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# SUSTAINABILITY IN BUILDINGS AND WASTE SECTOR: METRICS, CHALLANGES AND OPPORTUNITIES

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Anna Degli Esposti: Sustainability in buildings and waste sector: metrics, challanges and opportunities,
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*To my family*
*I could not have done this without you, Simone*

*I keep reminding the young people*
*if we go to the same route we go to the same destination,*
*if we want to go to the new destination*
*we have to build new roads.*
*(Muhammad Yunus)*

# ABSTRACT

Nowadays, the scientific community has devoted a consistent effort to the sustainable development of the waste management sector and resource efficiency in building infrastructures. Waste is the fourth largest source sector of emissions and the municipal solid waste management system is considered as the most complex system to manage, due to its diverse composition and fragmentation of producers and responsibilities. Nevertheless, given the deep complexity that characterize the waste management sector, sustainability is still a challenging task. Interestingly, open issues arise when dealing with the sustainability of the waste sector.

In this thesis, some recent advances in the waste management sector have been presented. Specifically, through the analysis of four author publications this thesis attempted to fill the gap in the following open issues: (i) the waste collection and generation of waste considering the pillars of sustainability; (ii) the environmental and social analysis in designing building infrastructures; (iv) the role of the waste collection in boosting sustainable systems of waste management; (v) the ergonomics impacts of waste collection. For this purpose, three author publications in international peer – reviewed journals were selected among the wholly author's contributions (i.e., final publication stage), and one manuscript under peer review were also provided.

Particularly, with reference to the first point, the authors gave a valuable contribution to the formulation and promotion of waste prevention strategies.. The authors have proposed a methodology to monitor waste generation and waste service costs at the municipal level: an algorithm to support the identification of a priority order for three project categories was provided (i.e., drinking water dispenser in town/city, drinking water dispenser in school, replacement of disposable goods in school canteens). More specifically, by adopting a life-cycle perspective, the environmental, economic, and social consequences of waste prevention measures within the selected categories were assessed. Thus, a set of indicators for the evaluation of the effectiveness and the efficiency of the projects was defined. Authors have also

demonstrated the high potential for preparing for reuse and reusability within the municipal solid waste collection system. The authors have proposed a model to support waste management operators of municipal solid waste services: a framework to evaluate the potential of preparation for reuse as a strategy to jointly decrease social, environmental, and economic impacts and meet the legal targets on waste management was proposed. The proposed reusability indicator includes one coefficient evaluating the potential for reuse, and three impact indicators for the assessment of social, environmental, and economic performances. The indicator can be calculated by using real data, gathered by the waste collection operators in collaboration with reuse centers and referred to previous years.

Regarding the second point, it has demonstrated the high potential for recycling the Reclaimed Asphalt Pavement and the steel slags in the road construction sector, as a secondary raw material and a by-product, respectively. The authors have also demonstrated that the Life Cycle Assessment is an appropriate tool to compare and to communicate the environmental performances of different asphalt mixtures in road constructions. By reducing the global environmental impact and recycling by-products, the firm and the co-located companies which have been considered in the study were a case study of industrial symbiosis at the meso-level.

Finally, the authors have the ambition to shed light on the role of waste collection and ergonomics' impacts of the door – to – door collection systems. A theoretical framework for assessing the sustainability of the waste collection in a life cycle perspective has been provided. The framework has quantitatively assessed the impact of the door-to-door collection system on the health and safety of the workers, and it has provided indications to waste collection operators on how the load carried by workers can be minimized, and the economic and social sustainability can be improved. The analysis is complemented by an economic analysis, which estimates the costs associated with the collection system under consideration, and by a social life-cycle assessment. The authors have demonstrated that the use of 120-liters capacity bins would effectively improve the ergonomics and optimize the costs of the investigated activity. More specifically, due to the use of mechanized collection, the more limited number of lifting and carrying operations would expose the workers to lower ergonomic risks.

## **PUBLICATIONS** INCLUDED IN THE THESIS

Ideas and figures presented in this thesis have been previously published or submitted for publication in the following journal articles:

1. Bonoli A.; **Degli Esposti, A**.; Magrini, C., (2020). *A case study of industrial symbiosis to reduce GHG emissions: performance analysis and LCA of asphalt concrete made with RAP and steel slags*, Frontiers in materials. 7, 1 – 14.

2. Magrini, C.; **Degli Esposti, A**.; De Marco, E.; Bonoli, A., (2021), *A framework for sustainability assessment and prioritisation of urban waste prevention measures.* Science of the total environment. 776, 1 – 12.

3. **Degli Esposti, A**.; Magrini, C., Bonoli A., (2021). *Municipal solid waste collection systems: An indicator to assess the reusability of products.* Waste management and research. 39, 1200 – 1209.

4. **Degli Esposti, A.**, Magrini, C., Bonoli, A., (2022). *Door-to-door waste collection: a framework for the sustainability assessment and ergonomics optimisation*. Waste management. 156, 130 - 138.

## **PUBLICATIONS** NOT INCLUDED IN THE THESIS

Some ideas presented in this thesis have been previously published in conference proceedings and scientific journals:

1. Carollo, F., Cecere, G., Bottausci, S., Camana, D., Cappucci, G., M., **Degli Esposti, A**., Demichelis, F., Magrini, C., Mazzi, A., Miranda, G., Sciarrone, M., Rigamonti, L., Fedele, A. *Il ruolo della LCA nei piani regionali di gestione dei rifiuti in Italia*, in: Conference proceeding, 2022, pp. 1 - 1 (atti di: Convegno della rete italiana LCA, Palermo, 24-25 Giugno 2022) [**Conference Proceedings**];

2. **Degli Esposti, A.**, Magrini, C., Bonoli, A., Cavani, S., Monti, M., *Door-to-door paper waste collection: a case study of cost and ergonomics optimisation*, in: SARDINIA 2021. 18th International Symposium on waste management and sustainable landflling. Conference proceedings, Eurowaste srl, «SARDINIA...», 2021, pp. 1 - 2 (Proceedings: SARDINIA 2021 - 18th International Symposium on waste management and sustainable landflling, Santa Margherita di Pula, Cagliari, 18-20 November 2020) [**Conference Proceedings**];

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# REFERENCES

## ACRONYMS

ATERSIR Emilia-Romagna territorial agency for the water, sanitation, and waste services

BM Business Model

BW Bottled Water

CE Circular Economy

CMA Cold Mix Asphalt

CO2eq carbon dioxide equivalent

CR Collection Route

DF diffusion factor

DTD Door – To - Door

EAF Electric Arc Furnace

EAPA European Agency Pavement Association

EC European Commission

EEA European Environment Agency

EMR Emilia-Romagna Region (IT)

EPD Environmental Product Declarations

EPR Extended Producer Responsibility

EU European Union

GDP Gross Domestic Product

GHG Greenhouse Gas

GPP Green Public Procurement

GWP Global Warming Potential

HMA Hot Mix Asphalt

IA Impact Assessment

IE Industrial Ecology

IE inhabitant equivalent

IS Industrial Symbiosis

ISO International Organization for Standardization ISPRA Italian Institute for Environmental Protection and Research IT Italy

IWMS integrated waste management system

JRC Joint Research Centre of the European Commission

LCA Life-Cycle Assessment

LCC Life-Cycle Costing

LCIA Life Cycle Impact Assessment

LCT Life Cycle Thinking

LI Lifting Index

MMH Manual Material Handling

MS Member State

MSD Musculoskeletal Disorder

MSW Municipal Solid Waste

MSWM Municipal Solid Waste Management

MWM Municipal Waste Management

NIOSH National Institute of Occupational Safety and Health

OD Occupational Disease

OECD Organization for Economic Cooperation and

Development

PE Population Equivalent

PfR Preparation for Reuse

PET Polyethylene Terephthalate

RAP Reclaimed Asphalt Pavement

RC Reduction of Cost

SDG Sustainable Development Goal

SETAC Society of Environmental Toxicology and Chemistry

S LCA Social Life Cycle Assessment

SM Sustainability Metric

SUP Single Use Plastic

SWC Separate Waste Collection

UN United Nations

UNI Italian body of standardization

UNEP United Nations Environment

Programme US United States (of America)

UW Urban Waste

WFD Waste Framework Directive

WM Waste Management

WMA Warm Mix Asphalt

WMS Waste Management System

WMP Waste Management Plan

WP Waste Prevention

WPM Waste Prevention Measure

WSL Work Shift Lenght

# PREFACE

I started as PhD student in November 2019 at the University of Bologna in the Department of Civil Chemical Environmental and Materials Engineering (DICAM) in collaboration with the “Geovest” firm. During the years of PhD, three experiences left their marks.

Firstly, the participation of a Summer School in September 2019 and the “Economy of Francesco” live-streaming event from the 19th to 21st November 2020. I attended the Summer School “Economia e lavoro: Circolarità e Cooperazione” (Circular Economy and Co – operation paths) which belongs to the Italian project created in 2019 and entitled “Percorsi Assisi”. This project stem from an initiative of the the Sacro Convento located in Assisi, Father Mauro Gambetti, and the General Director of LUISS Guido Carli (“Libera Universita Internazionale degli Studi Sociali”) Giovanni Lo Storto, as well as three Universities – “Politecnico of Milan”,“Federico II ” - Naples, and “Alma Mater Studiorum” - Bologna:

As the Nobel Prize Muhammad Yunus told us during a Lectio Magistralis: “*I keep reminding the young people if we go to the same route we go to the same destination, if we want to go to the new destination we have to build new roads”.* Thanks to the participation in the Summer School, I decided to be involved in the global event Economy of Francesco, a call made by the Holy Father to young economists and entrepreneurs worldwide to take part in the global initiative very close to Pope Francis’ heart.

From the letter sent by the Holy Father for the Economy of Francesco: “*An event that will allow me to encounter young men and women studying economics and interested in a different kind of economy: one that brings life not death, one that is inclusive and not exclusive, humane and not dehumanizing, one that cares for the environment and does not despoil it. An event that will help bring us together and allow us to meet one another and eventually enter into a “covenant” to change today’s economy and to give a soul to the economy of tomorrow”.*

Since in December 2019 among more than 3000 applications coming from 120 Countries I was selected as a member of this global movement of 2000 researchers, I took part in the live streaming event as well as the "Life and Lifestyle" Village. Indeed, in the months before the event, 12 Villages were created for working sessions of the participants on the economy of today and tomorrow. Through working sessions and key lectures from speakers coming from all over the world, the aim was to talk about growth models, environment, social equity, and future generations.

The need for a new economy and new models of growth, amplified by the COVID-19 pandemic, has called for a profound rethinking of my life and life - style. Following my interest in these topics and the topics of the research study, I started the collaboration to the activities of the LCA Network and the working group – "Gestione e Trattamento dei rifiuti" (Waste Management and treatment) with prof. Lucia Rigamonti PhD of the Politecnico of Milan, and Eng. Andrea Fedele. Within the framework of the waste management systems, the activity of the network aims at developing new Life Cycle Thinking methodologies. The collaboration provided three publications: i) one conference paper; ii) one publication in a national journal (Rigamonti et al., 2020); and iii) one manuscript submitted for publication in the international peer – review Waste Management journal.

Finally, the collaboration to the activities of Symbiosis User Network (SUN)[2] working group 4 - "Certificazione e standard per la simbiosi industriale" (Standardization of industrial symbiosis)[3] aims at monitoring industrial symbiosis models, mapping case study of industrial symbiosis, developing dedicated tools for companies and firms, training on standardization, networking with national and international standardization bodies (i.e., International Standardisation Organisation). The collaboration provided a manual entitled "Gli standard per la Simbiosi Industriale" (Industrial Symbiosis Standards), actually under review.

# INTRODUCTION

With an urban population of several billions, world generates billions of tonnes of waste annually. It is well known that designing sustainable systems of waste is advantageous from any waste management strategy such as prevention, reuse and recycle. Nowadays, the concept of sustainability is a complex and interconnected issue, and it is also referred to as sustainable consumption and production. It has been increasingly relevant from a sustainable development perspective to face the environmental crisis that affects society nowadays.

In the last half-century, the scientific community devoted a consistent effort to the sustainable development of the waste management sector and resource efficiency in building infrastructures. Systems solutions as a circular economy and industrial symbiosis gives us the power to grow prosperity and resilience. Driven by the conceptual framework of circular economy and sustainable development goals, researchers tackle global challenges like climate change, biodiversity loss, waste, and pollution.

For this purpose, the main objective at the basis of this thesis is the definition of metrics and indicators for the evaluation of the sustainability in building infrastructures and waste sectors. As decisive criteria for the implementation of the waste hierarchy, the social and economic dimensions of sustainability have been investigated together with environmental aspects in a life cycle perspective. In this context, the collaboration to the activities of the Italian Network of the Geovest firm, Life Cycle Assessment, and the Symbiosis User Network, has pointed out the opportunities and the limitations of life cycle thinking.

However, given the deep complexity that characterize waste and buildings sectors, sustainability is still a challenging task. Interestingly, open issues arise when dealing with the substantiality of the waste management systems and building infrastructures.

Among them, the following open issues appear particularly stimulating:

(i) How to monitor the collection and generation of waste?
(ii) How can the effects of a waste collection system be measured considering the pillars of sustainability?
(iii) Can environmental and social analysis support the design of buildings and waste management systems?
(iv) What is the role of waste collection in boosting sustainable systems of waste management? (v) How can ergonomics impacts of different waste collection be assessed and compared?

In such a framework, to fill the afore-mentioned gaps the author proposes some metrics for the evaluation of the sustainability in the waste sector. Essentially, the advancements pursued in the framework of waste management at European, national, regional, and local levels are shown and discussed.

Firstly, a comprehensive state of art about the municipal solid waste sector is given in Chapter 1. The mentioned review attempts to put the waste management to the wide national and regional legislation in this field. Within the framework of the circular economy and the European "waste hierarchy", the main challenges of the municipal solid waste sector are also discussed.

Secondly, focusing on waste collection, the evaluation of the sustainability of waste collection measures is conducted in Chapter 2, together with a literature review on novel indicators for the waste sector. This review attempts to put waste collection in order for the wide scientific production in this field. Additionally, the future challenges of the municipal solid waste sector are also discussed.

Then, in Chapter 3 the state of the art of the Life Cycle Assessment and Social Life Cycle Assessment tools, and Industrial Symbiosis strategy is proposed. Within the framework of Life Cycle Thinking, the Life Cycle Assessment analysis is described as a considerable method to evaluate the environmental impacts of the waste sector. Then, the integration of social criteria into Life Cycle Assessment is explored describing the approaches for Social Life Cycle Assessment. In line with that, the Industrial Symbiosis is proposed as a strategy to substantially reduce waste generation through recycling and reuse options. Dealing with the sustainability issue, the pertinent Sustainable Development Goals are mentioned as a link to the waste issue mentioned in Chapter 1 and Chapter 2. Finally, Chapter 4 provides the publications of the author on the above-mentioned topics. Final conclusions are delineated in the Conclusions section.

# 1

***State of art of the waste policy**. In Chapter 1 a comprehensive review of the European and Italian legislation on municipal solid waste is presented. This review attempts to put the waste management to the wide national and regional legislation in this field. Within the framework of the European "waste hierarchy" and circular economy, the main challenges of the municipal solid waste sector are also discussed.*

The European Waste Framework Directive (WFD) defines waste as an object the holder discards, intends to discard or is required to discard (EC, 2018). In Europe every year about 5 tonnes of waste are produced by the average European and only 38% of which is recycled (EU, 2022). Consequently, it means that over 60% of household waste still goes to landfill in most of the EU countries. Moreover, waste is the fourth largest source sector of emissions (Eurostat, 2020), and its generation is globally recognised as an intrinsic product of several factors, such as the urbanization, the population growth, the changing lifestyles, and the development of societies (Kaza et al., 2018, AlHumid et al., 2019). In this context, municipal waste represents around 10% of the total waste generated in the EU and it is considered as the most complex stream to manage, due to its diverse composition and fragmentation of producers and responsibilities (EC, 2018, Rossi et al., 2022).

Concerning EU waste policy, a key principle is to move waste management up the 'waste hierarchy' and to follow the principles of a circular economy (CE). The basic principles of a CE are to maintain resource value in the economic cycle for as long as possible, and to prevent and reduce the negative effects of obtaining primary resources on the environment and society.

According to the WFD and the so-called waste hierarchy, waste prevention (WP) is the most favorable option, followed by reuse and preparing for reuse (PfR), recycling and other methods of recovery, while waste disposal is the least favorable option. Within this framework, in order to comply with the WFD the EU Member States (MSs) have to set out clear long-term policy objectives (e.g., economic instruments and measures to provide incentives for the application of the waste hierarchy, end-of-waste criteria, guidance documents, case-by-case decisions, Extended Product Responsibility schemes), planning, plans and programmes (i.e., WMPs, WP programmes), and national targets (i.e., waste collection rate). Specifically, the WFD following articles 1, 4, 13, 16, and 28, requires that each member state assesses a national WMP with mandatory requirements (EU, 2018). From a policy and legislative perspective for developing an ideal WMP, optional criteria have also been established from the European Union (EU), (EC, 2009, EC, 2012). As for the evaluation of environmental impacts, within the framework of Life Cycle Thinking (LCT), the Life Cycle Assessment (LCA) has been listed among the tools that aim at supporting the assessment of the impacts and the benefits associated with different policy options (Sala et al., 2016).

Concerning LCT and LCA, Sala et al. (2016) also stated that in recent years several documents referring to the environmental discussion have been published (i.e., 15 environmental policies, 8 EU Directives, 4 Regulations). In this context, a series of literature studies explored the evolution of LCA oriented policies at European level (Sala, et al. 2021, Di Maria et al. 2020, Lehmann et al. 2015) and they all conclude that strengthening the science-policy binomial would allow the decision makers to wholly benefit from LCA applications.

Likewise, the United Nations Agenda 2030 promotes sustainable development through a plan of action for people globally (UN, 2015). The 17 sustainable development goals (SDGs) aim to build a global partnership for sustainable development and to improve human lives and protect the environment. Concerning global challenges in the field of waste management, SDG11 encourages safe, resilient, and sustainable cities, while SDG 12 promotes sustainable consumption and production patterns, and it includes targets focused on environmentally sound management of all waste through prevention, reduction, recycling, and reuse strategies (targets 12.4 and 12.5).

