilka et al. (2021)
Denmark	1	Martinez-Sanchez et al. (2016)
Ecuador	1	Jara-Samaniego et al. (2017)
Germany	1	Sanjuan-Delmás et al. (2021)
Hungary	1	Sanjuan-Delmás et al. (2021)
Japan	1	Ahamed et al. (2016)
Kenya	1	Ddiba et al. (2022)
Kuwait	1	Aleisa and Al-Jarallah (2018)
Lebanon	1	Maalouf and El-Fadel (2019)
Lithuania	1	den Boer et al. (2007)
Netherlands	1	Tonini et al. (2020)
Poland	1	den Boer et al. (2007)
Portugal	1	Ferrão et al. (2014)
Qatar	1	Al-Maadeed et al. (2012)
Russia	1	Tulokhonova and Ulanova (2013)
Slovakia	1	den Boer et al. (2007)
Sri Lanka	1	Menikpura et al. (2012b)
Turkey	1	Yıldız-Geyhan et al. (2019)
United Arab States	1	Abdeljaber et al. (2022)
Wales	1	Emery et al. (2007)

Only one of the selected case studies (Makan and Fadili, 2020) describes a complete system of impact categories for sustainability assessment without applying it to a specific physical location. Additional two reports focus on the WMS implemented in unusual contexts, namely North Atlantic Treaty Organisation (NATO) warships (Bilgili, 2020) and the Hong Kong Airport (Lam et al., 2018). Finally, average European data were used in two papers (Albizzati et al., 2021; Manfredi and Cristobal, 2016).

2.4. Relevance of the environmental, economic, and social pillars of sustainability

Among the analysed papers, 90% include environmental indicators and impact categories, 87% deal with the economic aspect of sustainability, and only 67% deal with the social impact of MSWMSs, a value that can be easily justified by the lack of normative on the implementation of sLCA, as the first proper guidelines for social assessment were published by the United Nations Environment Programme (UNEP) in 2011 (Benoît Norris et al., 2020). Even though approximately 12% of papers focus on a single pillar, more than half of the analysed case studies can be considered LCSAs, as they include indicators and impact categories related to all pillars of sustainability (Table 2).

3. Environmental assessment of MSWMSs

3.1. Environmental LCA

The environmental pillar of sustainability has been largely investigated and assessed in the field of MSWMSs, through the application of the environmental LCA (eLCA), which uses several types of impact categories focusing on environmentally relevant aspects (Zhang et al., 2021). Usually, the attribute "environmental" is redundant when discussing LCA as, since their initial development, the LCT tools have focused on defining exclusively the environmental impact through life cycles. Recently, the use of eLCA has become increasingly popular, as it provides useful information to policymakers, businesses, and consumers, who need guidance in identifying environmentally friendly products (Benoît Norris et al., 2020; Olivier et al., 2016).

In the following paragraphs, the midpoint and endpoint impact categories were drawn from the analysed case studies and their use within eLCA was critically discussed.

3.2. Environmental midpoint impact categories

The use of suitable environmental indicators is expected to be reflected in relevant impact categories. The use of midpoint ones for the environmental assessment of MSWMSs is largely diffused. While several authors selected standardised LCIA methods, others preferred establishing their own collections of impact categories (Tab. S2) (Owsianiak et al., 2014). The availability of data and indicators affects the choice of the impact categories. Similarly, the choice of the midpoint categories has a strong influence on both the impact assessment and result interpretation phases, since differences in the characterisation models can even lead to different LCIA results (Owsianiak et al., 2014). A narrow set of impact categories tends to simplify the result interpretation, but it may also ignore relevant burdens of the life cycle. Therefore, the number and types of impact categories should be chosen based on the level of knowledge of the life cycle and its identifiable hotspots (Angelo et al., 2017).

Table 2
Distribution of case studies with regard to the investigated sustainability pillars.

Assessment type	Percentage of related case studies
Environmental assessment	3%
Economic assessment	4%
Social assessment	4%
Environmental and economic assessment	26%
Environmental and social assessment	7%
Economic and social assessment	1%
Sustainability assessment	54%

Even though a limited number of case studies used methods as the Carbon Footprint, which focuses exclusively on the global warming impact, or the IMPACT 2002+, that includes the "climate change" among its endpoint impact categories, the analysis of the selected papers revealed that some of the most largely applied LCIA methods for the evaluation of MSWMSs are the CML, ReCiPe, and ILCD methods. They all include the impact categories "acidification", "climate change", "resource depletion", "ecotoxicity", "eutrophication", "human toxicity", "ozone layer depletion", and "photochemical oxidation" (Acero et al., 2016; Jolliet et al., 2003).

Most of these categories are extensively used for the environmental assessment of MSWMSs, even when standardised methods are not applied. The reason behind this choice may be partly due to the accessibility of most data to quantify such impact categories and partly due to their effectiveness in accurately representing the most common environmental burdens of different waste management scenarios.

The most used impact categories for the land compartment, are related to its usage (Chhabra et al., 2021; Dong et al., 2014), also indicated as "use-saving" (Ayodele et al., 2018), "consumption" (Menikpura et al., 2012a), "occupation" (Fernández-González et al., 2017), and its "transformation" (Bilgili, 2020), or "degradation" (Rahimi et al., 2021). The analysis of the case studies highlighted the relevance of these impact categories to assess the environmental effects of new MSW plants construction; also, this kind of impact becomes fundamental when landfilling is involved in the waste management strategy under investigation, as it requires larger spaces in comparison to other waste handling options. Nonetheless, when evaluating the impact associated with variations to already existing treatment plants, it is not possible to omit these categories, as certain treatments, such as recycling or energy recovery, allow to minimise the impact on land transformation, as they allow to reduce the resources necessary from land. Usually, the impact categories dealing with land use refer to its transformation and to the consequential loss of soil (arable, natural, forest, etc.), which can be expressed in terms of either surface area or soil organic carbon content (SOC). The categories are representative of the generation of carbon emissions from the terrestrial ecosystem to the atmosphere and of the altered capacity of land to adsorb GHG emissions from the air, but presently there is no unanimity on the framework for evaluating the impact of land use and transformation on soil quality and, for this reason, several case studies, express this indicator simply in terms of lost surface (Bessou et al., 2020; Brandão et al., 2022). For example, Chhabra et al. (2021) found that the land used for pyrolysis of unsorted waste in India can be up to 24 kg SOC for one tonne of MSW, while Bilgili (2020) observed that recycling processes for waste generated on warships can spare up to 6 km^2 of forest land, compared to the base scenario for which most waste is directly thrown in the sea.

A commonly assessed midpoint category is "water depletion", which is expressed in units of volume (Chhabra et al., 2021). The water consumption is determined from the volumes of water used during the different waste management activities, which are then summed up to establish the impact on the entire life cycle (Ferrão et al., 2014). Differently, in the study of Chhabra et al. (2021) that focused on the sole treatment phase, a specific volume of used water was established, equal to 0.94 m^3 per ton of treated waste. Another study where such category provided an interesting result was that of Sanjuan-Delmás et al. (2021), comparing the prevention of organic waste to both traditional and innovative treatments. In this case, it was observed that the prevention of organic waste generation can determine a reduction of impact on the "water use" category in comparison to the reference scenarios (Tonini et al., 2020). Theoretically, prevention strategies could be applied to other types of urban waste, reducing the impact on this category, whose relevance is dependent on the water availability of the area where a

MSWMS is set. While the category "water depletion" focuses on the amount of consumed water, another less popular midpoint category, "water quality" (Rahimi et al., 2021), describes the content of organic matter in water due to the interaction with waste management activities and consequently its impact on the environment or the need for severe wastewater treatment activities. For this reason, Makan and Fadili (2020) and Prateep Na Talang and Sirivithayapakorn (2021), evaluated the presence of leachate (i.e., the liquid produced during composting or landfilling), and the environmental impact caused by the treatment of wastewater from WMSs.

The categories describing the impacts on the atmosphere, namely "ozone depletion" (Rosenbaum et al., 2018), "photochemical oxidation" (Nubi et al., 2022a), "particulate matter formation", and "ionizing radiation" (Abu Bakar et al., 2019), are broadly accepted and prevalent in the environmental assessment of MSWMSs. These categories refer to natural phenomena influenced by the release in the atmosphere of specific substances, that are produced during the different phases of waste management and treatment, including the transport and collection phases. The "global warming" category belongs to the atmosphere compartment too, and it is one of the most used in MSWMS environmental assessment, as it represents the impact in terms of equivalent carbon dioxide of emitted greenhouse gases and has direct effects on climate change. It is also labelled as "GHG emissions" (Tsydenova et al., 2018) and "climate change" (Li et al., 2015), while "avoided CO_2 emissions" can be found as well (Magrini et al., 2021). To limit the amount of GHG emissions released in the air, legislative norms have been widespread, linking this environmental category to both the economic and the social pillars of sustainability as well: indeed, the presence of norms influences the commitment of the local governments and the fees normally associated to such legislations are monetary transfers (Annicchiarico and Di Dio, 2017). Even though this category should be used for the sustainability assessment of all types of waste treatments and all phases of MSWMSs, it is particularly relevant when studying either the biogas recovery or incineration treatments as they are responsible for the generation of a great number of dangerous emissions. It provided an interesting insight on recycling practices as well, as several studies proved that recycling cuts the impact on global warming, due to the reduction of materials and fossil fuels necessary to process raw materials, meaning that in this case, the prevented impacts determine positive effects on this category (Alamu et al., 2021; Ayodele et al., 2018; Botello-Álvarez et al., 2018). In general, the atmosphere-related categories have a strong influence on the "human health". For instance, it has been observed that when implementing incineration, "global warming" is responsible for 90% of the health damage, due to the large emissions derived from the combustion of different materials (Menikpura et al., 2012a).

The "eutrophication", "acidification", and "ecotoxicity" impact categories are also extremely common among LCA applications of all kinds, as they are often included in standardised LCIA methods (Zhang et al., 2021). Nonetheless, as these categories describe impacts depending on the emission flows of pollutants and their damage pathways, they are largely used to assess the environmental sustainability of MSWMSs. Indeed, it is possible to evaluate the impact on each category based on the affected ecosystem: air, aquatic (freshwater and marine), and terrestrial ecosystems (Bilgili, 2020; Manfredi and Cristobal, 2016; Yıldız-Geyhan et al., 2019). Consequently, a proper evaluation of the impact on these categories for every ecosystem should be based on a deep knowledge of the damage pathways of multiple substances. Otherwise, it is possible to assess the impact on each category in terms of an equivalent mass of substances released into the environment, without distinguishing among the affected ecosystems. Even though this is a more generic approach, it is easier to apply, as it only focuses on the emitted substances and not on their path and destination.

Assessing the impact on the eutrophication category is fundamental when the waste management process aims to recover and use fertilizers from organic waste. The proper management of this type of waste is indeed essential to prevent the uncontrolled release of nutrients in the environment, which is the main cause of eutrophication and affects especially the aquatic environments (Maalouf and El-Fadel, 2019; Sanjuan-Delmás et al., 2021; Z. Wang et al., 2020). The acidification considers all the acidifying substances that can be emitted from either waste degradation or waste treatments. Incineration, biogas production as well as waste transport are the MSWM stages which can generate pollutants that interact with water vapor in the air to form acids (Menikpura et al., 2012b; Yu and Li, 2020). Finally, the ecotoxicity impact depends on the substances discharged in the ecosystems, which is associated to several MSWMS phases, including transportation, landfilling, and incineration, which causes a high release of heavy metals in the atmosphere determining a strong impact on this category (Bilgili, 2020; Dong et al., 2014; J. Wang et al., 2018).

Another relevant group of impact categories is the one pertinent to the effects of MSWMSs on human health. The categories "human health cancer", "human health non-cancer", "human health respiratory pollutants", and "human health toxicity" depend on both the characteristics of the substances spread in nature and their specific effects on human health (Alamu et al., 2021; Chhabra et al., 2021; Prateep Na Talang and Sirivithayapakorn, 2021; Z. Wang et al., 2020). The variety of pollutants that are dangerous for human health is wide and they can reach the population through several pathways, including inhalation and ingestion. Besides, it is not simply the people living closer to waste treatment plants, especially incineration plants, but also those living in the nearby areas that can be exposed to human health risks (Alamu et al., 2021; Ddiba et al., 2022). Improper waste management (e.g., open dumping and open burning) has been observed to have the worst health-related impacts (Prateep Na Talang and Sirivithayapakorn, 2021). Independently from the type of waste treatment or WM phase being evaluated, it is relevant to consider the impact on these categories, as the health of the people should be a priority for sustainability assessments.

The pertinence of these categories to the environmental pillar of sustainability is due to the tight link between the release of harmful substances in nature and people's physical health. Nonetheless, as pollution could negatively impact people's physical health, the human health impact categories have a social connotation as well.

The impact of MSWMSs on the resources is evaluated through multiple impact categories, either related to the consumption or the recovery of different kinds of resources. Indeed, the following categories are determined not only from the consumption of resources, but also from their recovery through waste treatments, in particular through reuse and recycling (Maalouf and El-Fadel, 2019).

The "abiotic depletion" (Edwards et al., 2018; J. Wang et al., 2018) and the "abiotic depletion (fossil fuel)" (Dong et al., 2014; Sanjuan-Delmás et al., 2021) refer to extracted non-renewable resources, whose consumption should be limited for the sake of sustainability (Tulokhonova and Ulanova, 2013). In particular, the latter category focuses on the consumption of fossil fuels, which is still the main provider of energy worldwide, and according to J. Wang et al. (2018), it is indicative of a country's economic prosperity. Indeed, it can be also expressed as the monetary cost of the damage to resources availability and of the expenses for fossil fuels extraction. Potentially, waste treatments aiming at the recovery of materials and/or energy as well as waste prevention strategies could have a positive impact on these categories (Bilgili, 2020; Martinez-Sanchez et al., 2016).

The study of scientific literature further highlighted case studies using the categories "natural resources" (Ddiba et al., 2022; Nie et al., 2018) and "mineral resources" (Fernández-González et al., 2017; Martinez-Sanchez et al., 2016). The former category represents the consumption of all types of natural resources, including water and forest land, determining double-counting issues with the categories "water depletion" and "land use" (Ddiba et al., 2022). Avoiding the use and increasing the recovery of "natural resources" is also associated with a reduced impact on "global warming" and a more efficient use of primary resources, including nutrients recuperated from composting and digestion processes to be used as fertilisers (Angelo et al., 2017; Martinez-Sanchez et al., 2015). Similarly, the "mineral resources" category depends on the consumption of materials from mineral extraction (Drielsma et al., 2016; Prateep Na Talang and Sirivithayapakorn, 2022). This category can also be included in the "natural resources" one and thus be omitted, unless the study focuses specifically on waste treatments aiming at recovering minerals from waste. For example, Angelo et al. (2017) compared several collection and treatment systems for organic waste, considering the positive effects of using anaerobic digestate in place of mineral fertilizers, thus preventing the extraction of N, P, K. Finally, according to Rigamonti et al. (2016), only the products with a market value should be included among the recovered products, linking them to their economic sustainability as well. It would be interesting to define separated categories for consumed and recovered resources, to account for the lost recovered resources and to better understand to which extent they could effectively be included in the economy, thus determining a reduction in terms of environmental impact and resource consumption.

The waste-related categories include "waste reduction", "organic waste diversion from landfill", and "recycling rates", which are normally expressed as percentages of the total amount of treated waste or as mass (Milutinovic et al., 2016). The first category is generally associated to prevention strategies, and it is particularly relevant for the evaluation of any type of waste, as it indicates the amount of waste that is prevented from being disposed of in landfills, which should be the primary aim of waste management. However, it could indicate the amount of waste that is prevented from being generated thanks to the implementation of reusable products, thus measuring an avoided impact (Stefanović et al., 2016; Zurbrügg et al., 2012). The category "organic waste diversion from landfill" indicates the amount of organic waste fraction separated from the remaining waste stream, that is treated with composting or digestion processes. Thus, this category is helpful in the sustainability assessment of organic waste-oriented treatments and in the evaluation of sorting collection activities. This category is also helpful in quantifying the amount of organic fraction that can be valorised, bringing economic advantages (den Boer et al., 2007; Tsilemou and Panagiotakopoulos, 2007). Finally, the "recycling rate" is indicative of the quantity of materials recycled from the waste streams and it is also representative of the efficiency of recycling plants. This category should be evaluated per each macro group of waste (plastic, paper, glass, etc.), and it is not simply influenced by the type of waste treatment that they are subjected to but, similarly to the category "organic waste diversion from landfill", it also depends on the type of waste sorting and collection system, as the separation of the different classes of waste at a domestic level is essential to improve the "recycling rate", as having already separated waste fractions facilitates the decision on what types of treatment to use and improves the quality of the recovered materials (Milutinovic et al., 2016; Tsydenova et al., 2018). Even though these two impact categories appear to be similar to the resource-related ones, they better represent the recovery of secondary materials, as the recovery of organic waste and recycling provide products that can be used in the economy but that have already been treated and, as a consequence, their new destination uses are limited, unlike in the case of primary resources.

The accentuated attention given nowadays to energy issues and their consequences on climate change has determined a rise in the attempts to evaluate the environmental impact on this compartment (Makan and Fadili, 2020). For the scenarios implementing Waste-to-Energy (WtE) approaches, thus generating energy in the form of electricity and/or fuels from waste, the "energy consumption" (Edwards et al., 2018; Yu and Li, 2020) and "energy recovery" (Rigamonti et al., 2016; Vinyes et al., 2013) are among the most relevant midpoint impact categories and are usually expressed in Joules. Even though the "energy consumption" should be assessed for all types of waste treatments, it can be particularly difficult to evaluate it in the case of recycling processes, as it should also account for the energy saved by limiting the production of materials from raw ones (Shahivand and Rouhani, 2020). Meanwhile, the "energy recovery" accounts for both the energy directly recovered through thermal processes, and for the recovered fuels from biological treatments (Rigamonti et al., 2016; Vinyes et al., 2013). Even though using these two categories separately allows to better evaluate the consumption and the recovery of energy in MSWMSs, it is also possible to assess a third category, that combines the impacts of the first two: the "Cumulative Energy Demand" (CED), which has been a popular impact category since the first applications of LCA and is expressed in Joule as well (Bueno et al., 2015; Frischknecht et al., 2015). The "CED" category evaluates the burden caused by the difference between the energy consumed by the system and that recovered; a positive value indicates that more energy is consumed than what is produced, while a negative value means that more energy is recovered than what is used, and it is normally associated to LCA studies on WtE plants (Ahamed et al., 2016; Yu and Li, 2020). While it makes sense to always assess the "energy consumption" category, as it also has relevance for the economic assessment, the evaluation of the "energy recovery" and "CED" has value only for waste management systems that include phases aiming at recovering energy from waste, either in the form of heat and electricity from incineration, or in the form of biofuels which can be produced from biological treatments. Even specific collection choices can influence this category, as specific types of waste can be used to produce energy and biofuels (Vinyes et al., 2013; Yu and Li, 2020).