*Waste prevention*

In Europe, the waste management (WM) sector accounts for 3% of total greenhouse gas emissions in 2017 (Eurostat, 2020). The implementation of best practices might boost the achievement of the 2050 European climate-neutrality target, or the intermediate goal envisaging at least −55% net GHG emissions by 2030, as stated by the European Green Deal (European Commission, 2020). As the European waste hierarchy places the greatest preference on WP which is the most favorable WM option, above reuse, recycling, and recovery (EU European Union, 2008, EU European Union, 2018), WP is also an important element within the paradigm of sustainable development. In the frame of United Nations Agenda 2030, SDG 12 (Ensure sustainable consumption and production patterns) includes targets focused on environmentally sound management of all waste through prevention, reduction, recycling, and reuse (targets 12.4 and 12.5) and reduction of food waste (target 12.3). At a global level, WP is particularly important in urban areas, where the population is increasing, and waste generation is higher. Accordingly, the SDG 11 (Make cities and human settlements inclusive, safe, resilient, and sustainable) aims to "reduce the adverse per capita environmental impact of cities, including special attention to air quality and municipal and other waste management", and the New Urban Agenda (United Nations, 2017) commits to "environmentally sound management and minimization of all waste".

For this purpose, WP may play a significant role in emission reduction and more specifically in climate change mitigation, if implemented globally (Gentil et al., 2011): the potential greenhouse gasses (GHG) savings from WP administration could greatly exceed the savings that can be achieved by advanced technologies managing post-consumer waste (ISWA, 2010). Nevertheless, over the time frame between 2013 and 2018, an increase in per capita generation of municipal solid waste (MSW) occurred in the European Union. Rising demand for and supply of primary resources weaken the EU's material self-sufficiency and put pressure on the environment. Although the political commitment to this topic, according to literature very little is understood about how to monitor and evaluate WP particularly among local authority waste managers who are most likely to implement intervention campaigns (Sharp et al., 2010; Corsini et al., 2018; Gusmerotti et al., 2019, Magrini et al., 2021).

*Reuse and preparation for reuse*

From a CE perspective, reuse directly contributes to waste prevention and reduces the demand for waste treatment and disposal, while indirectly reducing the demand for new items. Within this framework, preparation for reuse (PfR) is one of the most favorable strategies to select products that are likely to be reused and that may be prevented from being wasted through recovery operations.

*Recycling and recovery operations*

Recycling is one of the main ways for achieving sustainable waste management and for reducing the consumption of primary resources by replacing them with secondary materials made of recycled waste. The overall idea is to reconsider the whole life cycle of resources, to make the EU a “circular economy” based on recycling, and the use of waste as a resource (EC, 2011). This is the desired approach to achieving sustainability and material self-sufficiency. For this purpose, over the years the EC has put various policy initiatives in place to encourage the industries toward CE principles (e.g., construction industry). Moreover, the use of alternative materials would therefore be a strategy to be boosted, establishing regional industrial symbiosis (IS) agreements which can support companies to gain competitiveness and reduce the environmental impact associated with their day-to-day business activities (Martin- Portugues Montoliu et al., 2019). According to the WFD (EU, 2018), MSs are encouraged to adopt implementing acts to establish detailed criteria on the application of the by-product status, end of waste system, and prioritizing replicable practices of industrial symbiosis (e.g., Green Public Procurement).

For that reason, the EC has recently launched an industry led IS reporting and certification system (EC, 2020) where the symbiotic activities can be applied at different levels. According to Roberts, 2004, they can involve a single firm or organization (i.e., micro level); companies co-located in the same area (i.e., meso level); and the entire regional or national production system (i.e., macro level). Specifically, the greatest benefits are achieved at the meso level, where the clustering of complementary companies provides a complexity of functions (Roberts, 2004; Taddeo, 2016).

Following this issue, as Europe's public authorities are major consumers of goods, services and works, they can make an important contribution to sustainable consumption and production through the so called Green Public Procurement (GPP) or green purchasing[1]. The EC also stated that to be effective the voluntary instrument requires the inclusion of clear and verifiable environmental criteria for products and services in the public procurement process,

[1] https://ec.europa.eu/environment/gpp/index_en.htm

as it has a key role to play in the EU's efforts to become a more resource-efficient economy. For this reason, the European MBs have developed guidance in this area, in the form of national GPP criteria.

In the Italian context the so called Minimal Environmental Criteria (“Criteri ambientali minimi – CAM”) are the environmental requirements defined for the various phases of the purchasing process in order to determine the best ecological solution for the project throughout its life cycle, taking into account market availability. The public administration defines the CAMs within the framework of the plan for the environmental sustainability of consumption, being adopted by decree of the Minister of the Environment for the Protection of Territories and the Sea (Law, 2015; Legislative Decree, 2016, Legislative Decree, 2017).

Concerning buildings and waste collection sectors, recently the Italian Minister of Environment have just published the CAM on the end of waste of CDW as well as the waste collection system (Decree, 152/2022; Decree, 182/2022): the challenge of furthering take- up by more public sector bodies and a level playing field that will accelerate and help drive the single market for environmentally recycled aggregates and waste collection services so that GPP becomes common practice.

## 1.1 Legislation on MSW at European, National (Italy) and Regional (Emilia-Romagna) levels

In Europe, over the last few years the CE framework has guided the overall policy decisions (EC, 2008, EU 2018). The Green New Deal in particular aims to foster sustainable practices for all fields in the European economy, including targets for urban waste management operators and local governments (EC, 2019).

Italian municipalities are required to reduce per capita waste production, to increase their separate collection rates, to increase recycling and recovery operations, to increase preparation for reuse rate, and to avoid landfilling unsorted waste (Legislative Decree 1997, Legislative Decree 2006). Five years after the adoption of the 2030 Agenda, the Italian political agenda has transposed the goal to reduce the adverse per capita environmental impact of cities by 2030 (target 11.6), including by paying special attention to municipal waste management (UN, 2015; Italian Ministry of the Environment, Land and Sea, 2017).

The municipal solid waste management system in Europe, Italy and Emilia – Romagna Region is discussed considering two dimensions: a twelve years timeline (2006–2021), and the urban waste prevention, municipal separate waste collection, and urban waste treatment (i.e., re-use, preparation for re - use, recycling) which provides a deeply analysis of the Italian context in terms of sustainability indicators and targets. The Emilia – Romagna Region legislation was also investigated. The selected period reflects two distinct stages of the European, Italian and regional levels: the first period (2004 – 2006) in which the EU adopt legislation in all areas and particularly as it regards the solid waste management field (i.e. EU WFD); the following period, that can be considered as the implementation period (2008–2021*)*.

As it may be observed in the following tables, in recent years the legislation, policies, strategies and all the instruments related to the municipal solid waste management were enforced (i.e., EU WFD, ER WMP).

**Table 1.1** – Strategic and legal targets on urban waste prevention at European, National (Italy) and Regional (Emilia-Romagna) level.

| Actions | Institutional level | Documents | Indicators | Targets |
|---|---|---|---|---|
| Urban waste prevention | European Union, EU | Directive 98/2008/EC, modified by 851/2018/EC (EU WFD) (EU, 2018b) | - | - |
| | National, Italy | National Waste Prevention Programme / 2013 (Italian Ministry of the Environment, Land and Sea, 2013) | Ratio of urban waste generation to GDP (Gross Domestic Product) | Reduction by 5% of municipal solid waste per GDP by 2020 (compared to 2010) |
| | Regional, Emilia – Romagna Region | Waste Management Plan (ER WMP) / 2016 (Legislative Assembly of Emilia-Romagna Region, 2016) | Municipal waste production | Reduction by 20-25 % of waste production (compared to 2011) by 2020 (equal to 539 kg/ inhab). |

**Table 1.2** – Strategic and legal targets on municipal separated collection at European, National (Italy) and Regional (Emilia-Romagna) level.

| Actions | Institu tional level | Documents | Indicators | Targets |
|---|---|---|---|---|
| Munici pal separa te waste collec tion | European Union, EU | Directive 2008/98/EC, modified by 851/2018/EC (EU, 2018b) | Separate waste collection | Separate waste collection at least for paper, metal, plastic and glass, and, by 1 January 2025, for textiles |
| | National, Italy | Legislative De crete 205/2010 (Italian government, 2010)<br>Legislative Decree 152/2006 (Italian government, 2006) | Separate waste collection;<br>Rate of sepa rate waste collection | Separate waste collection at least for paper, metal, plastic and glass.<br>If it is technically possible, separate collection for organic waste (LD 205/2010) and wood (LD 152/06).<br>Separate waste collection rate:<br>By 2006, 35 %; By 2008, 45 %; By 2012, 65 %. |

| Actions | Institu tional level | Documents | Indicators | Targets |
|---|---|---|---|---|
| Munici pal separa te waste collec tion | Regional, Emilia – Romagna Region | Regional Law 16/2015 (Emilia-Roma gna region, 2015) Waste Management Plan / 2016 (Legislative Assembly of Emilia Romagna Region, 2016) | Rate of sepa rate waste collection | By 2020, 73 % |
| | | | Waste collection system | The application of door-to-door or equivalent systems is suggested. |

**Table 1.3** – Strategic and legal targets on urban waste treatment collection at European, National (Italy) and Regional (Emilia-Romagna) level.

| Actions | Institu tional level | Documents | Indicators | Targets |
|---|---|---|---|---|
| Urban waste treat ment | European Unione, EU | Directive 2008/98/EC modified by 2018/851 EC (EU, 2018b)<br>Decision 2011/753/EU (for calculation methods) (EC, 2011) | Rate of prepar ing re – use and recycling | By 2020, 50 %<br>By 2025, 55%<br>By 2030, 60%<br>By 2035, 65% |
| | | Directive 2018/850/EC (EU, 2018a) | Rate of land filled urban waste | < 10% |
| | National, Italy | Legislative Decrete 205/2010 (Italian government, 2010)<br>Legislative Decrete 152/2006 (Italian government, 2006) | Rate of prepar ing re – use and recycling | By 2020, 50% |
| | Regional, Emilia – Romagna Region | Regional Law 16/2015 (Emilia-Romagna region, 2015) | Recycling rate | 70%, by 2020 |
| | | Regional Law 16/2015 (Emilia-Romagna region, 2015) | Per capita waste not sent to recycling | (average) 150 kilograms per year per capita for not recycled waste |

It should be noted that no targets nor indicators for evaluating environmental impacts have been set out from a legislative perspective at the selected institutional levels. For this purpose, the use of the LCA methodology applied to WMPs results particularly important when environmental profiles of different waste management systems need to be analyzed and compared (Fedele and Rigamonti, 2019; Rigamonti et al., 2020, Camana et al., 2020). Within the Italian context, some authors applied the LCA tool to assess the sustainability of waste management strategies, such as in this thesis for waste prevention measures (Magrini et al., 2021), reuse and preparation for reuse options (Degli Esposti et al., 2021). However, in Italy, it is not yet broadly used as a decision – support tool (Rigamonti et al., 2013, Tarantini et al., 2009). In this context, the recently published Italian WMP (i.e., PNGR) is based on the results of the technical-scientific study 'Analysis of municipal waste flows as support for the elaboration of national planning of municipal waste management and basis for Life Cycle Assessment', developed by ISPRA, the Italian National institute for environmental protection and research. ISPRA conducted the analysis using two tools: i. flow analysis of municipal waste management systems on a regional scale; ii. preliminary LCA of 8 of the 20 regional management systems. The results of the LCA analysis were expressed through two impact categories (i.e., global warming potential, depletion of fossil resources) selected from those identified by international standards (UNI EN ISO 14044:2018) and the PEFCR Guidance-2017 document, both because of their relevance to the waste management sector and because they have an effect on a global scale and are not linked to the environmental and territorial characteristics of the local scale.

Concerning the field of waste management planning, MBs might establish WP programmes that can be integrated into the WMPs and the mandatory requirements (EC, 1994, EC, 1999, EC, 2008, EU, 2018) for the designing of one or more than one WMPs are given below: 1. Cover the entire geographical territory of the MS concerned;

2. Set out an analysis of the current waste management situation in the geographical entity concerned;

3. Set out the measures to be taken to improve environmentally sound preparing for re-use, recycling, recovery and disposal of waste and an evaluation of how the plan will support the implementation of the objectives and provisions of this Directive;

4. Refer to the type, quantity and source of waste generated within the territory, the waste likely to be shipped from or to the national territory, and an evaluation of the development of waste streams in the future;

5. Refer to the existing waste collection schemes and major disposal and recovery installations, including any special arrangements for waste oils, hazardous waste or waste streams addressed by specific Community legislation;

6. Analyze the need for new collection schemes, the closure of existing waste installations, additional waste installation infrastructure in accordance with Article 16, and, if necessary, the investments related to;

7. Provide sufficient information on the location criteria for site identification and on the capacity of future disposal or major recovery installations, if necessary;

8. Contain general waste management policies, including planned waste management technologies and methods, or policies for waste posing specific management problems;

9. Contain organizational aspects related to waste management including a description of the allocation of responsibilities between public and private actors carrying out the waste management;

10. Evaluate the usefulness and suitability of the use of economic and other instruments in

tackling various waste problems, taking into account the need to maintain the smooth functioning of the internal market;

11. Use of awareness campaigns and information provision directed at the general public or at a specific set of consumers;

12. Analyze historical contaminated waste disposal sites and measures for their rehabilitation.

In this context, a recent report developed by the European Commission (EC) reviews 47 European WMPs at different policy levels (i.e., national, regional, local) and geographical context (EC, 2016). As for the Italian MWM system, it involves a system articulated between State, regional, provincial, and municipal competences. While the State is in charge of defining the general criteria for WM (Legislative Decree 152/ 2006 art.195 (Italian Government, 2006)), the Regions are responsible for planning activities (Legislative Decree 152/2006 art.196 (Italian Government, 2006)). Authors reviews 5 Italian WMPs alongside a set of evaluation criteria reflecting the mandatory requirements of the WFD: legislation (i.e., general information, information on waste streams, information on policy instruments, robustness and inner logic check), the geographical levels at which WMPs can be developed (i.e., level coherence check) and the connections and coherence with EU FD, sub-national and national WMPs (i.e., compliance check, information on fulfillment of targets and requirements, check against waste model, check on waste prevention programme, check against official EUROSTAT data). The selected Italian WMPs have been prepared only at regional level (i.e., Emilia Romagna Region, Marche Region, Tuscany Region, Umbria Region, Veneto Region). Consequently, the Italian WMPs have been rated as "sub standard". Specifically, the

Emilia-Romagna Region, in 2012 provides only the WMP and in 2013 the WP programme at regional level, whereas in 2022 the WMP has been revised, adopting the one over a time frame of 6 years. For this purpose, the Emilia-Romagna Region is committed to the WP: after the approval of the Italian national waste prevention program, the Emilia-Romagna Region Council approved in 2016 the "Emilia-Romagna Region waste management plan" which defines the regional waste prevention program (chapter 17, part IV), over a time frame of 7 years (2013–2020). The plan includes some prevention measures; each measure is divided into related actions, which have impact on different product life stages (see Section 2 of Appendix A of Magrini et al., 2021). The target is to reach 20–25% reduction of per capita urban waste production by 2020, compared to 2014. Since the implementation of a municipal WP program can be a complex process, re quiring important investments and the involvement of many actors, potentially belonging to the whole supply chain of goods and services (Nessi et al., 2015), the Region established a fund to promote prevention and reduction of waste among the Municipalities (Emilia-Romagna Region, 2015). This conforms to European Directive 851/2018, which suggests the application of economic incentives for regional and local authorities, to promote WP and intensify separate collection schemes (see annex IVa, titled "Examples of economic instruments and other measures to provide incentives for the application of the waste hierarchy"). The regional fund aims at: i) reducing the cost of WM for the citizens of the Municipalities which achieved the best results in reducing production of non-recyclable waste; ii) reducing the costs of changing the collection system, to implement a pay-as-youth row scheme; iii) financing the creation of municipal reuse centers and municipal projects promoting reduction in waste generation. The regional fund is managed by ATERSIR, the Emilia- Romagna territorial agency for water and waste services, which defines the criteria to allocate economic resources.

# 2

***State of art of the waste collection.*** *In Chapter 2 a comprehensive review of the European and Italian legislation on waste collection is presented, together with novel indicators for the waste sector. This review attempts to put waste collection in order for the wide scientific production in this field. The search strategy is deeply described in section 2.1, which resulted in a total of 56 search findings in Scopus, 3.000+ in Science Direct and 24 search findings from the review conducted by Campitelli and Schebek, 2020. The sustainability of waste management measures and the future challenges of the municipal solid waste sector are also discussed.*

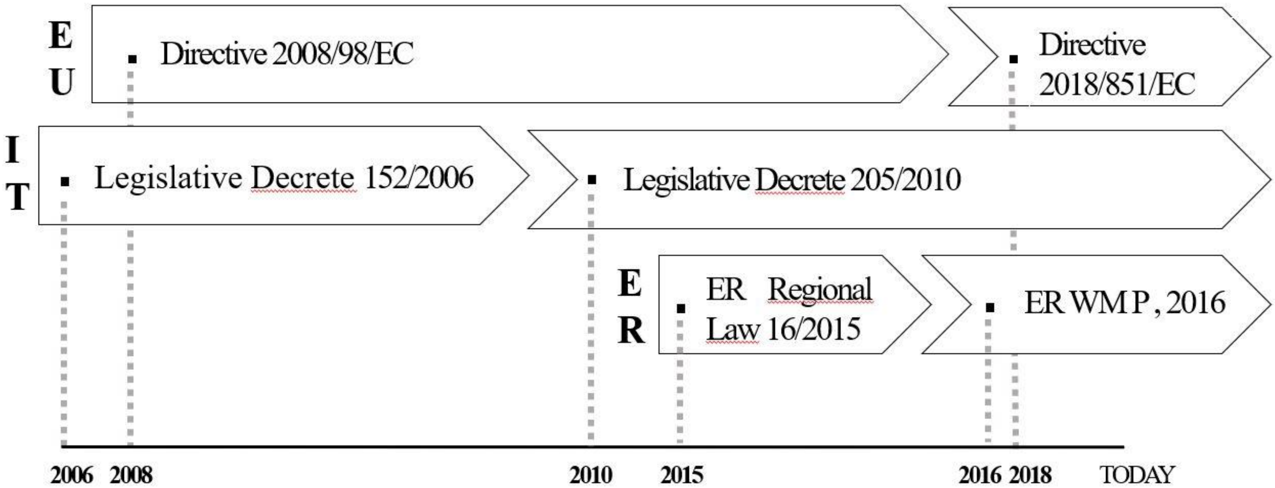
How to improve the efficiency and sustainability of the MSW collection service system is an important governance issue since it has been increasingly relevant for decision – makers, and younger generations (Romano et al., 2022). Every year about 11,2 billion tonnes of solid waste is collected worldwide (UNEP, 2022). Separate waste collection (SWC) is the first step of the waste management (WM) which is the most complex system to manage and its characteristics daily impact on the environment and human health (EC, 2018, Rossi et al., 2022).