3.3. Environmental endpoint categories

As defined by the standard ISO 14040, the endpoint categories are representative of environmental issues concerning the natural environment, namely: the quality of the ecosystems, the availability or scarcity of resources, and the health of human individuals (ISO, 2006). Modelling the endpoint impact categories adds value to the LCAs, as they relate the damage associated to the single LCA midpoint impact categories to the AoPs (i.e., ecosystems, human health, natural resources). Besides, endpoint categories simplify the LCAs results, making them accessible to a larger audience, but they also introduce a strong element of subjectivity, as the passage from midpoint to endpoint categories requires the application of weighting and aggregating procedures (see Fig. 2) (Fernández-González et al., 2017; Hardaker et al., 2022; Huijbregts et al., 2017; Smurthwaite et al., 2023).

Due to the lower accuracy of these categories and to the fact that they do not evaluate the direct impact on small groups, but on a global scale (Botello-Álvarez et al., 2018), only a limited number of case studies assessed the LCIA results for the endpoint impact categories, focusing specifically on the AoPs: "resources", "health", "ecosystem", and "climate" (Tab. S3).

Regarding the "resources" AoP, several case studies used the endpoint category "fossil resources", which is used for the evaluation of MSWMSs that strongly rely on the consumption of fossil fuels, expressed as kg oil-eq or Joules (Fernández-González et al., 2017; Sanjuan-Delmás et al., 2021; Tonini et al., 2020). It can be described as the additional future costs that must be paid because of the extraction of such resources in the present and can therefore be expressed either in monetary units, which simplifies the integration of this category in the economic impact assessments, or as the energy necessary for future extraction (Bilgili, 2020; Z. Wang et al., 2020). Nonetheless, it is a limited category, as it does not include all types of resources that are consumed or recovered by MSWMSs (Menikpura et al., 2012a; Sanjuan-Delmás et al., 2021). Other papers applied endpoint categories indicating the impact due to all types of consumed non-anthropogenic resources, without distinction between biotic and fossil resources, namely the "resources availability" or "natural resources". The latter category has a homonymous midpoint impact category, but they represent different types of impact, at different levels of the damage pathway (Botello-Álvarez et al., 2018; Tonini et al., 2020; Z. Wang et al., 2020). Finally, the "resources productivity" is an endpoint category with both an environmental and economic value, used to define the number of saleable products that can

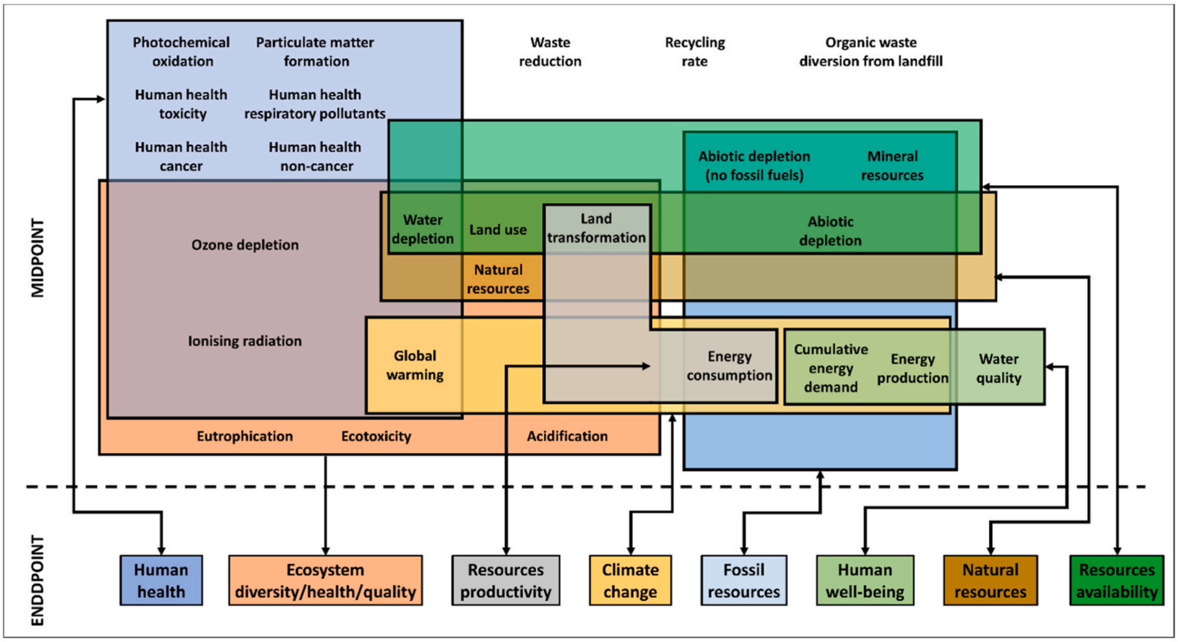

Fig. 2. – The figure represents the relationships between environmental assessment impact categories for MSWMSs at the midpoint and endpoint level, highlighting the overlapping between multiple categories.

be obtained from MSWMSs, meaning that it also accounts for the recovered resources from waste management activities (Prateep Na Talang and Sirivithayapakorn, 2021). The evaluation of endpoint categories concerning the state of resources is particularly relevant when considering the rising interest toward the efficient use of primary resources and waste treatments like recycling or energy recovery. Indeed, the savings from energy substitution have a strong influence on this AoP and it has been observed that additional waste management activities (sorting, refining, collection, etc.) can have a negative impact on the "resources" category as they require additional energy consumption, generally derived from fossil fuels, but the recovery of resources through these activities can counterbalance the impact (Tonini et al., 2020; Zilka et al., 2021). The implementation of prevention strategies is essential to limit the consumption of resources and therefore reduce such impact (Sanjuan-Delmás et al., 2021). These categories depend on the midpoint categories directly related to the resources, but evaluating the contribution of either the recycled materials or the recovered energy in the form of biofuels is necessary to better consider the entire life cycle of waste (Z. Wang et al., 2020).

"Human health" is a standard endpoint category applied in eLCAs, which should be linked exclusively to environmental midpoint impact categories. Several studies on MSWMSs included this category among the social impact categories, even though it only includes environmental aspects and excludes the social ones (Albizzati et al., 2021; Sanjuan-Delmás et al., 2021; Tonini et al., 2020). Nonetheless in some scenarios, the authors suggested using the category "human well-being" instead, to include additional social aspects, namely the implementation of measures meant to safeguard workers' health, to prevent environmental pollution and its consequences on both workers and the community, and finally proper safety training (Zurbrügg et al., 2012). These categories are expressed through the disability-adjusted loss of life years (DALY), which indicates the loss of healthy years due to activities related to MSWMSs (Bilgili, 2020). Even though the evaluation of MSWMSs impacts on "human health" should always be a priority, this category is particularly useful when focusing on uncontrolled WMSs that release high quantities of pollutants directly into the environment or for the sustainability assessment of waste treatments generating particularly unhealthy substances as incineration (Lam et al., 2018; Prateep Na Talang and Sirivithayapakorn, 2021). The evaluation of the endpoint category "human health" depends on multiple impact categories. For example, according to the ReCiPe method, it is necessary to consider the categories "particulate matter", "ozone formation", "ionizing radiation", "human toxicity (cancer and non-cancer)", "global warming", "water depletion" (Huijbregts et al., 2017).

The endpoint category "ecosystem" is also referred to as "ecosystem quality" (Bilgili, 2020), "ecosystem diversity" (Z. Wang et al., 2020), and "ecosystem health" (Tonini et al., 2020), all indicating the potential disappeared fraction of species per surface per year, due to harmful impacts to the environment, thus representing the impact on the biodiversity (Bilgili, 2020; Hardaker et al., 2022; Sabia et al., 2020). This is mainly associated with acidification and eutrophication phenomena, and to the occupation and consumption of land (Menikpura et al., 2012a). The assessment of the "ecosystem" category has proved the positive action of prevention strategies, especially that of the organic fraction, and it has been observed that for most waste treatments the main contributor to the impact on this category is the "global warming" (Prateep Na Talang and Sirivithayapakorn, 2021). Besides, J. Wang et al. (2018) described an ex-ante LCSA method in which the possibility to distinguish between terrestrial and aquatic ecosystems damage was considered. In this case, it was necessary to consider the "terrestrial ecotoxicity" and "terrestrial acidification" for the first impact category, and the "eutrophication", "freshwater aquatic ecotoxicity", and "marine aquatic ecotoxicity" for the latter one. For the aquatic ecosystem, the case study highlights how there is a lack of proper midpoint categories assessing the impact caused by the presence of plastic waste in the marine ecosystem due to improper dumping, a frequent practice in developing countries. According to the damage pathways of the contaminants and emissions released through the different phases of waste management, it is possible to consider the impact on the "ecosystem", starting from the midpoint categories "acidification", "eutrophication", "ecotoxicity", "land use", "land transformation", and "global warming", the latter being excluded in some case studies (Bilgili, 2020; Fernández-González et al., 2017).

Unlike the previously described endpoint categories, "climate" was found to be less commonly applied in LCA studies, being used only in two of the analysed case studies, which implemented the LCIA method IMPACT 2002+ (Fernández-González et al., 2017; Zilka et al., 2021). Instead of linking the midpoint impact category "global warming" to one or more of the traditional AoPs, usually the “human health” and the “ecosystems”, this method establishes a direct damage pathway from the midpoint category “global warming” to the endpoint category “climate change” (Bilgili, 2020; Botello-Álvarez et al., 2018; Jolliet et al., 2003). When climate change stands as an endpoint category instead of being integrated into other categories, double-counting issues are avoided, and this has proved to be particularly useful when assessing the environmental sustainability of MSWMSs that are highly responsible for emissions. For instance, it is particularly helpful for the environmental assessment of landfilling, which is typically characterised by the release of gas from fermentable waste: in this case, the recovery of biogas produced from landfills could drastically reduce its contribution to the greenhouse effect, as well as the impact on the “resources” category (Fernández-González et al., 2017).

4. Economic assessment of MSWMSs

4.1. LCC

The economic assessment of MSWMSs is fundamental for defining their sustainability and it is often conducted via the LCC.

As eLCA, LCC quantifies the impact of a product or system throughout its life cycle, but this is expressed in terms of monetary value (Hoogmartens et al., 2014; Neugebauer et al., 2016; Sharma and Chandel, 2021). LCC provides useful information to companies and stakeholders interested in the implementation of financial measures, as it encourages the prevention of economic burdens shifting among different involved actors or life stages of a process (Kerdlap and Cornago, 2020). Besides, the popularity of LCC among practitioners is due to the accessibility of data on costs and expenses related to products and processes, unlike the eLCA tool, and to the widespread knowledge of the monetary metric (Kambanou and Sakao, 2020).

Over time, several methods have been derived from the LCC methodology, to focus on multiple aspects of sustainability and these are often implemented to study MSWMSs: the financial LCC (fLCC) (Reich, 2005), the environmental LCC (eLCC) (Martinez-Sanchez et al., 2016; Rigamonti et al., 2019), and the social LCC (sLCC) (Albizzati et al., 2021; Tonini et al., 2020). A fLCC is also defined as a conventional LCC; it focuses only on the costs for one group of actors (i.e. consumers, manufacturers of goods, facility owners, etc.) and, normally, it excludes the environmental costs (Hoogmartens et al., 2014; Kerdlap and Cornago, 2020). However, when a fLCC is extended to include the environmental costs (i.e., waste disposal costs, CO_2 taxes, climate change adaptation costs, etc.), it is addressed to as an eLCC (Hoogmartens et al., 2014). Finally, a sLCC encompasses all costs covered by the people, monetising public health and human well-being (Hoogmartens et al., 2014; Neugebauer et al., 2016).

Independently from the use of either LCSA or LCC tools in the case studies, all the considered costs are referred to impact categories, which can be compartmentalised in indicators, midpoint, and endpoint categories as detailed in the following paragraphs.

4.2. Economic midpoint impact categories

Several mainstream impact categories were drawn from the analysis of the available literature. They are all arranged in highly specific compartments, expressed in terms of monetary value, and can be linked to the functional unit of MSWMSs (i.e., the mass of treated waste) through a ratio between the spent or gained money per unit of mass of waste.

The first midpoint impact category that should be considered in LCC studies of MSWMSs is the “capital cost”, also indicated as CAPEX. It defines the value of the investment costs of a MSWMS, which encompass all expenses for acquiring the land to establish a waste management facility, for the construction works, and for the equipment purchase (Alamu et al., 2021; Chhabra et al., 2021; Zhao et al., 2011). These expenses are assumed to be paid only once throughout the entire life cycle of the considered MSWMSs. The “capital cost” of landfilling mostly depends on the cost of the acquisition of land, which is excluded from non-georeferenced case studies, leading to the need to estimate it, thus limiting the precision of the LCC evaluations (Demichelis et al., 2022; Martinez-Sanchez et al., 2015; Sanjuan-Delmás et al., 2021).

The compartment of the operational (OPEX) costs is generally representative of all the expenses for the materials and energy necessary for the MSWMSs activities (Tonini et al., 2020; Zilka et al., 2021) and, therefore, it includes several categories. Among these, the “maintenance cost” represents all those associated to the activities to preserve the equipment and it depends on their level of complexity and on the costs for both ordinary and unplanned maintenance activities, as well as on the costs for the acquisition cost of new or substitutive machineries (Ayodele et al., 2018; Sharma and Chandel, 2021). The “labour cost” accounts for all the expenditures for the staff and workers’ wages, and it also accounts for the expenses for special training or insurance (Emery et al., 2007; Z. Wang et al., 2020). Even though these impact categories can be used separately, several studies opted for including all these aspects in a single midpoint category, namely “operational cost”, which is calculated as the sum of the expenses for the material and energy supply, the costs related to the maintenance and labour activities, as well as the cost for the transportation activities and auxiliary supplies. It should be noted that the use of dissimilar definitions for the same categories can be confusing and prevent comparability among studies (Makan and Fadili, 2020; Yu and Li, 2020). It has been observed that the operational expenditures can greatly vary between treatments, based on the complexity of the mechanical equipment as well as on the cost of disposing of leftover waste, and they are difficult to predict. Nonetheless, it has been recognized that the waste treatments with the highest and lower “operational cost” impact are incineration and landfilling, respectively (Ayodele et al., 2018; Milutinovic et al., 2016; Stefanović et al., 2016).

The economic impact of the decommissioning phase of the life cycle of WMSs is expressed through the impact category “end-of-life cost”, also labelled as OELEX (Taelman et al., 2020; Z. Zhou et al., 2019). This category describes the cost to properly finish operations and dismantle the facilities, which mostly depend on the dimensions of the facilities themselves, on the used equipment, on the necessary labour to conduct the dismissing operations, and on how much waste was treated through their lifespan (Sanjuan-Delmás et al., 2021; Tonini et al., 2020). OELEX is often excluded from LCC studies on MSWMSs, as it is not as relevant as either the CAPEX or OPEX. Indeed, it is often assumed to be equal to the “residual value”, which represents the remaining value of the treatment plant after it has been fully dismissed (Zhao et al., 2011). Even when this phase of the life cycle is included in LCC evaluations, it is ignored in eLCAs as the emissions from this phase are irrelevant in comparison to those from the treatment phase (Dong et al., 2014; Yang et al., 2022). Nonetheless, this indicator was included in the definition of a life cycle model meant to evaluate the environmental, economic, social, and energy sustainability of WtE management systems, presented in Z. Zhou et al. (2019) and it was also included in the sustainability assessment of different options for the management of organic waste (composting, anaerobic digestion, incineration), but in every scenario, the “end-of-life cost” was around one order of magnitude smaller than the CAPEX and OPEX costs. Thus, it is acceptable to exclude such costs from LCSAs, but in order to account for a proper Life Cycle approach, it would be necessary to include the impacts associated to the decommissioning phase of MSWMSs on all aspects of sustainability, as it also determines a huge impact on the workers’ employment and community’s accessibility to waste management.

Among the midpoint impact categories, that of “revenues”, also indicated as “benefits” (Ahamed et al., 2016; Nie et al., 2018), was identified in several case studies. Unlike the other economic midpoint impact categories, the “revenues” indicate the amount of money obtained from a transaction, instead of the spent money (Kerdlap and

Cornago, 2020) and basically refer to the sale of both recovered materials and energy from waste. Hence, high earnings are associated to the optimal use of waste, meaning that all the materials must be recycled or recovered, and the residual waste must be treated to produce energy (Fernández-González et al., 2017; Gadaleta et al., 2022; Shahivand and Rouhani, 2020; Yu and Li, 2020). The "revenues" also include the cash inflows from tax forgiveness, incentives, or subsidies, but it must be considered that defining whether a certain expense is a cost, a revenue, or a transaction within WMSs depends on the point of view of the main actors of the LCC study (Ayodele et al., 2018; Reich, 2005). Indeed, the selling of recovered materials or energy represents a "benefit" for the producers (i.e., the facilities owners), while it represents an expense for the consumers. Moreover, the revenues are subject to the fluctuations in the market, making it difficult to predict their value (Prateep Na Talang and Sirivithayapakorn, 2022). This impact category is particularly useful to evaluate the viability of less impacting MSWMSs, as they must generate enough revenues to compensate for their higher capital and operational costs (Paes et al., 2020). In this regard, studies focusing on specific MSW management options highlighted that the treatment of organic waste through composting has the highest revenues in comparison to other options, while incineration is the best option for treating combustible waste.

With the purpose of leading a more complete sustainability impact assessment, multiple papers included midpoint categories concerning environmental and social issues, but still relevant from an economic perspective. Indeed, some LCT tools, namely the environmental life cycle costing (eLCC) (Reich, 2005), the economic input-output LCA (Yu and Li, 2020), the life cycle cost-benefit analysis (Lam et al., 2018), and the eco-efficiency analysis (Abdeljaber et al., 2022), allow to directly convert the environmental impacts of an eLCA study into monetary burdens (Daylan and Ciliz, 2016). These tools are particularly useful for the evaluation and comparison of the environmental and economic burdens of MSWMSs in unison, but they tend to exclude the social pillar of sustainability (Yang et al., 2022).

The information provided on the monetary burden of emissions and the consumption of natural resources is gaining more relevance in the sustainability assessment of MSWMSs (Paes et al., 2020), so that several case studies include the "environmental cost", that is the monetary impact of the environmental emissions (Alamu et al., 2021; Menikpura et al., 2012a, 2012b; Vinyes et al., 2013). Thus, this midpoint category is strictly connected to the environmental category of "global warming", and it also accounts for the economic burden of natural resources consumption, along with the "emission charges" indicator (Paes et al., 2020). The "environmental cost" should always be included in LCC studies of MSWMSs, as the community may have to pay it in the form of health costs. Indeed, Menikpura et al. (2012a) expresses this category as the willingness to pay for solutions to prevent health problems. The main issue with the inclusion of "environmental cost" in life cycle studies that also consider the economic or social issues is the double-counting risk (Woon and Lo, 2016). Besides, as previously stated, the environmental impact associated with the consumption of different types of natural resources is often expressed in monetary value, thus it can be easily integrated in the evaluation of the economic impact of MSWMSs.