As SWC is a policy priority for EU countries, over the last few years European regulations have defined targets for WM operators and local governments (EC 2008, Agovino et al., 2020). Consequently, each MB is required to increase their separate collection rates at least for paper, metal, plastic, and glass by 2025 (EU, 2018b), as for Italian Municipalities (Italian Government 1997, Italian Government, 2006).

In this context, SWC at source has proved to be the most efficient method for returning high quality materials suitable for high recycling efficiency (Di Maria et al., 2018, Laurieri et al., 2020, Romano et al., 2022), and a key success factor for enabling re-use and preparation for reuse (Degli Esposti et al., 2021).

Within the European, Italian and Emilia - Romagna Region context **Figure 2.1** depicts the indicators and targets set out by legislation for the waste collection.

**Figure 2.1.** Overview of the European (EU), Italian (IT) and Emilia – Romagna region (ER) legislation on waste collection..



Dealing with this issue, in the following sections (Section 2.1, Section 2.2, Section 2.3) a literature review on waste collection systems in terms of social, economic, environmental, and ergonomic aspects are provided, both by considering documents from literature and the opinion of local experts in this field. This review attempts to put waste collection in order the wide scientific production in this field. Details on the search strategy is shown in the following section (Section 2.1).

## 2.1. Search strategy

For the systematic literature review database and information sources as Scopus and ScienceDirect (SD) were consulted. Scopus was used as one database, whereas in Web of Science (WoS) and in SD the keywords were inserted to identify matching titles, abstracts, and keywords. The limits of the search are defined as follows: only peer-reviewed research articles in English published (i.e., final publication stage) and available in early access status from the 01 of Jenuary 2019 to 31$^{st}$ of August 2022 (i.e., article in press). Likewise, the study conducted by Campitelli and Schebek, 2020 covers the peer-reviewed research articles in English published or available in early access status before the 31$^{st}$ of May 2019, by selecting as refining search criteria the assessment method “Benchmark and indicators'', while “waste collection and transport” as the selected component of the WMS.

Conference abstracts and papers, book chapters, preliminary works, encyclopedia, editorials, practice guidelines were excluded during the search process. The Boolean operators AND/OR/NOT were applied in Scopus and WoS to link the keywords and to find out the results. The same was done for SD with the exception of using only AND/OR operators in the search query, due to the restricted use of Boolean operators (max. 8) in the advanced search. In WoS and Scopus the strategy to refine journals, which evidently do not address the issue (e.g. artificial intelligence, developing countries), was provided. The described search strategy resulted in a total of 56 search findings in Scopus, 3.000+ in SD, and 24 search findings from the review conducted by Campitelli and Schebek. The selected search query, the refining search criteria (limits) and the associated search results for each database are listed in Table 2.2.

Additionally, 10 relevant articles, which did not result from the defined search strategy, but had been identified using suggestions after the article downloading process (especially in SD), were also included in the screening process to select the relevant studies for review.

**Table. 2.1.** Review of the existing literature on waste collection split into source, query, and results.

| Source | Query | Results |
|---|---|---|
| Scopus, WoS and SD databases. Literature review on Articles published in international journals written in English | SD database:<br>“waste collection” AND (indicator OR review OR framework OR performance OR comparison) limit to the 2019, 2020, 2021 and 2022 years<br><br>Scopus databases:<br>title AND - ABS ( ( municipal* OR town* OR city ) OR "waste management" OR ( indicator* OR review* OR framework* OR performance* OR comparison* ) OR ( ergonomic* AND manual AND cost* AND social* AND environment* AND sustainabilit* AND sustainable ) ) AND TITLE ( "waste collection" ) AND ( LIMIT-TO ( SRCTYPE , "j" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) ) AND ( LIMIT-TO ( PUBYEAR , 2022 ) OR LIMIT-TO ( PUBYEAR , 2021 ) OR LIMIT-TO ( PUBYEAR , 2020 ) ) (56 results).<br><br>From the study performed by Campitelli and Schebek (2020), who reviewed 366 peer-reviewed research articles in English assessing the WMS of cities or countries focusing on MSW, articles reported to use “Benchmark and indicators” and “waste collection and transport” as assessment method (24 results). | 80 articles |
| Experts’ consultation | Interview to Geovest urban provider (Italy) | consultation |

The literature review investigates the indicators on municipal SWC, with a twofold focus: first, it outlines the theoretical framework where the waste collection is analysed (Section 2.2). Second, it considers the theoretical results of the investigation given the selected indicators (Section 2.3).

## 2.2. Waste collection framework

In recent years, municipal solid waste management (MSWM) systems are widely debated in several publications concerning organization, planning, administration, engineering, financial, environmental and health aspects, and they were lately reviewed particularly as regards with the safety of the workers involved in COVID-19 war (Behera, 2021, Yousefi et al. 2021), and the effect of COVID-19 pandemic on urban planning and management (Sharifi and Khavarian Garmsir, 2020, Babaee Tirkolaee and Aydın, 2021). WM at municipal level includes collection, transportation, treatment and disposal of urban waste and it involves legislative, urban planning and human aspects as well as the environmental, social, and economic dimensions of sustainability (Bamonti et al., 2012, Rodrigues et al., 2018, Lu et al. 2020). As a clean city is attractive to tourists, citizens and investors, waste collection is also a key utility service on which the external 'image' of a city depends (Wilson et al. 2014). Together with street cleaning, waste collection is also the most important service provided at municipal level in terms of social, economic, and environmental impacts on public health and citizens quality of life, and operational impacts on the efficiency and effectiveness of the service (Karagiannidis, Xirogiannopoulou, Perkoulidis, & Moussiopoulos, 2004, Ilic and Nikolic, 2016, Benito et al., 2021). Some authors consider collection of waste a particularly important part of MSWM in terms of costs (Lu et al., 2020) and as the most significant essentials for the achievement of sustainable solid waste systems (Hannan et al., 2020). Likewise, some studies are focused on costs and efficiency of local governments in managing waste collection (Benito et al., 2021), while others on the economic regulation of waste collection (Di Foggia and Beccarello, 2018, Magrini et al., 2021b). In this context, an improper waste collection may lead to an ineffective waste management: an improved approach to integrate social, economic, institutional, legal, technical, and environmental aspects is essential for planning a sustainable management of solid waste (Das et al., 2019).

The waste sector is also characterized by significant health issues, since its work activity involves, among other risk factors (e.g., weather, air, noise exposure), the MMH of loads, i.e. receptacles: this can potentially cause MSDs (Botti et al., 2020, Thomas et al., 2021, Rossi et al., 2022). Despite being a relatively small sector in terms of employment, the waste collection records a significant fatal injury rate and its characteristics impact on workers' exposure to non-fatal injuries due to the manual material handling (MMH) of waste containers, and mainly on the risk of developing work-related musculoskeletal disorders (MSDs) (Battini et al. 2018, Botti et al. 2020, Rossi et al., 2022). A recent review developed in Europe on ergonomic interventions among waste collection workers cites 15 studies on occupational health (Emmatty et al., 2019). Specifically, questionnaires and medical examinations have globally reported MSDs and other diseases (liver disorders, Hepatitis A, Hepatitis B, respiratory problems, and cardiovascular diseases) (Engkvist et al. 2011, Jozwiak et al., 2013, Emmatty et al., 2019). National data from Italy show that MSDs are the main type of recognised Occupational Diseases and they have apparently stabilised since 2012, after growing continuously over recent years (EASHW, 2019).

Regarding ergonomics, Botti et al. (2020) report very high ergonomics risk due to MMH when waste collectors empty the waste containers into the collection vehicle, suggesting critical areas of improvement (e.g., avoiding torsion and awkward postures). Moreover, the same authors demonstrate that 2-wheeled containers bigger than or equal to 120-litre capacity are safer and preferable than standardized small containers (with a capacity equal to 25 litres). Similarly, Thomas et al., 2021 demonstrate that services using wheeled bins have lower MSD-related absence rates than those services requiring bending and lifting operations. Specifically, from an epidemiological perspective, the results of the study identify a correlation between collection methods and prevalence of MSDs, concluding that systems comprising 4-wheeled bins and 2-wheeled bins appear to be consistently less hazardous for workers when compared to systems using sacks and boxes. According to the authors, a sustainable door-to-door (DTD) waste collection system should improve: i) equipment (e.g., use of standardized containers), ii) organization (e.g., collection frequency), iii) operations (e.g., training for door-to-door waste operators), and technology (e.g., truck container design). Concerning DTD waste collection, a recent review conducted by Rossi et al., 2022 demonstrated that the existing evaluations mainly focus on traditional waste collection systems (i.e., street collection, door-to-door collection), and they converge on the good environmental performance of the DTD methods compared to street collection ones. The best performance is due to its higher purity and its separation rate of collected waste. However, they highlight that the DTD methods are not sustainable for the operators' health. In this context, the authors stated that in designing waste collection routes (CRs), the company in charge of waste collection service should consider both socio-economic implications and the environment together with ergonomics aspects, not widely debated in literature. Consequently, they conclude that the definition of the best effective methods of waste collection is still an open challenge and the so-called ECOFIL method seems to effectively incorporate the benefits of the DTD (i.e., environmentally friendly) and the street collection (i.e., socially sustainable). This means that

Likewise, lack of knowledge on service quality under different delivery regimes is also a relevant issue, because it is not only costs, but also quality that matters for social welfare (Bel and Sebo, 2020). Therefore, authors state that evidence available on service quality is much scarcer than other information (e.g., economic, environmental), most likely because measuring and monitoring data quality is laborious and costly, due to the high number of waste type, flows, and actors i.e., producers, managers and administrators (Shrestha and Feiock, 2011, Cifrian et al., 2015, Bel and Sebo, 2020). In this context, benchmarking indicators which cover all the above mentioned sustainability aspects can help municipalities to improve municipal waste performance, to judge its own performance, to provide information for decision – making, and monitor changes over time (Wilson et al., 2014, Ilic and Nikolic, 2016).

For this purpose, the mentioned literature review aims to put waste collection in order for the wide scientific production in this field and to find out the sustainability aspects considered in the articles (i.e., environmental, economic, social, governance, technical, organizational, ergonomics).

**Table. 2.2.** Overview of the literature review conducted by the author with a time frame of four years (2019 - 2022) and the review conducted by Campitelli and Schebek, 2020 with a time frame of ten years (2010 - 2019).

| **Information about the article** | | **Assessment method** | | **Sustainability aspects** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Source | Location | Life Cycle Approach | Benchmark and indicators | Environmental | Economic | Social | Governance | Technical | Organitional | Ergonomics |
| Rossi et al., 2022 | Italy | x | x | x | | x | x | x | x | x |
| Viegas et al., 2022 Portugal | | | | | | | | | x | |

| **Information about the article** | | **Assessment method** | | **Sustainability aspects** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Oteng et al., 2022 | Australia | | | | | | | | x | |
| Mahdavi et al., 2022 | Teheran, Iran | x | x | x | x | x | | x | x | |
| Liang et al., 2022 | - | | | | | | | | x | |
| Leeabai et al., 2022 | - | | | x | | | | x | | |
| Demuth et al., 2022 | Germany | | | | | | | | | |
| Romano et al., 2022 | Italy | | x | x | x | x | x | x | x | |
| Singh et al., 2022 | India | x | x | x | x | x | x | x | x | |
| Fattah et al., 2022 | Bangladesh | | | | | | | x | | |
| Ramalho et al., 2022 | - | | | | | | | x | | |
| Fang et al., 2022 | China | | | | | | | x | | |

| Information about the article | | Assessment method | | Sustainability aspects | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Landi and Russo, 2022 | - | | | | | | | x | | |
| Radwan et al., 2022 | Jeddah, Saudi Arabia | | x | | x | | | x | | |
| Ewert et al., 2021 | - | x | x | x | x | | | x | | |
| Salazar-Adams, A., 2021 | Mexico | | x | | x | | | x | | |
| Ladele et al., 2021 | | | | | | | | x | | |
| Moonsammy et al., 2021 | | | | | | | | x | | |
| Babaee Tirkolaee and Aydın 2021. | | | | | | | | x | | |
| Bel, and Sebő, 2021 | Barcelona, Spain | | | | | | | x | | |

| Information about the article | | Assessme nt method | | Sustainability aspects | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ziaei et al., 2021 | | | 1 | | | | | x | | x |
| Hannan et al., 2020 | | | x | x | x | x | x | x | x | |
| Bel and Sebő, 2020 | Barcelo na, Spain | | x | | x | | x | x | | |
| Fan et al., 2020 | China | | x | | x | | x | x | | |
| Wu et al., 2020a | China | | x | x | x | | | x | | |
| Amal et al., 2020 | Sfax, Tunisia | | x | x | | | | x | | |
| Goes et al., 2020 | Rio de Jainero, Brazil | | x | x | | | | x | | |
| Botti et al., 2020 | Italy | | x | | | | | x | x | x |
| Delgado-Anteque ra et al., 2020 | Antequer a, Spain | | x | | | | | x | | |
| Tallentire and Steubing, 2020 | | | x | x | x | x | x | x | | |
| Sulemana et al., 2020 | Ghana, Africa | | x | | x | | x | x | | |

| **Information about the article** | | **Assessme nt method** | | **Sustainability aspects** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Agovino and Musella, 2020 | 550 Municipa li ty in Campani a Region, Italy | | x | | x | x | x | x | x | |
| Wu et al., 2020b | | | x | x | x | | | x | | |
| Meriläinen | and Finland | | x | x | x | x | x | x | | |
| Tukiainen, 2020 | | | | | | | | | | |
| Agovino et al., 2020 | | | x | x | x | x | x | x | | |
| Thürer et al., 2019 | | | x | | | | | x | | |
| Calabrò and Komilis, 2019 | Reggio Calabr ia, Italy | | x | | | | x | x | | |
| Zhou et al., 2019 | China | | | | | | | x | | |
| Bueno-Delgado et al., 2019 | | | x | x | x | x | x | x | | |

| Information about the article | | Assessment method | | Sustainability aspects | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Calabrò and Komilis, 2019 | Reggio Calabria, Italy | | x | | | | x | x | | |
| Zhou et al., 2019 | China | | | | | | | x | | |
| Bueno-Delgado et al., 2019 | | | x | x | x | x | x | x | | |
| Garofalo et al., 2019 | Calabria Region, Italy | | x | | x | x | x | x | | |
| Valenzuela-Levi, 2019 | Comparison between Barcelona and London | | x | | | | | x | | |
| De Feo et al., 2019 | | x | x | x | x | x | x | x | x | |
| Bányai et al., 2019 | | | x | x | x | x | x | x | | |
| Savastano et al., 2019 | | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | |
| Hatem Abdulaziz et al. 2019 | Qassim Region, Saudi Arabia | | x | x | x | x | x | x | x | |

| **Information about the article** | | **Assessment method** | | **Sustainability aspects** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Source | Location | Life Cycle Approach | Benchmark and indicators | Environmental | Economic | Social | Governance | Technical | Organitional | Ergonomics |
| Da Silva et al., 2019 | 4 cities of Rio Grande (Brazil) | | x | x | x | x | x | x | x | |
| Wilson et al., 2016, Sharma et al., 2018 | Himachal Pradesh (4 cities), India | | x | x | x | x | x | x | x | |
| Scheinberg et al., 2010, Muhammad and Salihi, 2018 | Kano, Nigeria | | x | x | x | x | x | x | x | |
| Wilson et al., 2015, Ferronato et al. 2018 | La Paz, Bolivia | | x | x | x | x | x | x | x | |

| **Information about the article** | | **Assessment method** | | **Sustainability aspects** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ElSaid and Aghezzaf, 2018 | Kairo, Egypt and Brussels, Belgium | | x | x | | | x | x | x | |
| Fuss et al., 2018 | Belo Horizonte, Brazil | | x | x | | x | x | x | x | |
| Oduro-Appiah et al. 2017 | Accra, Ghana | | x | x | x | x | x | x | x | |
| Milan et al., 2017 | China compared to different cities | | x | | | | x | | x | |
| Wilson et al., 2015, Byamba et al. 2017 | Ulaanbaatar, Mongolia | | x | x | x | x | x | x | x | |
| Rigamonti et al., 2016 | Lombardia region 4 cities Milano, Bergamo Pavia, Mantova, Italy | | x | x | x | | | x | | |

| **Information about the article** | | **Assessment method** | | **Sustainability aspects** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Karagiannidis, Xirogiannopoulou, Perkoulidis,Moussio poulos, 2004, UN, HABIT, 2005, Ilić et al. 2016 | Serbia (15 municipa li ties), Ireland (Carlow) | | x | | | | | x | x | |
| Cailean and Teodosiu, 2016 | Roma nia en EU | | x | x | | | | x | | |
| Aleluia and Ferrão 2016 | Surabay a (Indone sia), Bangalo re (India) Quy Nhon (Viet Nam), and Matale (Sri Lanka) | | x | | | | | x | x | |

| **Information about the article** | | **Assessment method** | | **Sustainability aspects** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wilson et al. 2014 | 50 countries (developed + developing ) | | x | x | x | x | x | x | x | |
| Cifrian et al., 2015 | Cantabria, Spain | | x | | x | x | x | x | x | |
| Topic and Biedermann, 2015 | Republika Srpska, Bosnia and Herzegovina | | | x | x | x | x | x | x | |
| Masood et al., 2014 | Lahore, Pakistan | | x | x | x | x | x | x | x | |
| Mendes et al. 2013 | Loulé Municipality, Algarve, Portugal | | x | x | x | x | x | x | x | |

| Information about the article | | Assessment method | | Sustainability aspects | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cifrian et al., 2013 | Cantabria, Spain | | x | x | | | | x | | |
| Friedrich and Trois, 2013 | South Africa | | x | x | | | | | | |
| Wilson et al., 2012 | 20 cities, high bis low income | | x | x | x | x | x | x | x | |
| Al Sabbagh et al., 2012 | Bahrain, and other 20 cities | | x | x | x | x | x | x | x | |
| Fragkou et al., 2010 | 27 municipalities in Barcelona, Spain | | x | | | | | x | | |

2.3. Waste collection indicators for the sustainability assessment

In this section the search strategy was applied to find out the information about waste collection indicators (see section 2.1). **Table 2.3** and **Table 2.4** show the results of the mentioned literature review in terms of technical, environmental, economic, governance, organizational, social and ergonomics indicators that might be useful for potential users (e.g., Decision makers, waste collection operators, municipalities).

**Table. 2.3.** Indicators of waste collection.

| **Components of the waste management system** | | **Sustainability indicators** | | | | |
|---|---|---|---|---|---|---|
| Action | Potential users | Technic al indicat or | Environm ental indicator | Econo mic indicato r | Social / Governance / Organisatio n al indicator | Ergono mic indicat or |
| Collect ion and transp ortatio n | Decision makers, waste collection operators, waste local administrators and managers of the waste system, policy-makers, reserachers, LCT experts, municipalities | Indicato rs on mechanic al and technolo gical informatio n of waste collection system | Indicators on environmen t al information of the waste collection system | Indicato rs on economi c informati on of the waste collecti on system | Indicators on social, governan ce and organizatio nal issues of the waste collection system | Indicato rs on ergonom ic s impact of the waste collecti on system |

**Table. 2.4.** Review of the indicators of waste collection.

| Sustainability issue | Indicators |
|---|---|
| Technical | [1] Waste generation indicators (kg/day/capita) (Mendes et al., 2013, Topic and Biedermann, 2015, Cifrian et al., 2015, Ilić et al., 2016, Cailean and Teodosiu, 2016, Cailean and Teodosiu, 2016, Aleluia and Ferrão, 2016, ElSaid and Aghezzaf, 2018, Hatem Abdulaziz et al. 2019, Delgado-Antequera et al., 2020, Agovino and Musella, 2020, Moonsammy, et al., 2021)<br>[2] MSW generation (kg / year / capita) (Cifrian et al., 2013, Topic and Biedermann, 2015, Wilson et al., 2016, Byamba et al. 2017, Sharma et al., 2018)<br>[3] Solid waste collected (kg/day)(Botti et al., 2020, Salazar-Adams 2021) [4] Collected waste (ton / year) (Wilson et al., 2016, Ferronato et al. 2018, Bueno Delgado et al., 2019, Benito et al., 2021)<br>[5] Collection of WSM per capita (Da Silva et al., 2019)<br>[6] Total waste collected compared to the total of waste generated (%) (ElSaid and Aghezzaf, 2018, Fus et al., 2018)<br>[7] Separate collection rate (%) (Da Silva et al., 2019, Valenzuela-Levi, 2019, Agovino et al., 2020, Botti et al., 2020, Romano et al., 2022)<br>[8] Waste separation rate for recycling (ton / year) (Hatem Abdulaziz et al. 2019)<br>[9] Solid waste management system profile (Cailean and Teodosiu, 2016) [10] City profile (e.g, population size, elevation above sea) (Agovino et al., 2020, Agovino and Musella, 2020, Delgado-Antequera et al., 2020, Meriläinen and Tukiainen, 2020)<br>[11] Municipal waste collection coverage (%) (Scheinberg et al., 2010, Topic and Biedermann, 2015, Wilson et al., 2015, Wilson et al., 2016, Aleluia and Ferrão 2016, Ferronato et al. 2018, Muhammad and Salihi, 2018, Sharma et al., 2018, Hatem Abdulaziz et al. 2019, Da Silva et al., 2019, Salazar-Adams, 2021)<br>[12] Coverage of the selective collection door-to-door in relation to the urban population (Da Silva et al., 2019)<br>[13] Quality of waste collection service (%) (Topic and Biedermann, 2015, Wilson et al., 2016, Ferronato et al. 2018, Sharma et al., 2018)<br>[14] Households covered by waste management services (ElSaid and Aghezzaf, 2018) |

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|---|---|
| | [15] Average household income (Density (inhabitants) (Benito et al., 2021, Salazar Adams, 2021)<br>[16] Population density (population per square meter) (Valenzuela-Levi, 2019, Garofalo et al., 2019, Agovino et al., 2020, Meriläinen and Tukiainen, 2020, Fan et al., 2020, Agovino and Musella, 2020, Benito et al., 2021, Salazar-Adams, 2021)<br>[17] No. employees per ton of daily waste generated (Hatem Abdulaziz et al. 2019)<br>[18] Municipal employees (%) (Meriläinen and Tukiainen, 2020, Salazar-Adams, 2021, Fan et al., 2020)<br>[19] Inefficient waste collection vehicles (Hatem Abdulaziz et al. 2019) [20] Equipment cleaning frequency (No. /total collection vehicles) (Hatem Abdulaziz et al. 2019)<br>[21] Segregation of waste collected for each category (Hatem Abdulaziz et al. 2019, Da Silva et al., 2019)<br>[22] Level of collection of recyclables from the containers (Hatem Abdulaziz et al. 2019)<br>[23] Rate of increase total amount of MSW generation % (Hatem Abdulaziz et al. 2019)<br>[24] Percentage of vehicles fleet using any renewable fuel (Da Silva et al., 2019) [25] Water usage (Da Silva et al., 2019)<br>[26] Land usage (Da Silva et al., 2019)<br>[27] Energy generation (Da Silva et al., 2019)<br>[28] Share of households receiving basic waste collection services weekly (Fus et al., 2018, Demuth et al., 2022)<br>[29] Proximity (%) (Demuth et al., 2022)<br>[30] Density of collection points (number of containers / km of route) (Benito et al., 2021)<br>[31] Recyclable material recovered per worker compared to previous working month (%) (Fus et al., 2018)<br>[32] Amount of waste properly treated per treatment method (%) (Fus et al., 2018) [33] Percentage of collected waste treatment (%) (Milan et al., 2017) [34] Population's coverage with sanitation services (%) (Cailean and Teodosiu, 2016)<br>[35] Waste captured by the solid waste managemet and recycling system (%) (Wilson et al., 2015)<br>[36] Quality of 3Rs provision (Wilson et al., 2015)<br>[37] Packaging Waste Collection and recycling by an Integrated Management System |

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|---|---|
| | (Cifrian et al., 2015)<br>[38] Installation of Municipal Collection Points (Cifrian et al., 2015) [39] Use of handling capacity (kg/eqquip year) (Mendes et al. 2013) [40] Dimension of full-time staff (workers/103 t) (Mendes et al. 2013) [41] Waste separation rate for recycling (%) (Mendes et al. 2013, Romano et al., 2022)<br>[42] MSWM self-suffient indicator (Fragkou et al., 2010)<br>[43] Infrustructure devolpment (Singh et al., 2022)<br>[44] Collection mechanism (Singh et al., 2022)<br>[45] Monitoring & enforcement (Singh et al., 2022)<br>[46] Certification and licensing (Singh et al., 2022)<br>[47] No. of trips (Radwan et al., 2022)<br>[48] Tour Lenght (km) (Hatem Abdulaziz et al. 2019, Agovino et al., 2020, Ama et al., 2020, Wu et al., 2020a, Wu et al., 2020b, Ewert et al., 2021)<br>[49] Energy consumption (kWh) (Ewert et al., 2021<br>[50] Man power (Radwan et al., 2022)<br>[51] Fuel consumption (l) (Radwan et al., 2022),<br>[52] Solid waste volume (m3) (Radwan et al., 2022)<br>[53] No. vehicles and equipment for collecting MSW (Bueno-Delgado et al., 2019, Giel and Dabrowska, 2021, Meriläinen and Tukiainen, 2020, Bel and Sebo, 2020, Fan et al., 2020, Amal et al., 2020, Wu et al., 2020b, Salazar-Adams, 2021, Giel and Dabrowska, 2021)<br>[54] No. hotels per 100,000 inhabitants (Salazar-Adams, 2021)<br>[55] Curbside collection as the main method of collection (Salazar-Adams, 2021) [56] Municipality carries out separate collection of waste (Salazar-Adams, 2021 [57] Reduced services (Moonsammy, S., et al., 2021)<br>[58] Time spent at Waste Collection Point (WCP)(Giel and Dabrowska, 2021 [59] Waste Collection Point cover type (Giel and Dabrowska, 2021)<br>[60] Truck distance from WCP (Giel and Dabrowska, 2021)<br>[61] Building type (Giel and Dabrowska, 2021)<br>[62] Planned clenneaning (Giel and Dabrowska, 2021)<br>[63] Capacity of vehicles (t) (Amal et al., 2020)<br>[64] Average number of potential plastic bins in the residential area (unit) (Botti et al., 2020)<br>[65] Average weight of the plastic bin (kg) (Botti et al., 2020)<br>[66] Maximum load capacity of vehicle (litre) (Wu et al., 2020b) |

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|---|---|
| | [67] Fuel consumption rate per unit distance while vehicle is empty (litre/km ) (Wu et al., 2020b)<br>[68] Fuel consumption (e.g., vehicle is at full load) ( L/km ) (Wu et al., 2020b) [69] Total amount of fuel consumption (e.g., vehicle idling) L/min) (Wu et al., 2020b)<br>[70] Distance between waste bins and households (Calabrò and Komilis, 2019, Wu et al., 2020b)<br>[71] Service time of smart waste bin (Wu et al., 2020b)<br>[72] Waste collection point (Thürer et al., 2019),<br>[73] Collection capacity (Thürer et al., 2019<br>[74] Cross-docking center (Thürer et al., 2019)<br>[75] Application layer (Thürer et al., 2019)<br>[76] Resource management layer (Thürer et al., 2019)<br>[77] Presence of waste of human or animal origin or weeds, leaves or of other vegetable residues (Calabrò and Komilis, 2019<br>[78] Accessibility of bins for citizens for depositing waste and operators for emptying operations (Calabrò and Komilis, 2019)<br>[79] Bins and area status (Calabrò and Komilis, 2019)<br>[80] Quantity of recyclable materials recoverable from unsorted residual waste (De Feo et al., 2019)<br>[81] Waste volume transported to the waste treatment site (Bányai et al., 2019 [82] Stored waste treatment site (Bányai et al., 2019) |

| **Sustainability issue** | **Indicators** |
|---|---|
| Environmental | [1] Aghezzaf, 2018, Bueno-Delgado et al., 2019, Bányai et al., 2019, Wu et al., 2020a, Wu et al., 2020b)<br>[2] Per capita saving of CO2 eq. (De Feo et al., 2019)<br>[3] Collection route with overloaded truck (CO2, SO2, CO, HC, NOX, PM) (Bányai et al., 2019)<br>[4] Collection route without overloaded truck (CO2, SO2, CO, HC, NOX, PM) (Bányai et al., 2019)<br>[5] Additional routes to eliminate overloading (CO2, SO2, CO, HC, NOX, PM) (Bányai et al., 2019)<br>[6] Collection route without overloaded truck (CO2, SO2, CO, HC, NOX, PM) (Bányai et al., 2019)<br>[7] Shares of utilities consumed during the recycling processes (electricity, gas, water, etc.) compared annually (Fus et al. 2018)<br>[8] Share of population served per type of vehicles with non-fossil fuel (Fus et al. 2018)<br>[9] Decrease of environmental impacts of MSW treatment on air pollution and ecosystem (%) (Fus et al. 2018)<br>[10] Material Recovery Indicator (Rigamonti et al., 2016)<br>[11] Energy Recovery Indicator (Rigamonti et al., 2016)<br>[12] Self sufficiency indicator (Cailean and Teodosiu, 2016)<br>[13] Air quality indicators (t of pollutant/year) (Cailean and Teodosiu, 2016) [14] Carbon footprint indicator (i.e., cf associated to each collection, transfer and transport steps of each waste stream to each final Treatment) (kg CO2e/t of waste) (Cifrian et al., 2013, Cailean and Teodosiu, 2016)<br>[15] Eco-efficiency of Municipal Solid Waste Generation (Cifrian et al., 2015) [16] Eco-efficiency of the generation of waste (HW and NHW) of the company (Cifrian et al., 2015)<br>[17] Green Practices (Singh et al., 2022)<br>[18] Environmental Programme (Singh et al., 2022) |

| Sustainability issue | Indicators |
|---|---|
| Economic | [1] Application of life cycle costing (LCC) (Hatem Abdulaziz et al. 2019) [2] Total cost of the waste collection (i.e., operator cost/ton of waste generated, effective cost) (Mendes et al., 2013, Hatem Abdulaziz et al. 2019, Bueno-Delgado et al., 2019, Bel and Sebő, 2020, Wu et al. 2020, Ewert et al., 2021, Benito et al,, 2021, Perez-Lopez et al., 2021)<br>[3] Cost of municipal wastes disposal per metric ton (Hatem Abdulaziz et al. 2019) [4] Recycling cost/ton of waste (Hatem Abdulaziz et al. 2019)<br>[5] Budget data (Scheinberg et al., 2010, Muhammad and Salihi, 2018) [6] SWM budget per capita per year (US$)(Scheinberg et al., 2010, Muhammad and Salihi, 2018)<br>[7] SWM budget per capita per as % of GDP (Scheinberg et al., 2010, Muhammad and Salihi, 2018)<br>[8] Percentage of recoverable costs after sorting waste (due to selling recyclables) (ElSaid and Aghezzaf, 2018)<br>[9] Annual revenue (i.e., from sales of recyclable products, plus annual saving due to reduced disposal cost compared to annual total costs, from sales of recyclable products, plus annual saving due to reduced disposal cost compared to annual total costs, per-cappita tax revenue) (Mendes et al. 2013, Fus et al. 2018, Demuth et al., 2022)<br>[10] Cost indicator (Rigamonti et al., 2016)<br>[11] GDP (Topic and Biedermann, 2015, Fan et al., 2020)<br>[12] Eco-efficienty in the generation of MSW (Euros/t) (Cifrian et al., 2013) [13] Economic and environmental cost (Mahdavi et al., 2022)<br>[14] Inflation rate (Topic and Biedermann, 2015)<br>[15] Investment of MSW collection services (ten thousand yuan) (Fan et al., 2020)<br>[16] Added value of tertiary industry (one hundred million yuan) (Fan et al., 2020) [17] Cost of per unit carbon emission (CNY) (Wu et al., 2020b)<br>[18] Fixed cost of per unit vehicle (CNY) (Wu et al., 2020b),<br>[19] Price of per unit fuel consumption (CNY) (Wu et al., 2020b)<br>[20] Total potential economic saving (De Feo et al., 2019)<br>[21] Potential economic saving for each citizen (De Feo et al., 2019, Meriläinen and Tukiainen, 2020)<br>[22] Income tax (Valenzuela-Levi, 2019)<br>[23] Autonomous revenue (%) (Valenzuela-Levi, 2019) |

| Sustainability issue | Indicators |
|---|---|
| Social | [1] Persons not satisfied with the waste management services % (Hatem Abdulaziz et al. 2019)<br>[2] Community's involvement in improving exsting practices (Hatem Abdulaziz et al. 2019)<br>[3] Public acceptance of waste management plans and actions (Hatem Abdulaziz et al. 2019)<br>[4] Level of awareness (i.e., stakeholder's awareness about CE, actions, community awareness about importance of SWM) (Mendes et al., 2013, Topic and Biedermann, 2015, ElSaid and Aghezzaf, 2018, Hatem Abdulaziz et al. 2019, Singh et al., 2022)<br>[5] No. of collection staff per 1000 households (Hatem Abdulaziz et al. 2019)<br>[6] Personal Training (Hours /employees /year) (Hatem Abdulaziz et al. 2019) [7] Total training hours (h/worker year) (Mendes et al. 2013)<br>[8] No. of sick days taken per field employee (Hatem Abdulaziz et al. 2019) [9] Inclusion of waste pickers in the selective collection system (planning and implementation) (Da Silva et al., 2019)<br>[10] Degree of nonconformity with the environmental regulatory framework (Da Silva et al., 2019)<br>[11] Quality of 3Rs provision (Wilson et al., 2015, Topic and Biedermann, 2015, Wilson et al., 2016, Sharma et al., 2018)<br>[12] User inclusivity % (Scheinberg et al. 2010, Wilson et al., 2015, Topic and Biedermann, 2015, Wilson et al., 2016, Sharma et al., 2018, Muhammad and Salihi, 2018, Ferronato et al., 2018, Byamba et al. 2017)<br>[13] Provider inclusivity % (Scheinberg et al., 2010, Wilson et al., 2015, Topic and Biedermann, 2015, Wilson et al., 2016, Sharma et al., 2018, Muhammad and Salihi, 2018, Ferronato et al., 2018, Byamba et al. 2017),<br>[14] Adequacy of national Framework (Wilson et al., 2015, Wilson et al., 2016, Sharma et al., 2018, Ferronato et al., 2018, Byamba et al. 2017)<br>[15] Local istitution policies (Wilson et al., 2016, Sharma et al., 2018, Byamba et al. 2017)<br>[16] Local institutional coherence and quality (Scheinberg et al., 2010, Wilson et al., 2015, Muhammad and Salihi, 2018, Ferronato et al., 2018, Garofalo et al., 2019, Agovino et al., 2020) |

| | |
|---|---|
| | [17] Existence and implementation of a local waste management plan and legislation (ElSaid and Aghezzaf, 2018)<br>[18] Information, visibility, transparency and accountability (ElSaid and Aghezzaf, 2018, Benito et al., 2021, Singh et al., 2022)<br>[19] Report of well-being (No. complaint and conflicts solved compared to previous year) (Fus et al., 2018)<br>[20] Income of the waste pickers in cooperative in relation to the minimal wages (%) (Fus et al., 2018)<br>[21] No. inspection actions related to recycling processes according to industry legislation compared to previous year (Fus et al., 2018)<br>[22] No.training programs and education for service providers and waste pickers with participation of decision makers per year (ratio compared to previous year) (Fus et al., 2018)<br>[23] Educational level (Fan et al., 2020, Agovino and Musella, 2020, Garofalo et al., 2019)<br>[24] Share of schools implementing waste awareness programs (Fus et al., 2018)<br>[25] Share of citizens with access to annual running local awareness campaigns (Fus et al., 2018)<br>[26] Documentation and records of all MSWM activities kept in archives to make follow up actions possible (Fus et al., 2018)<br>[27] Associativism (e.g. no. waste pickers in cooperatives compared to previous year) (Fus et al., 2018)<br>(%) (Fus et al., 2018)<br>[29] No. organized public communication activities (e.g., mass-media campaign, exhibitions, community cleanup contests, community meetings, recycling bazaars) compared annually (Fus et al., 2018)<br>[30] Inclusivity (Wilson et al., 2016, Oduro-Appiah et al. 2017)<br>[31] Sound institutions, proactive policies (Wilson et al., 2016, Oduro-Appiah et al. 2017)<br>[32] Financial sustainability (Scheinberg et al., 2010, Wilson et al., 2015, Topic and Biedermann, 2015, Byamba et al. 2017, Oduro-Appiah et al. 2017, Ferronato et al. 2018)<br>[33] Social variables related to generation of Municipal Solid Waste (Cifrian et al., 2015)<br>[34] Intensity on waste (HW and NHW) of the company (Cifrian et al., 2015) [35] Intensity on employment of the generation of waste (HW and NHW) of the company (Cifrian et al., 2015) |