To integrate the economic connotation of social issues from MSWMSs, the Social Life Cycle Cost (sLCC) has been proposed as well. It is a method meant to assess all the economic burdens from a social point of view. In sLCC all costs borne by anyone in society, whether today or in the future, and associated with the life cycle of a system, are considered. Impacts such as public health and human well-being must be quantified and translated into monetized measures, which is often challenging. For this reason, some case studies included the social categories "equity", "dependence on subsidies", and "poverty". The category "equity" is indicative of the equitable distribution of the economic burden of waste management among the citizens, which is measured based on the cost and income per person; similarly, the "dependence on subsidies" measures the reliance of a municipality on external aids, as opposite to its independence and ability to self-sustain (den Boer et al., 2007). Finally, J. Wang et al. (2018) used "poverty" as a midpoint category, which aims at quantifying the positive or negative impact of the implementation of a new MSWMS on the population living with an income below the international poverty line, in terms of education opportunities, employment, and health (Maier et al., 2016). Even though the integration of socially characterised impact categories for the economic assessment of MSWMSs is still uncommon, its use could be particularly helpful for the sustainability assessments of waste management systems in developing countries (J. Wang et al., 2018).

4.3. Economic endpoint impact categories

From the analysis of the available literature, it was possible to identify multiple criteria that function as endpoint categories for the economic burden assessment. Even though these economic metrics (Ayodele et al., 2018) are not proper endpoint impact categories, they accomplish the same function of quantifying the effects on certain areas of interest for the larger public. Similarly, to the environmental ones, the economic endpoint impact categories aim to simplify and aggregate the results derived from the assessment at the midpoint level (see Fig. 3). Many categories represent a cost balance over the entire life cycle of MSWMSs, while others are indicative of their feasibility and profitability.

Multiple papers used the category "total Life Cycle Cost", named after the homonymous LCT tool. It is described as one of the most relevant financial categories for the economic viability assessment of an investment project, and it is representative of the total cost of owning and running MSWMSs over their useful life (Ayodele et al., 2018). This category can be evaluated as the sum of the "capital cost", "operation cost", and "maintenance cost" (Nubi et al., 2022c; Sharma and Chandel, 2021), but other papers also included either the impact of the "environmental cost" (Menikpura et al., 2012b) or subtracted the "revenues" derived from the sale of materials and energy (Menikpura et al., 2012a; Woon and Lo, 2016). Z. Zhou et al. (2019) and Lam et al. (2018) respectively assessed the "net economic result" and "net economic cost" as the sum of "capital cost" and "operation cost" minus the "revenues", and other case studies used the endpoint impact category "total cost" to simply indicate the sum of all the expenses for the correct operation of MSWMSs (Li et al., 2015; Zilka et al., 2021), but excluding the revenues, when the management systems does not produce any earning.

Other case studies referred to the difference between the total expenditure and the total revenues, or the difference between the cash outflow and the cash inflow over the life cycle of MSWMSs, as the "net present value" (NPV) (Abdeljaber et al., 2022; Aleisa and Al-Jarallah, 2018; Demichelis et al., 2022). This endpoint category assesses the difference between the present value of all the costs that the system upholds (CAPEX, OPEX, etc.) and the present value of all the "revenues" over its lifetime (Ayodele et al., 2018). For a MSWMS to be economically sustainable, the NPV must be a positive value, meaning that the revenues must be higher than the expenses. Therefore, the economic sustainability of WMSs depends on their ability to produce wealth, through material and/or energy recovery. Therefore, the NPV is generally higher for composting, recycling, or incineration facilities and is lower or negative when landfilling is involved (Abdeljaber et al., 2022; Demichelis et al., 2022; Nubi et al., 2022c). This endpoint category was applied also by Ahamed et al. (2016) and Fernández-González et al. (2017), even though they respectively referred to the difference between the total cost and the benefits as "balance" and "rate payers' contribution", instead of NPV. Similarly, other authors used the category "prosperity" to estimate the economic burden starting from the CAPEX, OPEX, OELEX, and "revenues" (Albizzati et al., 2021; Tonini et al., 2020). In all cases, the main aim was to compare the overall economic inputs and outputs of the management systems.

As previously stated, some endpoint categories also include the

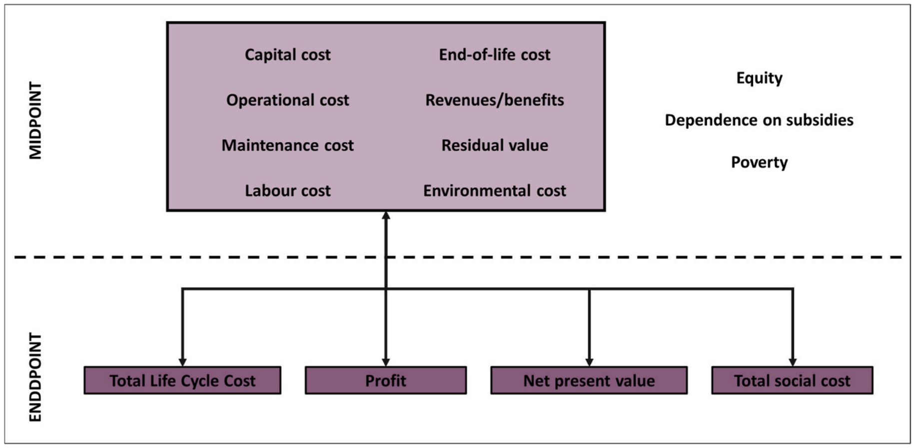

Fig. 3. – The figure represents the relationships between economic assessment impact categories for MSWMSs at the midpoint and endpoint level, highlighting the overlapping between multiple categories.

"environmental cost" midpoint category, depending on the relevance of the "emission charges" in specific cases. Among them, Mirdar Harijani et al. (2017) uses the category "profit", which describes the difference between the economic profit (i.e., the "revenues" minus the "capital cost" and "operation cost") and the "environmental cost". Instead, Paes et al. (2020) summed the "capital cost" to the "operation cost" and "environmental cost" and subtracted the "revenues", to evaluate the endpoint category "total social cost". Both endpoint categories are particularly helpful when the purpose of MSWMSs solutions is to maximise the profits without threatening the environment, meaning that the "revenues" must be high, while the "environmental cost" must be minimised (Mirdar Harijani et al., 2017).

All of these categories refer somehow to the comprehensive cost of the entire life cycle of MSWMSs. Nonetheless, other endpoint impact categories have been proposed for the assessment of projects. Among these, the "levelised cost of energy" (LCOE) corresponds to the minimum sale cost of recovered and produced energy necessary for the system to reach economic balance (Abdeljaber et al., 2022; Ayodele et al., 2018; Nubi et al., 2022c). Being directly related to the amount of energy produced by a system, this category is fundamental for the economic assessment of MSWMSs for energy recovery, including digesters or landfill gas recovery plants. Besides, it is strongly influenced by the "discount rate" indicator, and by the waste collection efficiency, as the greater is the waste amount for energy recovery, the more energy is produced, leading to a reduction in the cost at which the energy should be sold (Ayodele et al., 2018). A project can be considered profitable when the LCOE is lower than the up-to-date electricity tariffs (Abdeljaber et al., 2022). Unlike the previously described categories, which are expressed as money spent per year or per mass of treated waste, the LCOE is quantified as monetary value per kWh of energy (Nubi et al., 2022c).

Some endpoint categories are not expressed in monetary units, namely the "payback period" and the "internal rate of return". Both categories focus on a specific goal: reaching a breakeven condition, which happens when there is a financial return on the initial capital cost. The first category evaluates the time after which this happens and it is generally expressed in years (Abdeljaber et al., 2022; Demichelis et al., 2022), while the second one corresponds to the highest value of "discount rate" for which this condition is met and it must be calculated through an iterative process, resulting in the identity $NPV = 0$ (Ayodele et al., 2018; Nubi et al., 2022c). Similarly to the "levelised cost of energy", the "payback period" decreases with the increase in waste collection efficiency and revenues generation efficiency, as this impact category depends on both the revenues and the time necessary to recover the investment. It is assumed that a "payback period" of less than 7 years is acceptable for any WtE system, and in general it should always be lower than the lifespan of the facility (Ayodele et al., 2018; Demichelis et al., 2022; Nubi et al., 2022c). On the contrary, an "internal rate of return" superior to the actual discount rate testifies the feasibility of a project (Abdeljaber et al., 2022).

Finally, only a limited number of case studies tried to express the economic impact in relation to the functional unit of MSWMSs life cycle, by dividing the expenses and the revenues for the mass of waste treated in the management system (Gadaleta et al., 2022; Woon and Lo, 2016). This is extremely important to perform a proper LCSA, as the calculated impacts on the environmental, economic, and social impacts should be all expressed with reference to the same functional unit, to improve the accuracy of LCSAs on MSWMSs (Dong et al., 2014).

5. Social assessment of MSWMSs

5.1. Social LCA

In the current context toward sustainable development and responsible production and consumption, MSWMSs must be evaluated not only from an environmental and economic perspective, but from a social one as well. Thus, as part of the LCSA tools, sLCA is presented as the most effective technique to assess the social impacts of products throughout their life cycles (Ramos Huarachi et al., 2020).

The sLCA is a social impact assessment method that aims to assess the social aspects of products and their positive and negative impacts along their life cycle, contemplating the needs of a variety of stakeholders (Liu et al., 2013; Petti et al., 2018). Often, sLCA is meant to address socio-economic implications, so that possible overlapping with LCC can occur.