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|---|---|
| | [36] Absenteeism (%) (Mendes et al. 2013)<br>[37] Performance assessment index (Mendes et al. 2013)<br>[38] Citizens satisfaction index (%) (Mendes et al. 2013)<br>[39] Written response to complaints and suggestions (Mendes et al. 2013) [40] Projects and services implementation (Mendes et al. 2013)<br>[41] S – LCA social score (Mahdavi et al., 2022, UNEP, 2020)<br>[42] Unemployment rate (%) (Topic and Biedermann, 2015, Garofalo et al., 2019, Agovino et al., 2020, Agovino and Musella, 2020, Demuth et al., 2022) [43] Share of public employees (%) (Demuth et al., 2022)<br>[44] Vote share of leftist parties (%) (Demuth et al., 2022)<br>[45] Membership in municipality organization (Demuth et al., 2022) [46] Indipendent town (Demuth et al., 2022)<br>[47] Government initiatives (Singh et al., 2022)<br>[48] Public ethics (Singh et al., 2022)<br>[49] Voter Turnout (%) (Agovino et al., 2020, Meriläinen and Tukiainen, 2020, Benito et al., 2021)<br>[50] Effective Political Power Index of the local government (Benito et al., 2021)<br>[51] Couples with children (%) (Garofalo et al., 2019, Agovino et al., 2020, Agovino and Musella, 2020)<br>[52] Icumbents (%) (Meriläinen and Tukiainen, 2020)<br>[53] Women (%) (Meriläinen and Tukiainen, 2020)<br>[54] Per capita Added Value (Agovino et al., 2020)<br>[55] High School Completion Rate (%) (Agovino et al., 2020)<br>[56] Mass Cultural Consumption (Agovino et al., 2020)<br>[57] Elite Cultural Consumption (Agovino et al., 2020)<br>[58] Per capita saving of Disability Adjusted Life Years (De Feo et al., 2019) [59] No. Jobs for young people as communicators (De Feo et al., 2019) [60] Share of young population (Meriläinen and Tukiainen, 2020)+ [61] Share of old population (Meriläinen and Tukiainen, 2020) |

| Sustainability issue | Indicators |
|---|---|
| Ergonomics | [1] Working accidents (No. Of collection staff / 1000 household served) (Mendes et al. 2013, Hatem Abdulaziz et al. 2019)<br>[2] NIOSH VLI (Rossi et al., 2022, Botti et al., 2020)<br>[3] Snook and Ciriello (Rossi et al., 2022)<br>[4] RULA (Rossi et al., 2022) |

The literature review results in a total of 188 of which 82 technical indicators, 18 environmental indicators, 23 economic indicators, 61 social indicators, and 4 ergonomics indicators (2010 - 2022).

These findings indicate that there has been much attention to developing indicators for tackling sustainability in the SWC field. In this context, according to Sarigiannis et al., 2021, Rossi et al., 2022, several studies are mainly focused on environmental consequences related to different waste treatment, which have applied many tools as the LCA, to assess the environmental impacts and to identify the best option among several municipal waste collection systems. Few studies have been focused on social and ergonomics implications, aim at integrating the environmental aspects with economic, technical, social and ergonomics' ones.

The following section details the results of the literature review. (Section 2.3.1). By describing the so called "wasteaware" indicator set for Integrated Sustainable Waste Management (ISWM), the future challenges of municipal solid waste sector are also discussed in line with the concept of Life Cycle Thinking (LCT) and Industrial Symbiosis, as well as the pertinent Sustainable Development Goals (SDGs).

2.3.1 Discussion of the literature review

As a result of the literature review, the number of the publications with a time frame of eleven years (i.e., from 2010 to 2022) have been counted.

As depicted in **Figure 2.2**, the number of publications has been increasing over the past few years. By selecting six sustainability aspects (i.e., technical, environmental, economic, governance, organizational, social, ergonomics), **Figure 2.3** shows the number of publications per sustainability indicator.

**Figure 2.2.** Overview of the publications with selecting indicators with a time frame of 11 years (2010 - 2021).

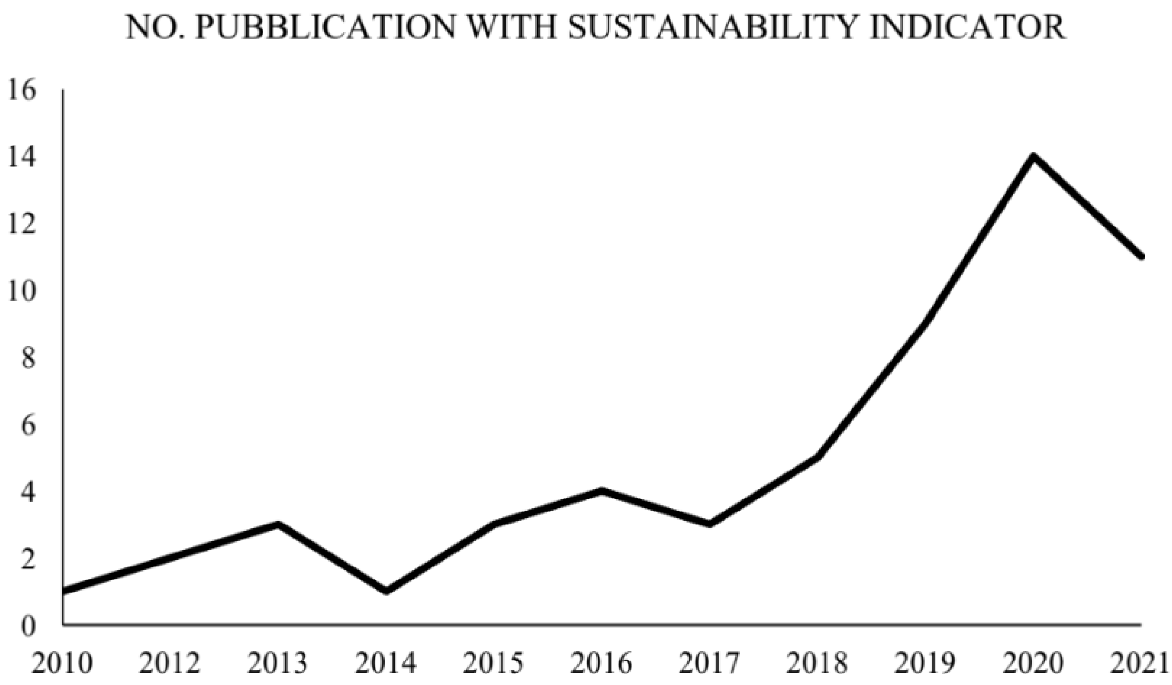
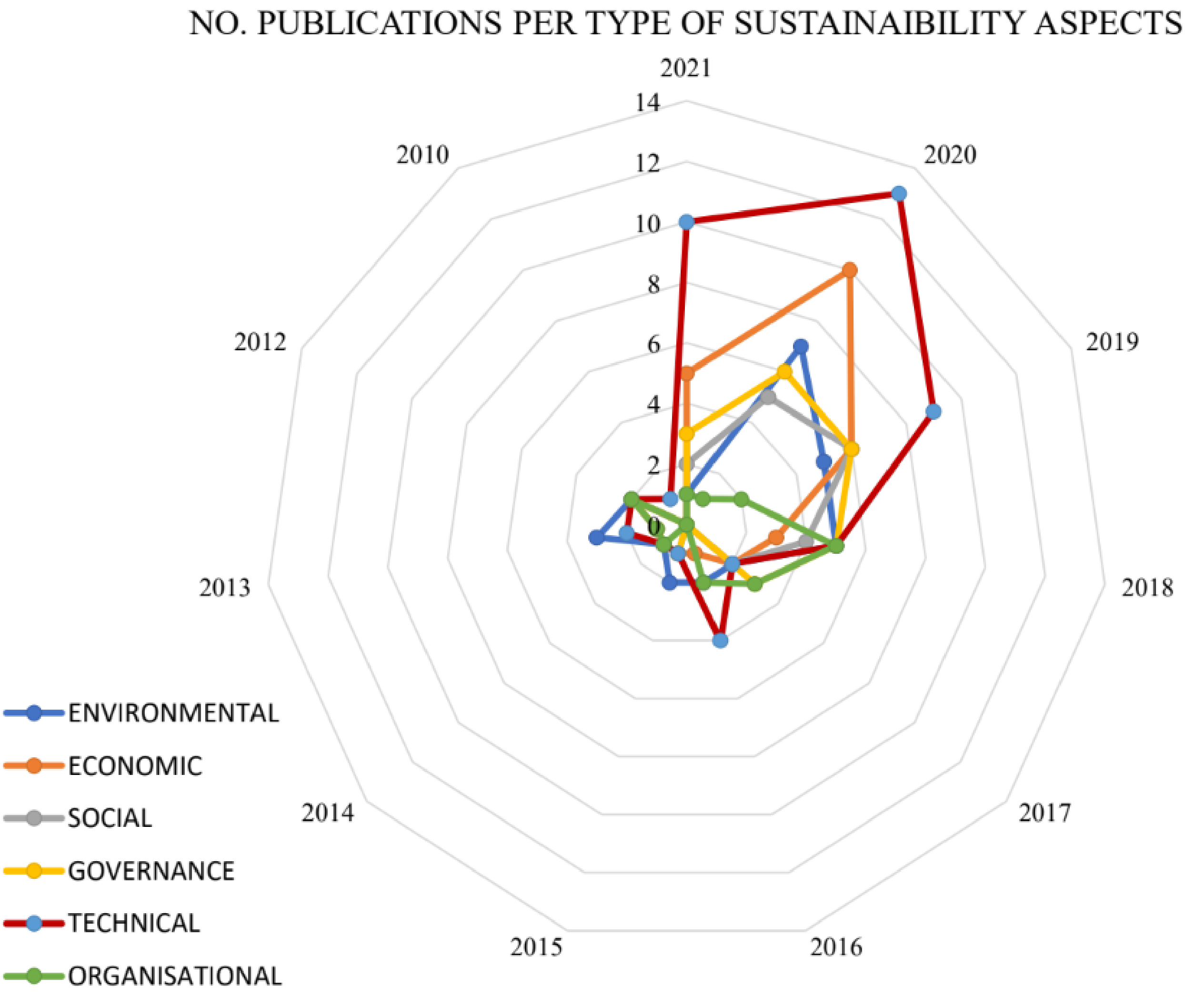
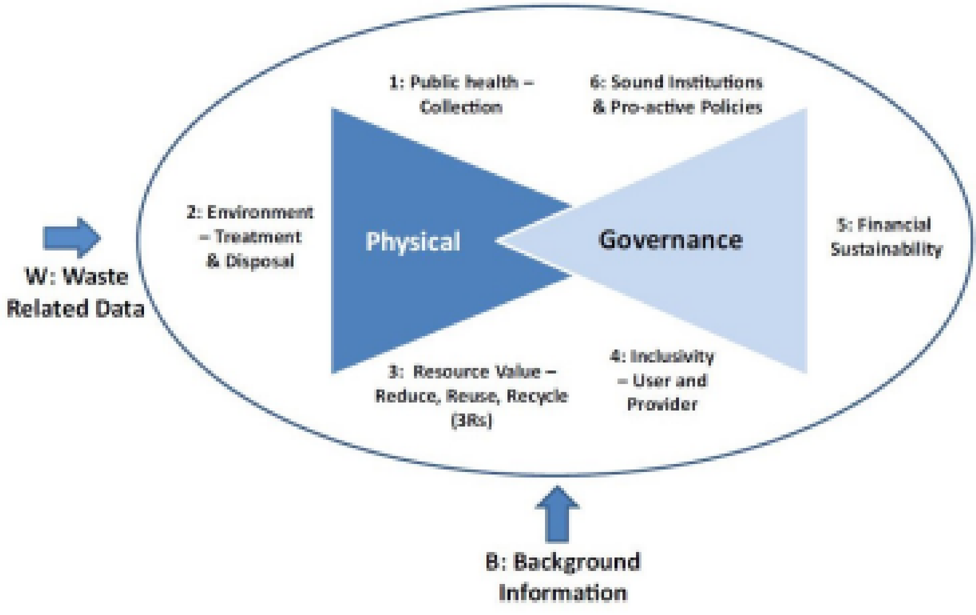


**Figure 2.3.** Overview of the publications with selecting indicators with a time frame of 11 years (2010 - 2021).



In this context, several authors have used the so called 'Wasteaware' benchmark indicators to reflect one of their primary purposes of raising stakeholder awareness of the state of the local solid waste management system at national level (Wilson et al., 2012, Wilson et al., 2015, Topic and Biedermann, 2015, Oduro-Appiah, 2017, Byamba and Ishikawa, 2017, Sharma et al., 2018, Ferronato et al., 2018). As depicted in **Figure 2.4,** the analytical framework is built around the concept of integrated sustainable (solid) waste management (ISWM) (Schübeler, 1996; Van de Klundert and Anschütz, 2001; IJgosse et al., 2004, Wilson et al., 2015).

**Figure 2.4**. *Wilson et al., 2015. The Integrated Sustainable Waste Management (ISWM) framework used by the Wasteaware indicator set. This is a simplified version of the original ISWM concept (Schübeler, 1996; Van de Klundert and Anschütz, 2001; IJgosse et al., 2004). This version of the figure was drawn by Darragh Masterson. David Wilson, Ljiljana Rodic, Costas Velis.*



As described by Wilson et al., 2015, the Wasteaware benchmark set of indicators s divided into two overlapping 'triangles': the physical triangle refers to three physical components, i.e. collection, recycling, and disposal, and the other (i.e., governance) comprising three governance aspects, i.e. inclusivity; financial sustainability; and sound institutions and proactive policies.

As for the ISWM framework, recently the concept of life cycle thinking (LCT) considers several sustainability aspects (i.e., social, institutional, political, financial, economic, environmental, and technical) for the analysis of WMs of products, processes, or services in a whole life cycle. Likewise, some authors assess the environmental impacts of waste collection using the Life Cycle Assessment (LCA) and the Life Cycle Cost (LCC) tools for the evaluation of the economic impacts (AlHumid et al., 2019, Hatem Abdulaziz et al. 2019), while others evaluate the GHG emissions in terms of kg CO2, and kg CH4 (Mendes et al., 2013, Friedrich and Trois, 2013, ElSaid and Aghezzaf, 2018, Bueno-Delgado et al., 2019, Bányai et al., 2019, Wu et al., 2020a, Wu et al., 2020b). However, concerning the social aspects according to Campitelli and Schebek (2020), who reviewed 366 studies on waste management systems of cities or countries and focused on municipal solid waste, few studies (89) consider at least one social aspect. Although Mohsenizadeh et al. (2020) argue that some studies on MSWM incorporate the social dimension of sustainability, considering methods such as social life cycle assessment (sLCA) (Mahdavi et al., 2022), and social indicators (e.g., creation of job opportunities, visual pollution, amount of reused waste), a recent review conducted by Hannan et al. (2020) show that only 6 out of 21 studies on solid waste collection considered the social dimension of the sustainability. Specifically, by reviewing 162 selected papers, the authors conclude that there are ten most common constraints in the sustainable waste collection. Narrowing down to the optimization constraints of the sustainable waste collection, the results show that only 2 out of those 6 studies evaluate the "labour constraint" in terms of human labour and job opportunities (Heidari et al., 2019, Hannan et al., 2020) and indirect social benefits in reducing CO2 emissions and improving quality of life and human health (Mohsenizadeh et al. 2020, Hannan et al., 2020). As for "social and non-negative constraints", the authors consider the involvement of various stakeholder groups in the decision-making process, and the impacts of social capital parameters (e.g., social network, social trust, social learning). In this context Rossi et al., 2022 recently stated that only 8 out of 19 reviewed articles on WMs have analysed social aspects through an ergonomic analysis (Catik, 2015, Garrido et al., 2015, Botti et al., 2020, Moore et al., 2021, Thomas et al., 2021), social impact in terms of employment (Ferrao et al., 2013), social life-cycle cost analysis (Teerioja et al., 2012), social impact based on observation and interview (Yildiz-Geyhan et al., 2019).

To the best of the authors' knowledge, a very limited number of studies focused on ergonomics aspects to improve waste collection (Catik, 2015, Garrido et al., 2015, AlHumid et al., 2019, Botti et al., 2020, Bettini et al., 2020, Thomas et al., 2021, Ziaei, 2021, Rossi et al., 2022). None of these evaluate the ergo-quality aspects, along with environmental, economic, and social implications of a SWC system.

Chapter 3 deeply analyses the S-LCA, LCA, SDGs as tools for the evaluation provided in Chapter 4.

# 3

***State of the art of sustainability indicators and tools in the waste sector**. In Chapter 3 the state of the art of the Life Cycle Assessment and Social Life Cycle Assessment tools, and Industrial Symbiosis strategy is proposed. Within the framework of the Life Cycle Thinking, the Life Cycle Assessment analysis is described as a considerable method to evaluate the environmental impacts. Then, the integration of social criteria into Life Cycle Assessment is explored describing the approaches for Social Life Cycle Assessment. In line with that, the Industrial Symbiosis is proposed as a strategy to substantially reduce waste generation through recycling and reuse options. Dealing with the sustainability issue, the pertinent Sustainable Development Goals are mentioned as a link to the waste issue mentioned in Chapter 1 and Chapter 2.*

## 3.1 Introduction

### 3.1.1 Introduction of the Life Cycle Assessment tool

The discussion on how to deal with environmental, social, and economic criteria already started more than 30 years ago (Fava et al., 1993, UNEP 2020). The LCA is a globally recognised method to evaluate the environmental impacts of a system, a product, or a process (ISO 1997). All the inputs such as energy and resources are identified, with the aim of quantifying the relevant emissions, the consumed resources, and the related environmental impacts. Considering a product, the impacts do not only arise during the manufacturing stage, but also along its entire life cycle, including the extraction and transportation of raw materials, use and maintenance, possible reuse, and end of life. Therefore, the approach encompasses the whole life cycle of a product, "from cradle to grave," as the first definition stated by SETAC, 1993: from “cradle,” where raw materials are extracted, put into production, and used, to “grave,” i.e., waste disposal, with the aim to provide a comprehensive picture of the environmental impacts of the system. According to a circularity perspective, a new philosophy, referred to as “from cradle to cradle”, is taking hold: at their end of life, materials are not considered as waste to be discarded, but as secondary raw material, thanks to an appropriate recycling process. In this way, a cradle-to-cradle closed loop is outlined. According to the ISO14040 standard, the four steps to perform a LCA are: i) the definition of the goal and scope of the analysis, ii) the inventory analysis, iii) the impact assessment, and finally, iv) the interpretation of the results.

*Goal and Scope Definition*

The context of the study and its purpose are set. The goal of the LCA states the intended application and the reasons for carrying out the study, the intended audience, and whether the results are to be used for internal purpose or for disclosure to the public. The scope includes the following items: functional unit, system boundary, allocation procedure, data requirements, impact assessment method, assumption, and data quality. In particular, the functional unit, that defines the quantification of the identified function of the product, has the primary purpose to provide a reference to which the inputs and outputs are related, ensuring the comparability of the LCA results. The system boundary defines the unit processes to be included in the system. Criterions for the choice of the system boundaries are physical (description of the productive cycle), geographical (reference area), and temporal (reference period).

*Inventory Analysis or Life Cycle Inventory*

It lists all the inputs (e.g., materials and energy) and outputs (e.g., products, co-products, and emissions) to be used to compare standards and processes. Inventory analysis involves data collection and calculation procedures, aiming at quantifying the relevant inputs and outputs of a product system. The life cycle inventory uses both primary and specific as well as literature and secondary data from international databases.

*Impact Assessment*

The life cycle impact assessment (LCIA) includes the following mandatory elements: the selection of impact categories and characterization models; the assignment of LCI results to the selected impact categories (classification); and the calculation of category indicator results (characterization).

*Interpretation*

Finally, the life cycle interpretation aims at the identification of substantial issues, based on the results of the previous steps. The evaluation includes considerations about the completeness and the consistency of the study, conclusions, limitations, and recommendations.It should be noted that, during the analysis, the results and the assumptions in subsequent stages might lead to the revision of what has been done in previous stages, in a process of continuous improvement. Information which was not available during the compilation of the previous phases can be added afterward.

### 3.1.2 Introduction of the Social Life Cycle Assessment tool

Social Life Cycle Assessment (S - LCA) is one of three methodologies that have been developed to assess the sustainability of the pillars of organizations, products, and services (UNEP, 2020). Research studies on S - LCA topic were initiated by the end of 2003 when the UNEP / SETAC Life Cycle Initiative recognized the need for a Task Force on the integration of social criteria into LCA, which have actively explored approaches for Social LCA. Consequently, various teams globally have developed and started publishing methods and case studies (UNEP, 2009, Benoît et al. 2013, Fontes, J., et al. 2016. Goedkoop et al. 2018, Macombe et al. 2018, UNEP 2020, UNEP 2021). More specifically, in 2009 the UNEP/SETAC Life Cycle Initiative published a first set of Guidelines for Social Life Cycle Assessment (S-LCA), which have represented the main reference for a S-LCA for a decade. Indeed, these Guidelines provide a map, a skeleton, and a flashlight to guide stakeholders engaging in the assessment of positive and negative social and socio economic impacts of the life cycle of products and of services. Since 2009, experiences, case studies and publications in S-LCA have increased, contributing to the numerous reference documents published on this topic (UNEP, 2020). Another crucial development is a policy instrument endorsed in 2011 by the UN Human Rights Council: The Guiding Principles on Business and Human Rights (UN, 2011). Therefore, within the wake of the Guiding Principles, countries have adopted the so-called “Human Rights Due Diligence” e.g., France, the United Kingdom, Australia, the Netherlands, and Switzerland. Likewise, this wave of legislation related to the Guiding Principles coupled with the widespread SDGs are now incentivizing companies to establish a process to learn about, prioritize and act upon their social risks. In this context, by assessing positive impacts associated with business activities in life cycle management, the S-LCA is a considerable method that can be applied for the purpose of Human Rights Due Diligence (Mazijn and Revéret, 2015, Fontes, et al. 2016). According to the Organisation for Economic Cooperation and Development (OECD, 2016), "Due diligence" is the process through which organizations identify, consider, and address the potential environmental and social impacts and risks relating to concerned activities as an integral part of their decision-making and risk management systems. In this context, in 2015 the UN defined goals to "address the global challenges we face, including those related to poverty, inequality, climate, environmental degradation, prosperity, and peace and justice" (UN, 2015). Recently, Goedkoop et al. (2018) published the Handbook for Product Social Impact Assessment (PSIA) which builds on the UNEP 2009 S-LCA Guidelines and the Methodological Sheets to present a method with a specific set of indicators that can be applied to assess social impacts at the product level. In addition, by making suggestions for further developments on social topics UNEP, 2018 presents the state of the art in measurement of social impacts and has compiled. Consequently, UNEP in 2020 edition also looks at how to link the social impacts of a product's production and consumption to the larger impacts associated with an organization's influence across the life cycle of a product, by providing an organizational perspective that guides many organizational decisions and experts, which are also known as stakeholders categories e.g., Workers, Local communities, Value chain actors (e.g. suppliers), Consumers, Children, and Society (UNEP, 2020). Moreover, the following impact subcategories have been newly introduced i.e., Employment relationship, Sexual harassment, Smallholders including farmers, Wealth distribution, Ethical treatment of animals, Poverty alleviation, Education provided in the local community, Health issues for children as consumers, Children concerns regarding marketing practices. More recently, the methodological sheets have been reviewed (UNEP, 2021).

The three steps of SLCA are described in the following sections.

*Goal and scope definition*

As for LCA analysis, the context of the study and its purpose are set. Similarly, the goal of the S LCA states the intended application and the reasons for carrying out the study, the intended audience. The scope includes the following items: functional unit, system boundary, allocation procedure, data requirements, impact assessment method, assumption, and data quality.

*Impact assessment method*

The choice of impact assessment methods ought to be specified in the Goal and Scope of a study. This includes:

1. Select the impact assessment approach;

   1.a) Reference Scale S-LCIA; or

   1.b) Impact Pathway S-LCIA;

2. Identify the social topic(s) of interest;

   2.a) Select stakeholders, subcategories and/or impact categories, if using reference scale;

   2.b) Select stakeholders and impact categories, if using impact pathway;

3. Present the prerequisites for the respective S-LCIA method chosen;

   3.a) Reference scales used for assessment, if using reference scale;

   3.b) Characterization model and type of impact pathway used for assessment;

3.c) Determine the weighting approach (if applicable).

*Interpretation and communication*

As for the LCA analysis, the life cycle interpretation aims at the identification of substantial issues, based on the results of the previous steps. Similarly, the evaluation includes considerations about the completeness and the consistency of the study, conclusions, limitations, and recommendations.

### 3.1.3. Introduction of the Industrial Symbiosis strategy

Although the concept of Industrial Symbiosis (IS) has been wholly known for at least few decades till Erkman, 1997, several research studies have been published before (Parkins et al., 1934, Renner, 1947). In this context, in 2000 the first definition of IS was widely recognized by the international scientific community (Chertow, 2000). In line with that, over the last few years several authors have been proposed other definitions of IS (Erkman, 2001, Agarwal and Strachan, 2008, Lombardi and Laybourn, 2012, Taddeo et al., 2017; Domenech et al., 2018, Kosmol et al., 2021, SUN, 2022). More specifically, as a result of the collaboration with the SUN Network (SUN, 2022), the authors have newly introduced the following definition of IS:

Industrial Symbiosis is defined as an interaction among actors closely related to each other, based on the efficient management of tangible and intangible resources by fostering relationships, information, and innovations, and by obtaining economic, environmental, and social benefits[1].

## 3.2 Conclusions

Within the framework of the waste policy (chapter 1), waste collection and sustainability assessment (chapter 2), and IS (chapter 3) have obvious connections to the seventeen Sustainable Development Goals (SDGs) which have been internationally accepted by governments, industries, and organizations. According to the UNEP (2020), fourteen of the seventeen goals concern social impacts, most of which have obvious connections with the S LCA framework.

In this context, by linking the mentioned concepts with the pertinent SDGs, Table 3.1 provides an overview of the twofold connections: first SDGs and social and environmental impacts, second SDGs' targets to the concept of CE and IS[1].

[1] "La SI è una forma di interazione sinergica tra attori di un territorio basata sulla gestione efficiente di risorse materiali e immateriali, favorita da relazioni, informazioni e innovazioni e finalizzata all'ottenimento di benefici economici, ambientali e sociali" (Perotto et al., 2022 in press).

**Table 3.1**: The 17 SDGs (Source: AICS, 2022; ASVIS, 2022, SUN, 2022) and the contribution of the CE e IS to the SDGs (Authors' refinement of UN, 2015; Rodriguez et al., 2019; Schroeder et al., 2019; Rodriguez et al., 2022, Perotto et al., 2022).

| Goal | Description | Social impacts | Environmental impacts | Targets and connection with CE, IS |
|---|---|---|---|---|
|  | End poverty in all its forms everywhere. | ✓ | | 1.1 By 2030, eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.25 a day.<br><br>1.2 By 2030, reduce at least by half the proportion of men, women and children of all ages living in poverty in all its dimensions according to national definitions.<br><br>1.5 By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters.<br><br>1.b. Create sound policy frameworks at the national, regional and international levels, based on pro-poor and gender-sensitive development strategies, to support accelerated investment in poverty eradication actions. |

| Goal | Description | Social impacts | Environmental impacts | Targets and connection with CE, IS |
|---|---|---|---|---|
| 2 ZERO HUNGER | End hunger, achieve food security and improved nutrition and promote sustainable agriculture. | ✓ | | 2.1 By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round.<br><br>2.2 By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons.<br><br>2.3 By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment.<br><br>2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality. |

| Goal | Description | Social impacts | Environmental impacts | Targets and connection with CE, IS |
|---|---|---|---|---|
| 3 GOOD HEALTH AND WELL-BEING | Ensure healthy lives and promote well-being for all at all ages. | ✓ | ✓ | 3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination. |
| 4 QUALITY EDUCATION | Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all. | ✓ | | No target |
| 5 GENDER EQUALITY | Achieve gender equality and empower all women and girls. | ✓ | | No target |

| Goal | Description | Social impacts | Environmental impacts | Targets and connection with CE, IS |
|---|---|---|---|---|
| 6 CLEAN WATER AND SANITATION | Ensure availability and sustainable management of water and sanitation for all. | ✓ | | 6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all.<br><br>6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations.<br><br>6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.<br><br>6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.<br><br>6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate. |

| Goal | Description | Social impacts | Environmental impacts | Targets and connection with CE, IS |
|---|---|---|---|---|
| 7 AFFORDABLE AND CLEAN ENERGY | Ensure access to affordable, reliable, sustainable and modern energy for all. | ✓ | ✓ | 7.1 By 2030, ensure universal access to affordable, reliable and modern energy services.<br><br>7.2 By 2030, increase substantially the share of renewable energy in the global energy mix.<br><br>7.3 By 2030, double the global rate of improvement in energy efficiency.<br><br>7.b By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programmes of support. |

| Goal | Description | Social impacts | Environmental impacts | Targets and connection with CE, IS |
|---|---|---|---|---|
| 8 DECENT WORK AND ECONOMIC GROWTH | Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all. | ✓ | | 8.1 Sustain per capita economic growth in accordance with national circumstances and, in particular, at least 7 per cent gross domestic product growth per annum in the least developed countries.<br><br>8.2 Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labor-intensive sectors.<br><br>8.3 Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises, including through access to financial services.<br><br>8.4 Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-Year Framework of Programmes on Sustainable Consumption and Production, with developed countries taking the lead.<br><br>8.5 By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value.<br><br>8.6 By 2020, substantially reduce the proportion of youth not in employment, education or training. |

| Goal | Description | Social impacts | Environmental impacts | Targets and connection with CE, IS |
|---|---|---|---|---|
| 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE | Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. | ✓ | ✓ | 9.2 Promote inclusive and sustainable industrialization and, by 2030, significantly raise industry's share of employment and gross domestic product, in line with national circumstances, and double its share in least developed countries.<br><br>9.3 Increase the access of small-scale industrial and other enterprises, in particular in developing countries, to financial services, including affordable credit, and their integration into value chains and market.<br><br>9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.<br><br>9.b Support domestic technology development, research and innovation in developing countries, including by ensuring a conducive policy environment for, inter alia, industrial diversification and value addition to commodities.<br><br>. |

| Goal | Description | Social impacts | Environmental impacts | Targets and connection with CE, IS |
|---|---|---|---|---|
| 10 REDUCED INEQUALITIES | Reduce inequality within and among countries. | ✓ | | 10.1 By 2030, progressively achieve and sustain income growth of the bottom 40 per cent of the population at a rate higher than the national average.<br><br>. |
| 11 SUSTAINABLE CITIES AND COMMUNITIES | Make cities and human settlements inclusive, safe, resilient and sustainable. | ✓ | ✓ | 11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums.<br><br>11.2 By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons.<br><br>11.4 Strengthen efforts to protect and safeguard the world's cultural and natural heritage.<br><br>11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management. |

| Goal | Description | Social impacts | Environmental impacts | Targets and connection with CE, IS |
|---|---|---|---|---|
| 12 RESPONSIBLE CONSUMPTION AND PRODUCTION | Ensure sustainable consumption and production patterns. | ✓ | ✓ | 12.1 Implement the 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries.<br><br>12.2 By 2030, achieve the sustainable management and efficient use of natural resources.<br><br>12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses.<br><br>12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment.<br><br>12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse.<br><br>12.8 By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature<br><br>12.b Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products.. |

| Goal | Description | Social impacts | Environmental impacts | Targets and connection with CE, IS |
|---|---|---|---|---|
| 13 CLIMATE ACTION | Take urgent action to combat climate change and its impacts. | ✓ | ✓ | 13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries. |
| 14 LIFE BELOW WATER | Conserve and sustainably use the oceans, seas and marine resources for sustainable development. | ✓ | ✓ | 14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution.<br><br>14.2 By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans.<br><br>14.3 Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels. |

| Goal | Description | Social impacts | Environmental impacts | Targets and connection with CE, IS |
|---|---|---|---|---|
| | Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. | ✓ | ✓ | 15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements<br><br>15.2 By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally<br><br>15.3 By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world<br><br>15.4 By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development<br><br>15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species.<br><br>15.7 Take urgent action to end poaching and trafficking of protected species of flora and fauna and address both demand and supply of illegal wildlife products. |

| Goal | Description | Social impacts | Environmental impacts | Targets and connection with CE, IS |
|---|---|---|---|---|
| 16 PEACE, JUSTICE AND STRONG INSTITUTIONS | Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels. | ✓ | | 16.1 Significantly reduce all forms of violence and related death rates everywhere. |
| 17 PARTNERSHIPS FOR THE GOALS | Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development. | ✓ | | No target |

# 4

***Results.*** *In Chapter 4 four author publications in international peer-reviewed journals were selected among the wholly author's contributions i.e., final publication stage. See Annex for the final version of the published articles.*

In this chapter, four articles are selected among the author publications with the following preferred strategy: peer-reviewed research articles in English published i.e., final publication stage and available in early access status i.e., articles in press. Three of which were published in 2020 and 2021, (i.e., Frontiers in materials journal, Science of the Total Environment Journal, Waste Management and research journal), whereas the latest one was published in December 2022 in the Waste Management Journal.

As the answer of the mentioned research questions provided in the introduction chapter, the content of the following manuscripts reports four case studies evaluated in a life cycle perspective. In such a framework, the author proposes some metrics for the evaluation of sustainability in buildings and waste sectors as the main findings of the third-year research study conducted at the Department of Civil, Chemical, Environmental, and Materials Engineering - University of Bologna. Essentially, the case studies shed light on monitoring the collection and generation of waste considering the pillars of sustainability, and on supporting the design of buildings and waste management systems.

As a meaningful element for decision – makers, the sustainability dimensions of the WM are considered in terms of technical, environmental, economic, social, institutional, organizational and ergonomics aspects. The principle of the Life Cycle Thinking Sustainable Development Goals, and Industrial Symbiosis has guided the author through the complicated and interconnected issue of sustainability, which now more than ever have been characterizing waste and buildings sectors. The following general open issues are therefore discussed: i) Buildindings made with secondary raw material and by-products; ii) waste prevention; iii) reuse and preparation for reuse strategies; iii) waste collection. The formulation of some metrics and indicators seek to give a valuable contribution on the above-mentioned topics. More specifically, the Life Cycle Assessment tool was selected as it evaluated the environmental impacts of the preferred scenarios. A framework for the sustainability assessment and prioritization of waste prevention measures at consumption level was provided. A framework to evaluate the potential of preparation for reuse and waste collection as a strategy to jointly decrease social, environmental and economic impacts and meet the legal targets on waste management.