5.2. Social midpoint impact categories

The impact on the community participation can be characterised through different categories, namely: "acceptance", "involvement", "satisfaction", and "equity". Among these, only a limited number of case studies included the category "involvement", which is evaluated as the number of stakeholders who participate to project meetings over the invited or expected total and should be evaluated for the social assessment of new projects and variations of the WMSs (Taelman et al., 2020; Tonini et al., 2020). The "acceptance" of MSWMSs from both workers and citizens evaluates the overall perception of public communities about the utility of WMSs in their daily life. Nonetheless, it may be interestingly linked to the acceptance of the use of recycled materials and products, which may turn to be an obstacle to the proper implementation of specific waste management solutions (Sanjuan-Delmás et al., 2021). This category is influenced by multiple factors; indeed, the acceptability of WMSs is also influenced by its environmental and health impact, as well as the level of education of people on the MSWMS phases that most affect them (Berardocco et al., 2022). It is possible to evaluate the "acceptance" as opposed to either the negative perception of MSWMSs or the raise of the NIMBY (Not In My Back Yard) syndrome, as proposed by Taelman et al. (2020) and it can be quantified through surveys as done by Yıldız-Geyhan et al. (2019). However, it should be considered that the results of the quantification will be influenced by the level of knowledge and awareness of the participants. When a project is being evaluated, the acceptability may also be represented by the impact category "satisfaction", which refers to both the satisfaction of workers and citizens, who are asked to compare the present characteristics of MSWMSs to those of a previous system or of a hypothetical new one, in an ex-ante approach (Yıldız-Geyhan et al., 2017).

Another category that should be considered from the community perspective is the "accessibility", which depends on the facility with which people can access to the waste management services. Indeed, it is mostly used for the collection phase, and it is expressed as the percentage of doorways within an interval distance between the door and the waste collection points. The impact on "accessibility" improves when the number of collection points increase, meaning that door-to-door collection has the best results for this category (Taelman et al., 2020; Tonini et al., 2020).

Finally, the category "equity" evaluates the extent to which the economic burden is equitably distributed among the members of the community, but it can also represent the benefits of implementing a new MSWMS for the socially disadvantaged groups, in terms of higher salaries, better working conditions and new job opportunities (den Boer et al., 2007; Tsilemou and Panagiotakopoulos, 2007; Z. Wang et al., 2020). It can be measured as the ratio between waste management cost per person and income per person, thus acquiring an economic connotation.

The impact categories associated to the nuisance are the "disamenities cost" and the "landscape disamenities". The "disamenities cost", which is sensitive to the proximity of inhabited areas to the waste facility, indicates the cost associated to the nuisance. It can be evaluated starting from the variation of the housing prices in the surrounding areas (Taelman et al., 2020) and from the number of complaints filled by the community for the nuisance caused by noise, odour, traffic, and unpleasant living conditions associated to MSWMSs (Aleisa and Al-Jarallah, 2018; Lam et al., 2018). Similarly, Lam et al. (2018) used the category "land cost", to indicate the changes in the estate market in nearby areas due to the waste management activities and the consequential nuisances to the population. Nonetheless, the term "land cost" is normally used as an economic category for the investment costs, and it expresses the cost of buying land to establish new waste treatment plants and storage areas. In this scenario, it is instead indicative of how MSWMSs can alter the value of nearby land over time. Likewise, the "landscape disamenities" indicate the variation of property value due to waste management activities and infrastructures, and it mainly depends on their distance from inhabited areas (Sanjuan-Delmás et al., 2021; Tonini et al., 2020). These impact categories are particularly useful for the social assessment of different types of waste treatments and to evaluate the burden associated to several options for waste transportation and storage. Nonetheless, the main disadvantage of these categories is the difficulty to relate them to the MSWMSs functional unit of treated waste, even though they can be quantitatively expressed (Taelman et al., 2020).

"Public commitments to sustainability issues" is a midpoint category related to the legislative compartment of MSWMSs. It represents the commitment of the society to deal with sustainability issues through the implementation of environmental waste management solutions and it is evaluated in terms of percentage of actions made with public funds in relation to waste management, thus it can also be related to the economic pillar of sustainability. It mainly considers activities aiming to the increase of public awareness on waste issues and how to properly separate and recycle waste, hence it is particularly relevant for the evaluation of the social impacts on the community and the governance (Ibáñez-Forés et al., 2019; Zurbrügg et al., 2012). This category can be evaluated starting from the information on the recycling targets set by municipalities and their legislation framework, thus it is a useful impact category for the assessment of all phases of waste management, but especially for evaluating those solutions that aim at improving the environmental performance and circularity of WMSs, such as recycling.

The impact associated to the labour compartment can be assessed through multiple categories that are respectively associated to quantitative and qualitative indicators, namely the "employment opportunities" and the "job satisfaction". The former indicates the job opportunities expressed either as the total number of employees or in hours of labour per days per mass of treated waste and it includes all the phases of the waste management and all different skill levels. This category is useful when evaluating the sustainability of a new process that includes multiple phases, as they require more labour force, and it has been used especially for MSWMSs that include material recycling and energy recovery (Alamu et al., 2021; Menikpura et al., 2012a; Tulokhonova and Ulanova, 2013).

The category "job satisfaction" is often evaluated through surveys and it is strongly dependent on indicators including "discrimination" and "freedom of association", meaning that the quality of the work conditions determines the impact on this category. The evaluation of this category is frequent when assessing the sustainability of formal collection systems but should be assessed for all types of jobs in waste management and it is normally based on questionnaires results (Yıldız-Geyhan et al., 2019).

Among the impacts on society, those in terms of health should be also considered. As the health impact is related to the possible polluting effects of waste management activities, it is often evaluated through categories belonging to the environmental pillar of sustainability. Menikpura et al. (2012a) used several environmental impact categories, including "global warming", "photo-oxidant formation potential", and "human toxicity", to evaluate impact on the environmental endpoint category "human health", which was used as a social category, instead of environmental. Similarly, other case studies included "global warming" and "water depletion" among the midpoint categories necessary to evaluate the impact on the endpoint categories "human health" and "environmental health", using the first as a social endpoint category (Sanjuan-Delmás et al., 2021; Taelman et al., 2020; Tonini et al., 2020). The "global warming" category measures the contribution of certain anthropogenic emissions in increasing the radiative forcing of the atmosphere, which leads to an increment of the global average temperature affecting human health and thus making it a social category as well. The "water depletion" category measures the total water consumption to evaluate the impact of the extraction of water, which has a potential for damaging both ecosystems and human health (Taelman et al., 2020). Li et al. (2015) performed a health risk assessment to evaluate the impact on health due to the use of multiple treatment solutions (landfilling, incineration, recycling, and composting). This impact was estimated in terms of increase of lifetime cancer risk and hazard index. When considering facilities built in proximity of inhabited areas or waste collection solutions that expose the citizens to the waste for prolonged time, the impact on public health should always be evaluated. Nonetheless, the community can be exposed to pollutants and emissions from MSWMSs at every step of the management (collection, treatment, disposal, etc.) either directly through odours, polluting emissions, handling hazardous substances, or indirectly by ingestion of contaminated matter (Alamu et al., 2021; Menikpura et al., 2012b). This category is also commonly applied when treating contaminated waste or when the waste treatment leads to the production of fertilizers that could contaminate water, soil, or food (Sanjuan-Delmás et al., 2021).

Another category that can be used to assess the impact on the health compartment is the "health and safety" which is evaluated for both workers, community, and society, but especially in the case of workers, a proper indicator to assess the impact on this category is the number of accidents that involve the workers. Even though this category should be evaluated for all phases of waste managements, the risk of work accidents is particularly relevant when assessing the sustainability of collection systems and especially the passage from informal to formal collection. Instead, when evaluating the impact on this category for the community, the level of nuisances (odour, noise, etc.) should be considered, and this is frequently done for incineration plant, as they are often the loudest and produce more noise, while landfilling produces more odour emissions (Z. Zhou et al., 2019). Among other factors, this category depends not only on the possible risks of incidents, but also on the level of monitoring of all activities, on the level of training and education that both workers and citizens receive, on the use of protective equipment, and on the emissions produced from waste or by materials and substances used during the treatment (Aleisa and Al-Jarallah, 2018; Azimi et al., 2020; Yıldız-Geyhan et al., 2017). Finally, this category is also expressed as the "occupational health", which mainly focuses on the number of fatal and non-fatal accidents that happen per ton of treated waste (Taelman et al., 2020).

The main socio-economic midpoint categories withdrawn from literature are "contribution to economic development" and "affordability to resources and goods". The former depends on the revenues generated from the recycling of materials and the energy recovery from waste. Studies on the implementation of formal collection systems as opposed to informal ones have shown that the economic development is favoured by informal systems, as collectors have the chance to sell waste to recycling shops. Moreover, the proper treatment of waste from the government can lead to the use of equipment from foreign countries which has an additional negative impact on the local economy (Azimi et al., 2020; Yıldız-Geyhan et al., 2019). Instead, Vinyes et al. (2013) highlights how proper collection of a specific waste fraction (namely, used cooking oil) can benefit from the implementation of formal collection, as it allows to gather more waste and consequently produce more revenues from its manufacture. A numerically based way to express the impact on this category is to evaluate the contribution of waste management to the GDP of the country where the study is set (Nubi et al., 2021). Conversely, the "affordability to resources and goods" refers to the contribution of MSWMSs to the generation of resources, goods, and energy at affordable prices for the community, thus it can be applied in case studies that deal with management solutions for waste recovery (biological treatments, recycling, thermal treatments, etc.). Theoretically, the increase in affordability of resources recovered from waste management can improve the circularity, convincing more users to consume such products, besides the energy recovery has a positive impact on this category as it also helps to maximise the energy independence of the community (Nubi et al., 2021). Nonetheless it could also increase the consumption of goods and resources, preventing the assumed one-by-one replacement, thus having a positive effect on the prosperity and the well-being of people but negatively affecting the environmental sustainability (Ddiba et al., 2022).

5.3. Social endpoint impact categories

The social endpoint categories are related to four main compartments of interest, namely the community, health, labour, and economy (see Fig. 4).

The impacts associated to the human health are expressed through several endpoint impact categories. Several studies included the endpoint category "human health", which can be measured as DALY to quantify the health damages caused by "global warming", "photooxidant formation", "human toxicity" and it is usually assessed when evaluating the sustainability of recycling and incineration systems.

As already pointed out, even though the damage to "human health" is caused by environmental emissions, it is considered a social category too, as safeguarding health is of interest to the society. Poor WMSs can lead to damage to human health and shorten people's life, while it has been observed that high levels of recycling with bio-based treatments and the exclusion of incineration can help improve the impact on human health (Di Maria et al., 2020; Menikpura et al., 2012a). "Health and safety" is also used as an endpoint category and it affects all stakeholders' groups (Yıldız-Geyhan et al., 2017). It can be evaluated based on the health and safe working and living conditions, as well as on the number of workers with vaccinations necessary to work with waste and with no previously existing health issues (Ibáñez-Forés et al., 2019; Yıldız-Geyhan et al., 2019). However, other case studies included the endpoint category "human well-being", which has a more strictly social connotation, as it depends on "acceptance", "involvement", "accessibility", "landscape disamenities", "occupational health", and "employment opportunities", and it is indicative of the proper living and working condition, and of the integration of MSWMS solutions into the community (Albizzati et al., 2021; Sanjuan-Delmás et al., 2021; Tonini et al., 2020). Therefore, this endpoint category can be used to better describe how different MSWMSs can improve the living conditions of both the workers and the community.

The impact on workers can be defined through two similar endpoint categories, namely "human rights" and "working conditions". The evaluation of the first category depends on several indicators, including "forced and child labour", "freedom of association", "discrimination".

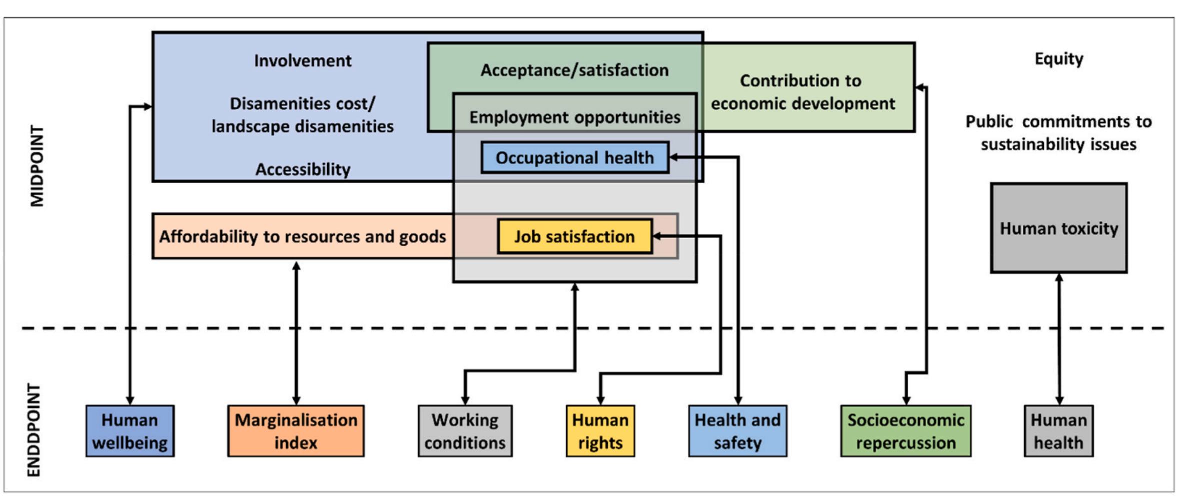

Fig. 4. – The figure represents the relationships between social assessment impact categories for MSWMSs at the midpoint and endpoint level, highlighting the overlapping between multiple categories.

To establish the impact on the "human rights" category, data from both interviews, direct observations, literature, and statics should be gathered. However, the data could be affected by the lack of proper recordings, especially in the case of informal collection systems. Usually, the impact of MSWMSs on the "human rights" endpoint is taken in account for case studies set in developing countries or that consider the passage to formal collection systems. Instead, for developed countries, it is assumed that the legal framework and monitoring system for workers is already solid enough for this category to be excluded from assessments (Di Maria et al., 2020). The endpoint category "working conditions" is evaluated from the analysis of "job satisfaction", "working hours", "salary", "forced labour", and "safety" (Yıldız-Geyhan et al., 2019). In some studies, this category was also evaluated according to the impact on safe and living conditions of the local community if they are affected by the waste management activities (Yıldız-Geyhan et al., 2017). Ibáñez-Forés et al. (2019) defined the impact on "human rights" only according to the impact on "child labour", but it also included the endpoint category "equal opportunities/discrimination", which evaluates the number of female workers, gender pay gaps, the number of undocumented workers, and the percentage of workers with no opportunity to work in a different sector. The study evaluated the results of the passage from an informal to a formal waste collection system in Brazil, thus the evaluation was done starting from questionnaires to the waste collectors and then defining the worst- and best-case scenario for each category and assigning them a score from 0 to 100, based on the interviewees' answers. For the "human rights", the involvement of children represents the worst scenario and thus has a 0 score, while the complete absence determines a score of 100 points. In the same case study, the authors referred to the "working conditions" category as "quality of job position" and only considered the impact associated to the "fair salary" and the working hours. Nonetheless, another endpoint category, namely the "working benefits", was included; this depends on the presence of legal employment with benefits and security, as well as on the number of workers and relatives with insurance (Ibáñez-Forés et al., 2019).

Another relevant issue for all stakeholders is the economy and to evaluate the social impact on this compartment the main endpoint category is the "socio-economic conditions". The assessment of this category depends on the level of education and training of workers and, in the case of informal waste management, on the schooling of children. The promotion of education programmes for workers has a positive impact on work satisfaction, and it can improve their lives and the efficiency of MSWMSs (Aparcana and Salhofer, 2013). This category has been evaluated both according to the answers provided by workers to questionnaires, and according to the impact on midpoint categories as "employment opportunities", "acceptance", "satisfaction", "contribution to economic development" (Yıldız-Geyhan et al., 2017). Ibáñez-Forés et al. (2019) referred to the "socio-economic conditions" as "local development". In this case the category depends on the development of environmental awareness and responsibility, and on the formal integration of workers from informal sectors. Instead, Menikpura et al. (2012a) applied a different endpoint category, named "income-based community well-being", which is indicative of the contribution of MSWMSs to the well-being of the community, through the direct income for workers and the indirect income for the local community, due to the recycling of materials. Indeed, this category depends on the "job creation", as well as the indirect income generation and cost of living. Finally, the "marginalization index" is a way to assess the socioeconomic condition of waste pickers in informal management systems. Marginalization is associated to a lack of social opportunities, or skills needed to acquire or generate such opportunities, as well as privation and lack of accessibility to basic goods and services required for well-being. The socioeconomic dimensions used to estimate the "marginalization index" include education, housing, and access to general goods (Botello-Álvarez et al., 2018).

6. Sustainability Composite Indexes

For the purposes of this work, it is interesting to notice that some case studies used the so-called Sustainability Composite Indexes (SCIs), revolving around multiple pillars of sustainability.

Some of the reviewed papers have made attempts to define SCIs, providing comprehensive information on the sustainability performance of MSWMSs. Even though the use of a single exhaustive index can simplify the comparison among multiple options, it is frequently argued that composite indexes could be too subjective, as their value depends on the chosen methods of normalisation, weighting, and aggregation (L. Zhou et al., 2012).

Table 3 reports the composite indexes, showing that some of them combine only the environmental and economic impact categories, even though Woon and Lo (2016) also approached the social pillar by including the midpoint impact category "disamenities cost" and expressing it as a fixed externality cost associated with the price of local properties, thus treating it as an economic category. Similarly, Prateep Na Talang and Sirivithayapakorn (2021) accounted for the impact on the community through the endpoint category "human well-being" but assimilating it to the environmental category "human health".

Even though several case studies labelled their composite index as "Eco-Efficiency Indicator", they used different definitions and formulas to establish its value.

It is worth pointing out that the concept of "eco-efficiency" was first described by the World Business Council for Sustainable Development as "the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the Earth's estimated carrying capacity". In general, an eco-efficiency indicator should account for both scientific and technical issues, as well as economic ones, but not for the social dimension; nonetheless, this pillar could be accounted for in an implicit way, for example by including the concept of social justice (Caiado et al., 2017). However, in sustainability assessments, the authors defined the influence on the environment and the economy with different categories and/or indicators, and they also used different methods of representation, either through formulas or via graphical illustrations, ending up in a wide variety of Eco-efficiency Indexes.

On the other hand, some papers have established a SCI as the normalised and weighted sum of the values obtained for the composite indicator of each one of the pillars of sustainability and can be described as:

$$SCI = I_{env} * w_{env} + I_{eco} * w_{eco} + I_{soc} * w_{soc}; \tag{1.1}$$

Where I represents the normalised value of the impact on either the environment, economy, or society, and w corresponds to the weight attributed to that pillar. Such indexes are extremely useful, especially for communicating the sustainability of MSWMSs to non-experts of the field; nonetheless, apart from the previously discussed issues related to composite indexes in general, in the specific case of the application of LCT tools, there are miscalculation problems related to the use of the same indicators to quantify more than one midpoint category (Costa et al., 2019), related to multiple aspects of sustainability. The aggregation of such impact categories in order to obtain a SCI can lead to double-counting problems and consequently to misinterpretation of the factual sustainability of a system.