The scientific tests have been only conducted at the Department of Civil, Chemical, Environmental and Materials Engineering by the author. The contributions to the formulation of the publications are deeply described in the "Credit authorship" section of the following tables which provide an overview of the manuscripts' content in terms of: title, status, keywords, journal, abstract, credit authorship and section of the Annex (**Table 4.1**, **Table 4.2**, **Table 4.3**, **Table 4.4**, **Table 4.5**).

## 4.1. Paper 1. A case study of industrial symbiosis to reduce GHG emissions: performance analysis and LCA of asphalt concretes made with RAP and steel slags (Bonoli et al., 2020)

### Brief introduction

This paper examines the use of alternative materials for the construction and rehabilitation of roads within the context of an industrial activity located in Emilia - Romagna, Italy. Specifically, this study aims at testing the use of Electric Arc Furnace steel slags and Reclaimed Asphalt Pavement in two mixtures of asphalt concrete. The physical and mechanical properties and the environmental performances are evaluated to define a standard characterization of asphalt concrete mixtures, and to identify practical implications of the use of recycled materials in new asphalt mixtures, from a life cycle and industrial symbiosis perspective. Either mechanical or physical properties are found according to the Italian standard series. The performance analysis of asphalt concrete made with Reclaimed Asphalt Pavement and steel slags is implemented by a Life Cycle Assessment. The evaluation of environmental implications refers to the Life Cycle Assessment Best Practices ISO 1440 series.

### Study findings

The use of the secondary raw material (i.e., Reclaimed Asphalt Pavement) and the by-product (i.e., Electric Arc Furnace steel slag) results in significant differences in tensile resistance and air void contents rather than the control mixtures made with virgin materials. However, the average value of Indirect Tensile Strength records for both experimental mixtures is considerably higher than the limit suggested by the Italian technical specifications (ANAS, 2019), which ranges between 0.72 and 1.60 MPa per wearing course, and between 0.72 and 1.40 MPa per binder course. Contrary to all the authors expectation, if the Italian technical specification is taken into account, the air void content is lower than the suggested ones, which ranges between 3 and 8%. The standard characterization of the mixtures evaluates the hardening effect of the old bitumen on the content blend. According to Noferini et al. (2018), the hardening effect becomes relevant when the Reclaimed Asphalt Pavement binder content is above 20% by weight of the mixture. In particular, the experimental bituminous mixtures per binder and wearing course (i.e., MixB1 and MixW1) are more rigid than the control ones (i.e., MixB0 and MixW0), but they are not excessively thickened because the final void value was less than 2%.

Interestingly, significant differences are also found in environmental benefits of experimental mixtures. More specifically, the reduction of greenhouse gas emissions and natural resources provide environmental benefits in all the impact categories (i.e., abiotic depletion, abiotic depletion of fossil fuels, global warming potential, ozone layer depletion, human toxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication). Therefore, the avoided impacts associated with the use of recycled material and with the reduction in the consumption of bitumen and aggregates overcome the impacts related to the waste transportation and the pre-treatment processes, resulting in a total reduction in environmental impact. According to the Life Cycle Assessment results, a reduction in all impact categories occurred, and mainly in human toxicity (−30.5%) and eutrophication (−24%), related to the intensive energy consumption and the utilization of non-renewable sources, during both the extraction and transportation phases. Specifically, a robust reduction in CO2eq emissions is demonstrated by the better performance of the category global warming potential (−21%), as it is estimated at 46 tons of CO2eq. for the experimental mixtures and at 58 tons of CO2eq for the control mixtures.

The case study is a strategy to be boosted worldwide, establishing regional industrial symbiosis agreements which can support companies to gain competitiveness and reduce the environmental impact associated with day to day business activities.

**Conclusion**

I. The inert nature of Reclaimed Asphalt Pavement and the excellent mechanical properties of the Electric Arc Furnace slags demonstrates the high potential for recycling in the road construction sector, as a secondary raw material and a by-product;

II. The use of secondary raw materials in 1 km of suburban road allows the company to save more than 400 tons of natural aggregates and more than 10 tons of virgin bitumen for the wearing course, more than 800 tons of natural aggregates and more than 20 tons of virgin bitumen for the binder course;

III. By reducing the global environmental impact and recycling by-products, the selected batch plant and the co-located companies are a real case study of industrial symbiosis at the meso-level.

**Author contributions**

Alessandra Bonoli and **Anna Degli Esposti** designed the study. **Anna Degli Esposti** collected information and materials from the company. Alessandra Bonoli and **Anna Degli Esposti** conceived and planned the experiments for the characterization of asphalt mixtures. **Anna Degli Esposti** carried out the experiment. **All the authors** contributed to the interpretation of the results. **Anna Degli Esposti** and Chiara Magrini designed the LCA model and analyzed the data. **All the authors** contributed to the interpretation of the Life Cycle Assessment results. Alessandra Bonoli took the lead in writing the manuscript. **All authors** provided critical feedback and helped shape the research, analysis and manuscript.

**Table 4.1**. Overview of the first manuscript (Bonoli et al., 2020).

| | |
|---|---|
| Title | A case study of industrial symbiosis to reduce GHG emissions: performance analysis and LCA of asphalt concretes made with RAP and steel slags |
| Status | Published |
| Keywords | LCA, CE; IS; Road construction; EAF steel slags; RAP |
| Journal | Frontiers in materials, 7, 1 - 14 |
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| Credit authorship | AB and AE designed the study. AE collected information and materials from the company. AB and AE conceived and planned the experiments for the characterization of asphalt mixtures. AE carried out the experiment. All the authors contributed to the interpretation of the results. AE and CM designed the LCA model and analyzed the data. All the authors contributed to the interpretation of the LCA results. AB took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript. |
| Annex | 1 |

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# A Case Study of Industrial Symbiosis to Reduce GHG Emissions: Performance Analysis and LCA of Asphalt Concretes Made With RAP Aggregates and Steel Slags

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The concept of sustainability in the road construction sector is a complex issue because of the various steps that contribute to the production and release of greenhouse gas (GHG) emissions. Addressing this issue, the European Commission has put various policy initiatives in place to encourage the construction industry to adopt circular economy (CE) and industrial symbiosis (IS) principles e.g., the use of recycled materials. *Cooperativa Trasporti Imola* (CTI), a company located in the Emilia-Romagna region (Italy), has been chosen for the current case study to examine practices, management, and the industrial symbiosis network among various companies in the road construction and rehabilitation sector. In this regard, the use of steel slags, obtained by an electric arc furnace (EAF), and reclaimed asphalt pavement (RAP), obtained by the deconstruction and milling of old asphalt pavement have been investigated. Two mixtures of recycled hot Mix Asphalt (HMA) i) were prepared incorporating different recycled material percentages for the wearing and binder course, respectively, ii) were characterized in terms of size distribution, strength modulus and volumetric properties, iii) and finally were compared to the performances of two mixtures entirely designed by virgin materials for the wearing and binder course, respectively. Therefore, the Life Cycle Assessment (LCA) tool was chosen to evaluate the environmental impacts that affect the designed road life cycle. The results show that recycling RAP and EAF slags in a CTI batch plant provides benefits by reducing the consumption of virgin bitumen and aggregates and by reducing $CO_{2eq}$ emissions. Finally, practical implications on the use of recycled materials in new asphalt mixtures from a life cycle and industrial symbiosis perspective are provided.

**Keywords: life cycle assessement, circular economy, industrial symbiosis, road construction, electric arc furnace steel slags, reclaimed asphalt pavement, recycled aggregates, standard characterization**

## INTRODUCTION

Greenhouse gas (GHG) emissions in infrastructure projects are a key indicator when sustainability is being assessed (Gasparatos et al., 2008; Fernández-Sánchez and Rodríguez-López, 2010). The road sector, due to its characteristics (high energy consumption; use of resources, raw material, and surface; generation of high volumes of waste; quantity of linked transports and long service life) is one of the main sectors that contributes to global warming (GW) (Cass and Mukherjee, 2011). Significant GHG emissions result from many stages of the road life cycle. Santero and Horvath (2009) stated that GHG emissions could range from negligibly small values to 60,000 tons of equivalent carbon dioxide ($CO_{2eq}$) per lane-kilometer over a service life of 50 years. Similarly, the emission factor per meter per year associated with the construction of road infrastructure has been estimated at 14.7 kg of $CO_{2eq}$ (Hill et al., 2012). In this sense, regarding road construction and maintenance, several steps contribute to the production and release of GHG emissions, i.e., site clearing, preparation of the sub-grade, production of construction materials (i.e., granular sub-base, base course, surfacing), site delivery, construction works, ongoing supervision, and maintenance activities. As European road infrastructure includes a growing network, with 4.8 million km at the end of 2013 (European Union Road Federation, 2017) and 5.5 million km at the end of 2016 (European Union Road Federation, 2019), this sector has broad margins for environmental improvement (Santero et al., 2011a; Santero et al., 2011b; JRC, 2016). For these reasons, this study is of particular interest.

Road construction is one of three main drivers of resource use in the European Union (Steger and Bleischwitz, 2011). Road construction not only requires large quantities of materials, but also their maintenance is highly material intensive. Construction works and regular maintenance of roads require materials that are produced through highly carbon-intensive and energy-demanding processes (Santos et al., 2015; Jiang and Wu, 2019). Previous studies have suggested that the life-cycle of GHG emissions associated with building roads can account for 10–20% of the emissions associated with the lifetime usage of the road by vehicles (Chester and Horvath, 2009; Hanson and Noland, 2015; Noland and Hanson, 2015). Previous research has also shown that the bulk of the emissions related to road construction and maintenance activities is often associated with the upstream emissions embodied in the materials used (Hanson and Noland, 2015; Huang et al., 2015; Noland and Hanson, 2015). Hence, the choice of materials impacts local pollution and environmental degradation. These materials primarily include asphalt, concrete, and steel (Hanson and Noland, 2015). Therefore, also considering the increase of landfilling restrictions on CDW, the use of alternative materials such as industrial by-products has gained greater significance and attention from academia and industrial sectors (Jamshidi et al., 2017).

The European Commission (EC) has put various policy initiatives in place to encourage the construction industry toward circular economy (CE) principles. The overall idea is to reconsider the whole life cycle of resources, to make the European Union (EU) a "circular economy" based on recycling, and the use of waste as a resource (EC, 2011).

The use of alternative materials for the construction and rehabilitation of roads would therefore be a strategy to be boosted, establishing regional industrial symbiosis (IS) agreements which can support companies to gain competitiveness and reduce the environmental impact associated to their day to day business activities (Martin-Portugues Montoliu et al., 2019). For that reason, the EC has recently launched an industry-led IS reporting and certification system (EC, 2020). In this sense, symbiotic activities can be applied at different levels. According to Roberts (Roberts, 2004), they can involve a single firm or organization (micro level); companies co-located in the same area (meso level); and finally the entire regional or national production system (macro level). The greatest benefits are achieved at the meso level, where the clustering of complementary companies provides a complexity of functions (Roberts, 2004; Taddeo, 2016).

## Background of Hot Mix Asphalt, Recycling of Reclaimed Asphalt Pavement and Electric Arc Furnace Steel Slags

Roads are built in layers and three main types of road pavements can be identified: flexible, semi-rigid, and rigid pavements. In Europe, the main pavement type is flexible (asphalt) (Sherwood, 2001; Garbarino et al., 2016). As shown in **Figure 1**, the main road layers for flexible pavement are:

- surface, binder, and base courses, which consist of bituminous mixtures;
- road base and sub-base courses, which consist of cement bound or unbound aggregates.

Asphalt mixtures are typically composed of approximately 95% of mineral aggregates mixed with about 5% paving bitumen, with bitumen functioning as the glue that binds the mineral aggregates in a cohesive mix (EAPA, 2011). In general, three types of asphalt mixtures can be used: hot mix asphalt (HMA), warm mix asphalt (WMA), and cold mix asphalt (CMA).

Some aggregates can, usefully, be created by recycling processes.

In this study, the use of steel slags obtained by an electric arc furnace (EAF), and reclaimed asphalt pavement (RAP) obtained by the deconstruction and milling of old asphalt pavement have been investigated. The HMA technology was used in the production process.

While recycling HMA results in a reusable mixture of aggregates and aged asphalt binders known as RAP (Al-Qadi et al., 2007; Noferini et al., 2018), recycling steel slags produces artificial aggregates, containing 90% iron oxide and smaller quantities of other oxides (calcium, magnesium, silicon, etc.), derived from additives used in steel production. Moreover, on the basis of production technology, steel slags can be classified as basic oxygen furnace (BOF), electric arc furnace (EAF), and ladle refining (LF) slags (Meng and Liu, 2000; Gu et al., 2018).

As is widely known, steel slags, produced during the separation of molten steel from impurities in a steel-making furnace, are one of the most common industrial wastes and they can be used for several applications. Thanks to their high hardness and cementing properties, they are commonly used in the road sector (Rashad, 2019). In steel plants, high-grade steel

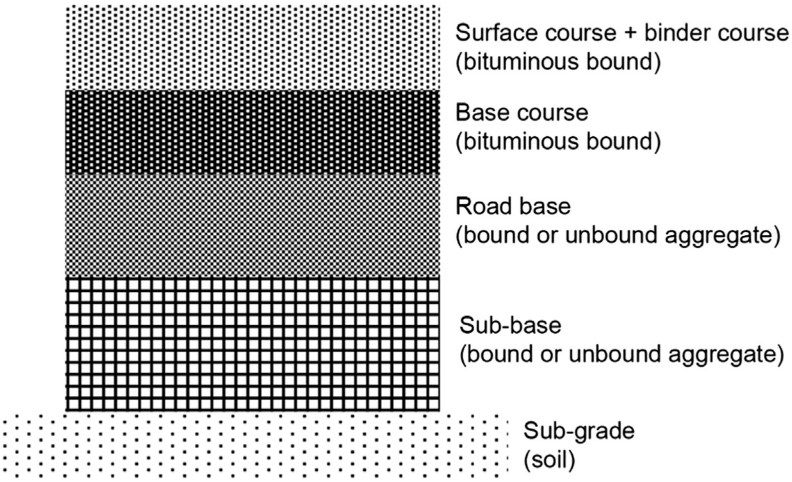


**FIGURE 1 |** Flexible pavement layer system (Garbarino et al., 2016). The sizes of each course represented in the figure do not necessarily correspond to the actual ones.

is melted, obtaining a sinking heavy liquid metal fraction, which agglomerates into a metal phase, separating metals from some light fractions such as chromium by reducing agents and liberating chromium from its compounds. Slag composition can be optimized in relation with application requirements and then it can be cast. In some processes (i.e., RecArc project, http://www.recarc.bam.de) the high-grade steel slags can be converted into a chromium-rich metal phase, which can be used as a raw material in high-grade steel production.

As far as the recycling of RAP and of EAF steel slags are concerned, several studies have shown that the use of these materials is common in pavement construction because of their technical performances and economic value. Miliutenko et al. (2013) have shown that HMA mixes with RAP content have the same technical characteristics (stiffness, fatigue, and deformation resistance) as virgin ones. Thanks to the incorporation of RAP in new asphalt mixtures, the need of neat bitumen is reduced, making RAP recycling economically attractive (Noferini et al., 2018; Pantini et al., 2018).

Similarly, other studies have demonstrated that steel slags with proper pre-processing and sufficient in-place quality control procedures can perform credibly well as asphalt aggregates (Del Fabbro et al., 2001; Ahmedzade and Sengoz, 2009; Gu et al., 2018). In particular, EAF slags have been frequently used as pavement aggregates due to their excellent mechanical properties, which make them suitable for asphalt layers with any kind of traffic load (Santos et al., 2015).

Moreover, Pasetto and Baldo (2017) studied the stiffness and the fatigue performance of five different base-binder bituminous mixtures, made with RAP and EAF steel slag, up to 70% by weight of the aggregate. They reported that the resulting mixes with RAP and EAF slag were characterized by improved stiffness and fatigue performance compared to the control asphalt concrete, made exclusively with natural aggregate.

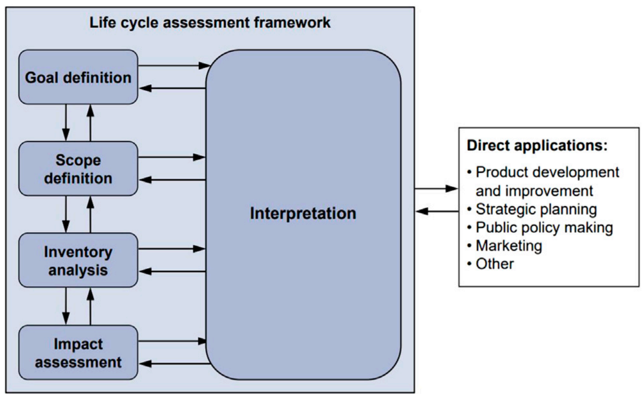


**FIGURE 2 |** LCA phases (EC et al., 2010).

## The Life Cycle Assessment and the Circularity Approach

The Life Cycle Assessment (LCA) is a considerable method to evaluate the environmental impacts of a system, a product, or a process. All the inputs (such as energy and resources) are identified, with the aim of quantifying the relevant emissions, the consumed resources, and the related environmental impacts. Considering a product, the impacts do not only arise during the manufacturing stage, but along its entire life cycle, including the extraction and transportation of raw materials, use and maintenance, possible reuse, and end of life. Therefore, the approach encompasses the whole life cycle of a product, "from cradle to grave," as the first definition stated (SETAC, 1993): from "cradle," where raw materials are extracted, put into production, and used, to "grave," i.e., waste disposal, with the aim to provide a comprehensive picture of the environmental impacts of the system.

According to a circularity perspective, a new philosophy, referred to as "from cradle to cradle", is taking hold: at their end of life, materials are not considered as waste to be discarded, but as secondary raw material, thanks to an appropriate recycling process. In this way, a cradle-to-cradle closed loop is outlined.

According to the ISO14040 standard, the four steps to perform a Life Cycle Assessment (LCA) are: the definition of the goal and scope of the analysis, the inventory analysis, the impact assessment, and finally, the interpretation of the results (**Figure 2**).