7. Discussion

The bibliographical research showed a worldwide rising interest towards the sustainability evaluation of MSWMSs, through the implementation of the LCSA methodology. Even though the knowledge gathered in the present study aims at addressing efforts made to improve this approach, with special regard towards strategies to evaluate CE

Table 3
Description of the identified Sustainability Composite Indexes.

Composite Sustainability Indexes	Description	Reference	Pillars
Welfare Economic Result	Aggregated results of fLCC and eLCC	Reich (2005)	Environmental and Economic
Eco-Efficiency Indicator	Graphical representation of the Life Cycle human Health Cost, on the x-axis, and of the LCC index, on the y-axis, a	Woon and Lo (2016)	
Composite Indicator	Graphical representation of the Material and Energy Recovery Indexes, on the x-axis, and of the Cost Index, on the y axis	Rigamonti et al. (2016)	
Eco-Efficiency Indicator	Ratio between global warming impact, normalised in regard to the Gross National Environmental Impact, and the cost impact, normalised in regard to the Gross Domestic Product	Zhao et al. (2011)	
Total Cost	Sum of Environmental cost and Net Cash Flow	Prateep Na Talang and Sirivithayapakorn (2021)	
Eco-Efficiency	Ratio between the normalised carbon footprint and the net present value of the MSWMS	Abdeljaber et al. (2022)	
Global Preference index	Weighted sum of the values for environmental, economic, and social pillars	Makan and Fadili (2020)	Environmental, Economic and Social
Net Cost	Sum of the cost and benefits related to the environmental, economic, and social aspects, and expressed in currency	Lam et al. (2018)	
Social Cost of Household Kitchen Waste	Sum of the environmental cost, household cost, direct cost	Yu and Li (2020)	
Preference Index	Weighted sum of the normalised values for environmental, economic, and social pillars	Gadaleta et al. (2022)	
Suitability Index	Weighted sum of the normalised values for environmental, economic, and social pillars	Mozaffari et al. (2023)	
Sustainability Index	Weighted sum of the environmental, economic, and social criteria	Stefanović et al. (2016)	
Sustainability Goal	Weighted sum of the values for environmental, economic, and social pillars	Li et al. (2015)	
Integrated Sustainability indicator	Graphical representation of the normalised values per impact categories related to environmental, economic, and social pillars	Di Maria et al. (2020)	
Composite Sustainability Index	Weighted sum of the normalised values for environmental, economic, and social pillars	Aleisa and Al-Jarallah (2018)	
Global evaluation	Weighted sum of the normalised values for environmental, economic, and social pillars	Fernández-González et al. (2017)	
Global Sustainability Index	Weighted sum of the environmental, economic, and social requirements satisfaction indexes	Pons et al. (2018)	

solutions and technologies applied to MSWMSs, more research is still necessary to overcome the limits of LCSA for WMSs and promote its further development.

7.1. Use of impact categories

Most of the identified limits in the use of the LCSA approach for MSWMSs are due to divergences in the use of the impact categories among the three main LCT tools included in this type of analysis (eLCA, LCC, sLCA). In general, all the indicators and parameters causing the same types of impacts should be gathered under the same midpoint impact categories. While this is a customary practice for the environmental categories, the economic costs and revenues are often grouped in categories depending on when they occur during the life cycle of the management waste facility. For example, it has been observed how the impact caused by labour costs is not always considered as its own category, but it is distributed among several impact categories that are representative of the economic costs during the initial phase of a project, while it is operating, and then at the end of its life cycle. Similarly, it has been observed how some social indicators and categories are exclusively related to the collection waste phase and are instead ignored during the rest of the life cycle, especially the ones linked to the level of acceptance or participation of the community. Therefore, there are some discrepancies in the characterisation of the environmental, economic, and social impact categories that limit the homogeneity of the LCSA approach for MSWMSs.

7.2. Definition of impact categories

Another relevant issue is related to the use of impact categories characterised by different definitions in the available literature. The lack of coherence in the definition of such categories leads to results incomparability among studies. Indeed, due to the absence of affirmed standard references for the economic and social categories, some of these are applied by life cycle analysts with different meanings, thus assessing different values and leading to the misinterpretation of the actual impacts caused by MSWMSs. This phenomenon has been mainly observed for the economic assessment phase, as in the case of the impact category “operational costs”, which can either include or exclude the “labour costs” or the “maintenance costs”, according to the interpretation applied. Other differences exist among the environmental categories related to resources recovery, due to the different interpretation of the term “resource”, which can include different types of primary and secondary resources, as well as recovered energy. Besides, the fact that in a proper LCSA some endpoint or midpoint categories depend on indicators that are pertinent to multiple sustainability pillars complicates their definition process. Indeed, it has been observed how the impact category “disamenities cost” can be considered either a social or an economic category, depending on how it is evaluated and on the indicators that it includes.

7.3. Stakeholders’ perspectives

Several elements of an LCSA study, such as the aspects of sustainability to evaluate and the phases of WMSs to incorporate in the study, depend on the perspective of the stakeholders included in the assessment. Such dependence can lead to an underestimation of burdens on some stakeholders’ groups, as in the case of the economic endpoint categories. These aim at evaluating the total expenditures or profits of the MSWMSs from the facilities owners’ perspective, while dismissing the costs and revenues for the community, thus neglecting the socio-economic impacts. Consequently, some indicators and impact categories can be differently interpreted depending on the considered stakeholders. Indeed, in some case studies, the “labour cost” category has a positive or negative connotation, depending on the sustainability pillar under evaluation or on whether the owners or workers perspective is being considered.

7.4. Double-counting phenomenon

The double-counting issue is another flaw highlighted in the present review, affecting the implementation of LCSA for the evaluation of WMSs. It takes place when indicators are used to assess the impact on multiple midpoint categories, or similarly when some midpoint categories are involved in the assessment of more than one endpoint category. This can lead to the overestimation or the concealing of relevant impacts making the approach unreliable. This phenomenon can interest categories related to the same sustainability pillar, as in the case of several environmental endpoint categories (e.g., “environment quality” and “human health”), or categories belonging to other aspects of sustainability.

7.5. Life cycle phases’ relevance

The literature review also underlined how certain processes are excluded from the boundaries of the MSWMS to evaluate, based on the aspects of sustainability for which the impacts are being assessed and the involved stakeholders. For example, it has been widely observed that the dismission phase of waste facilities has a limited economic impact on the owners, compared to the other costs during its lifespan, therefore all the economic burdens related to this phase are usually omitted from LCSA studies, even though they can still be relevant in terms of environmental and social burdens on the workers and the community. Thus, for a complete LCSA, all phases of waste management that bear an environmental, economic, and/or social impact should be considered, independently from their relevance in comparison to other burdens.

7.6. Data quality and availability

The LCSA strongly relies on the use of qualitative rather than quantitative data for the social sustainability assessment, possibly leading to a lack of objectivity. Several social parameters are based on the information provided by questionnaires dispensed to different stakeholders, making the social impacts difficult to quantify, if not through scoring systems. Besides, some of the data necessary to define quantitative social impacts, as well as economic and environmental ones, cannot be evaluated in an ex-ante approach, but they require already available data. For example, the “occupational health”, which focuses on the number of fatal and non-fatal accidents involving waste management workers, is difficult to estimate as a potential impact and is normally calculated on the basis of already occurred and recorded accidents. In relation to the data availability, it should also be considered that future efforts to make LCSA an efficient method for evaluating MSWMSs should be devoted to establishing a database containing numerical information about the environmental, economic, and social parameters regarding MSW.

7.7. Sustainability composite indexes’ limits

From the literature analysis it was also possible to observe that SCIs are often characterised by a common lack of objectivity in the impact categories normalisation, weighting, and aggregation processes, and even more interesting is the recurrent exclusion of the social impacts, in favour of the environmental and economic ones. Indeed, many case studies, attempting to include sustainability indexes in the assessments of MSWMSs, used the eco-efficiency index, which focuses exclusively on the environmental and economic burdens. Besides, such index can be evaluated in different ways, thus limiting its comparability among studies.

7.8. CE impact categories

Finally, the case studies analysis highlighted a growing interest towards the integration of CE solutions in WMSs and the consequent need for more indicators and categories to account for the impacts caused by the reintroduction in the productive chain of materials and energy recovered from waste, and by the actions aiming at waste prevention. The inclusion of such categories in LCSA studies would allow to better assess the sustainability of technologies and processes that aim at the reuse of resources, as well as the integration in the economy of recovered materials and energy. Thus, the better evaluation of the impact of the entire life cycle of waste throughout all the possible phases of its prevention, management, and reuse would allow to better evaluate the sustainability of CE choices.

8. Conclusions

The bibliographical research on the use of LCT tools for the sustainability assessment of MSWMSs has led to the conclusion that LCSA is still evolving and has the potential to become a useful tool for the evaluation of CE solutions applied to waste management. Nonetheless, there are multiple issues that still need to be faced. The relationship between indicators and categories must be properly defined to account for the impacts on all aspects of sustainability, while considering the effects on all the involved stakeholders, through the entire life cycle, and avoiding double-counting issues. In particular, the common aspects between the sustainability pillars should be further investigated, to develop an LCSA approach that evaluates sustainability in a coherent and integrated way, instead of as the combination of separate studies on the environmental, economic, and social burdens. Besides, the literature analysis showed a lack of indicators and categories that can quantify the impacts of using materials and energy recovered from waste, thus limiting the ability of LCSA to account for the effects of circular approaches through the entire life cycle of recovered waste. Therefore, further research is necessary to improve the LCSA method for MSWMSs.

CRediT authorship contribution statement

Annachiara Ceraso: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alessandra Cesaro:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122143.

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