### Goal and Scope Definition

The context of the study and its purpose are set. The goal of the LCA states the intended application and the reasons for carrying out the study, the intended audience, and whether the results are to be used for internal purpose or for disclosure to the public. The scope includes the following items: functional unit, system boundary, allocation procedure, data requirements, impact assessment method, assumption, and data quality. In particular, the functional unit, that defines the quantification of the identified function of the product, has the primary purpose to provide a reference to which the inputs and outputs are related, ensuring the comparability of the LCA results. The system boundary defines the unit processes to be included in the system. Criterions for the choice of the system boundaries are physical (description of the productive cycle), geographical (reference area), and temporal (reference period).

### Inventory Analysis or Life Cycle Inventory

It lists all the inputs (materials and energy) and outputs (products, co-products, and emissions) to be used to compare standards and processes. Inventory analysis involves data collection and calculation procedures, aiming at quantifying the relevant inputs and outputs of a product system. The life cycle inventory uses both primary and specific as well as literature and secondary data from international databases.

### Impact Assessment

The life cycle impact assessment (LCIA) includes the following mandatory elements: the selection of impact categories and characterization models; the assignment of LCI results to the selected impact categories (classification); and the calculation of category indicator results (characterization).

### Interpretation

Finally, the life cycle interpretation aims at the identification of substantial issues, based on the results of the previous steps. The evaluation includes considerations about the completeness and the consistency of the study, conclusions, limitations, and recommendations.

In **Figure 2**, the two-way arrows highlight the iterative approach of an LCA. During the analysis, the results and the assumptions in subsequent stages might lead to the revision of what has been done in previous stages, in a process of continuous improvement. Information which was not available during the compilation of the previous phases can be added afterward.

### The Life Cycle Assessment in the Road Construction Sector

Due to the high amount of GHG emissions generated during road construction, rehabilitation, and operation, the evaluation and reduction of the environmental impact related to the road sector have become an international challenge (Espinoza et al., 2019). In this sense, a systematic approach has emerged to assess the environmental impact of pavements. LCA is considered a relevant methodology to evaluate the environmental impacts that affect the road life-cycle (Espinoza et al., 2019) and the International Organization for Standardization (ISO) has established the principles, requirements, and guidelines to regulate the LCA analysis (ISO 14040, ISO 14044, ISO 14020, ISO 14024, and ISO 14025). Moreover, the Joint Research Centre (JRC) in 2016 proposed an LCA as an assessment methodology of road environmental performance, with reference to ISO 14067 or equivalents and ISO 14040/14044. Finally, according to Espinoza et al., (2019), the use of an LCA for evaluating the environmental performance of the construction of road projects allows construction companies to obtain information that can be used to predict the performance of their projects and to evaluate compliance with environmental requirements. Similarly, it allows the selection of optimal materials and construction processes, reducing the GHG emissions and permitting a more sustainable approach.

Therefore, LCA analysis performed by Espinoza et al., (2019) highlighted that HMA production generates the greatest environmental impact, considering the extraction of raw material and the construction of the HMA layers. Previous research has shown that HMA emits up to 18–22 $kgCO_2/t$ (Agentschap Wegen en Verkeer, 2012; JRC, 2016) and a recent LCA literature review for roads, carried out by JRC (2016), shows that the second largest source of environmental impact after the use phase is the production of construction materials. In addition, in low traffic roads, this can in fact be the most significant source of environmental impact (JRC, 2016). Moreover, the durability of road materials is a key factor that will influence the requirement for maintenance. The impacts of maintenance activities themselves are dominated by impacts from material production and transportation. Consequently, special attention to HMA production and construction materials is required in order to minimize GHG emissions. For these reasons, several studies have pointed out the environmental benefits of using recycled materials, such as RAP and EAF steel slags. Hasan et al. (2020) argued that RAP obtained after milling and screening existing asphalt pavements is a viable alternative to mitigate the high GHG burdens of bitumen and aggregates (Praticò et al., 2015; Guo et al., 2018) and transport agencies (AASHTO, 2012; Hasan et al., 2020). In particular, the use of steel slags in asphalt mixtures saves natural resources, by reducing the consumption of natural and non-renewable aggregates and the quantity of slag deposited on landfill sites (Ferreira et al., 2016) and the reduction of the landfill space requirements associated with the need to landfill industrial wastes and by-products (Carpenter et al., 2007; Huang et al., 2009; Miliutenko, et al., 2013, Mladenovic et al., 2015). The EAF is a less energy intensive process where electricity is used to melt steel into the end product. This could be a promising alternative that may have close to zero $CO_2$ emissions, theoretically (Ferreira et al., 2016; Morfeldt et al., 2015). Finally, Giani et al. (2015) explored the replacement of virgin asphalt by 10% RAP in a HMA surface course and by 20% RAP in a HMA binder course of a 1 km asphalt pavement section in Italy. They found that the HMA RAP alternative exhibited 688 tons of $CO_2$eq (6.8%) GHG emissions reductions, considering that the environmental burdens of asphalt significantly depend on the bitumen content (Häkkinen and Mäkelä, 1996).

## Description of Context: Recycling Asphalt Pavement in "Cooperativa Trasporti Imola Scrl" Company

The "Cooperativa trasporti Imola Scrl" (CTI) company has four plants for the production of asphalt mixes, three batch plants and one drum plant. In both the typologies, the mineral aggregates are dried and heated in a rotating drum. Nowadays, the predominant plant type in the U.S. and New Zealand is the drum-mix plant, while batch plants prevail in Europe, South Africa, and Australia (EAPA, 2018). While in batch plants aggregates are stored in hot bins to mix them with bitumen in discrete batches, in drum plants the mixing of aggregates with bitumen takes place in the same drum. After those processes, the mixtures are stored in silos or loaded into trucks for delivery. Afterwards, aggregates, temporarily stored in a silo, are transported by mechanical shovels, and loaded on hoppers for pre-dosage. The CTI plants have seven hoppers, five for aggregates and two for milled materials, with the possibility of introducing RAP. In the drum plant, the drum acts both as a dryer and a mixer, whereas in the batch plant the mixing of aggregates with bitumen takes place in different machines. The bitumen, heated to 130–150°C by an oil-fired oleothermal boiler, is kept at a constant temperature in the storage tanks. Considering hot in plant recycling, while the most conventional drum plants can accommodate up to 50% RAP, and the percentage of reusable RAP in batch plants ranges from 10 to 30% (Kandhal and Mallick, 1997; Noferini et al., 2018), nowadays multiple readily available for production technologies can accommodate up to 100% of recycled hot mix asphalt (Zaumanis et al., 2014; Noferini et al., 2018). The CTI batch plants might accommodate up to 45–50% RAP, while the percentage of reusable RAP in drum plants is approximately 50%. Hence, nowadays there is no technical limit on RAP content in new asphalt mixtures, as long as an adequate performance is achieved. However, it is a common practice to set a maximum value, to guarantee the durability of asphalt mixes in the long term (JRC, 2016), due to the possible compromising effect of the aged bitumen in RAP on the final mix. Moreover, the defined optimum content of RAP in asphalt mixtures varies widely from country to country, from 7 to 50% (up to 66%) by mass (Kalman et al., 2013; Garbarino et al., 2016). On average, western European countries have 40% RAP content in HMA and WMA mixtures, while Eastern European countries have 6% (BIOIS and EC, 2011; Blankendaal et al., 2014; Garbarino et al., 2016).

Moreover, according to the European Commission, steel slags can be used in road construction, meeting the requirements of European and national legislations and standards, although a specific recycling target is not set (JRC, 2016).

In Italy, the steel slags resulting from steelmaking are considered by-products, whereas RAP, as a result of the milling operations of existing road pavements at their end of life stage, is not considered to be waste, as long it is re-used within the domain of the asphalt sector (Italian M.D. 69/2018). Due to the fact that in Italy the use of steel slags and RAP for road construction is allowed, in this study, the content of RAP and EAF slags in the mixtures was designed to allow for the production of the mixtures in the CTI batch plant and to achieve acceptable values of physical and mechanical properties, in compliance with national legislations and technical standards.

## Objectives and Research Approach

This study aims at testing the use of EAF steel slags and RAP in two mixtures, for wearing and binder courses, respectively. The physical and mechanical properties and the environmental performances have been evaluated. The objectives of the research study are summarized below:

- define a standard characterization of mixtures in order to evaluate the physical and mechanical performances related to the use of virgin and recycled materials;
- assess the environmental impacts associated with the mixtures and model a best-case scenario for the CTI batch plant with the maximum percentages of steel slags and RAP;
- identify practical implications of the use of recycled materials in new asphalt mixtures, from a life cycle and industrial symbiosis perspective.

The research study is divided into two phases: in the first phase, the effects of recycled materials on asphalt mixture proprieties are investigated. Two specific types of asphalt mixtures are produced with different compositions:

(1) 35% RAP and 16% steel slags for the wearing course, by weight;
(2) 40% RAP and 15% steel slags for the binder course, by weight.

Asphalt materials are characterized in terms of size distribution, strength modulus (indirect tensile strength), and volumetric properties (air voids content).

The second phase aims at evaluating environmental impacts by applying LCA methodology to the geographical context of the CTI company. The novelty of this study is the integration of the technical analysis of material characterization, assessed by laboratory experiments, with the analysis of the environmental impacts.

**TABLE 1 |** Composition of asphalt mixtures, percentages of aggregates by weight.

| Material | Fraction (mm) | MixW0 (control) | MixW1 (35% RAP, 15% EAF steel slags) | MixB0 (control) | MixB1 (40% RAP, 16% EAF steel slags) |
|---|---|---|---|---|---|
| Gravel | 14/20 | | — | 15 | 6 |
| Gravel | 10/16 | — | — | 20 | — |
| Gravel | 8/12 | — | — | 10 | — |
| Gravel | 4/8 | 19 | 10 | 7 | — |
| Gravel | 3/6 | 30 | 9 | 12 | 10 |
| Sand | 0/4 | 45 | 30 | 32 | 25 |
| Filler | — | 6 | 1 | 4 | 3 |
| RAP | 0/8 | — | 35 | — | — |
| RAP | 8/12 | — | — | — | 40 |
| EAF slag | 4/8 | — | 15 | — | 16 |

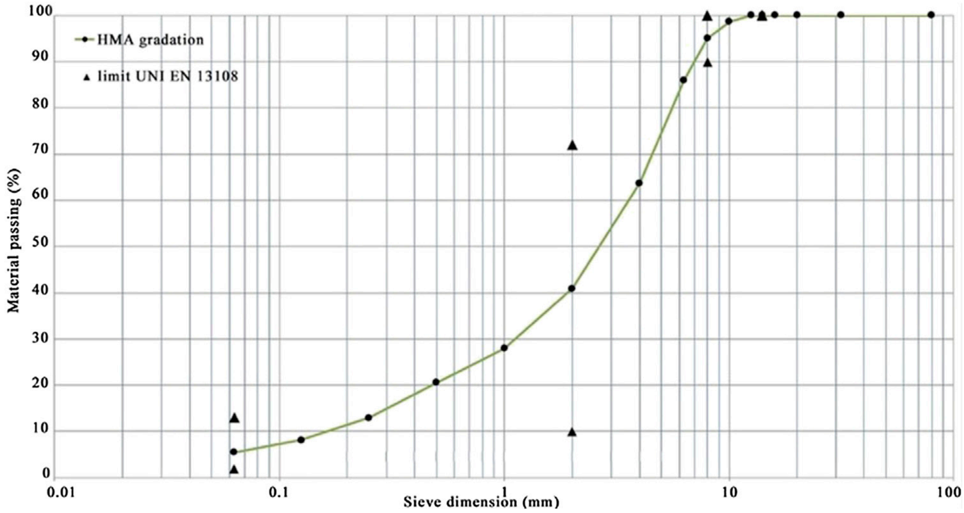


**FIGURE 3 |** MixW1 gradation and limits.

# MATERIALS AND METHOD

## Performance Analysis of Asphalt Mixtures

Four mixtures were analyzed:

- A control mixture for the wearing course (MixW0)
- An experimental mixture for the wearing course (MixW1)
- A control mixture for the binder course (MixB0)
- An experimental mixture for the binder course (MixB1)

A description of the four mixtures can be found in **Table 1**.

The design of the aggregate distribution was based on gradation limits specified in the UNI 13108 Italian technical specification for bituminous layers, as shown in **Figures 3**, **4**, with cumulative percentage passing on the *y* axis and logarithmic sieve size on the *x* axis. On the graphs, the sieve size scale (*x* axis) is logarithmic.

The experimental program can be divided into three different phases. In order to evaluate the physical and mechanical performances of the designed mixtures, MixW1 and MixB1 were characterized in terms of particle size distribution (1), volumetric properties (2), and strength modulus (3) according to the standard UNI EN 933-1 (2012), UNI EN 12697-12 (2018), UNI EN 12697-23 (2003), and UNI EN 12697-26 (2012). Asphalt mixtures were manufactured in a laboratory with design neat bitumen content of 6% for the wearing course and 5% for the binder course (these percentages include aged bitumen contained in RAP, 3.85% for the wearing course and 3.30% for the binder course, respectively). A neat binder was incorporated into the mixes, taking into account the presence of the aged binder in the RAP fractions. At the same time, the inclusion of recycled materials in the mixtures requires the addition of rejuvenating agents (ACF) to improve the adhesion properties, thermal susceptibility, viscosity, and workability of the mixes. The ACF

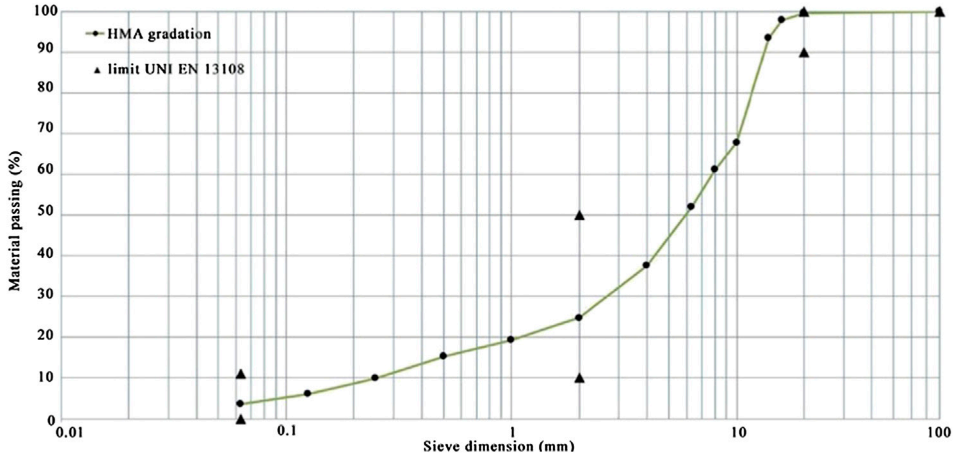


**FIGURE 4 |** MixB1 gradation and limits.

is incorporated in the commercial bitumen. Both aggregates and bitumen can directly replace their equivalent virgin products in the new mixtures (MixW1 and MixB1) at a ratio of 1:1. Aggregates were heated at 160°C. The physical and mechanical characterizations were then carried out. Asphalt mixes were tested for particle size distribution (EN 933 – 1), air void content (EN 12697-8), and indirect tensile strength (EN 12697 – 23).

### Determination of Particle Size Distribution (EN 933 – 1)

The sieve analysis was carried out in a laboratory to define the particle size distribution of MixW1 and MixB1. According to the EN 933-1 standard, a representative weighed sample for each mixture was separated on sieves of different sizes (Series 2). To find the percentage of the aggregate passing through each sieve, **Eq. 1** was used:

$$\%\,\text{retained} = \frac{W_{\text{Sieve}}}{W_{\text{Total}}} \times 100\% \qquad (1)$$

where: $W_{\text{Sieve}}$ is the mass of the aggregate in the sieve; $W_{\text{Total}}$ is the total mass of the aggregate.

In order to find the cumulative percentage of the aggregate retained in each sieve, **Eq. 2** was used. The total amount of the aggregate retained in each sieve and the amount in the previous sieves were added up. Then, the cumulative percentage passing of the aggregate was found by subtracting the percentage retained from 100%.

$$\%\,\text{cumulative passing} = 100\% - \%\,\text{cumulative retained} \qquad (2)$$

The % cumulative retained ($P_i$) used was calculated using **Eq. 3**:

$$P_{c1,i} \cdot \alpha_{C1} + P_{c2,i} \cdot \alpha_{C2} + \ldots P_{cj,i} \cdot \alpha_{Cj} + \ldots + P_{cm,j} \cdot \alpha_{Cm,j} = P_i \qquad (3)$$

where: $P_{cj,i}$ is the passing at sieve $j$; $\alpha_{Cj}$ is the percentage by weight of the total of the sieve $j$.

To solve **Eq. 3**, **Eq. 4** was provided:

$$\sum_{j=1}^{m} \alpha_{Cj} = \alpha_{C1} + \alpha_{C2} + \ldots + \alpha_{Cj} + \ldots + \alpha_{Cm} = 1 \qquad (4)$$

### Determination of Air Voids Content (EN 12697-8)

Once the mix design for MixW1 and MixB1 was defined, the following step in the research program considered their physical analysis. The compactability and workability properties of the HMAs were evaluated against gyratory compactor samples (EN 12697-31). For both mixtures, three specimens per MixW1 were compacted up to 180 times more than the gyratory compactor, and three specimens per MixB1 were compacted up to 210 times more than the gyratory compactor. The air voids content (v) of each specimen was evaluated according to the EN 12697-8 standard.

### Determination of Indirect Tensile Strength (EN 12697–23)

Finally, for each mixture, according to the EN 12697-23 standard, the indirect tensile strength (ITS) was performed at 25°C.

## Life Cycle Assessment Study

The present study has assessed the impacts arising from the hot-mix batch plant by applying an LCA methodology to the geographical context of the CTI plant, located in the Emilia-Romagna region. As previously described, an LCA study consists of four stages: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) results and interpretation.

### Goal and Scope Definition

Quantitative and comparative life cycle assessment results on road construction materials are essential first steps toward making informed decisions and toward more sustainable practices in road construction (Chowdhury et al., 2010). The present LCA study aims at evaluating the potential environmental impacts related to asphalt mixtures: 1) MixW0 compared to MixW1 and 2) MixB0 compared to MixB1. The final aim is to

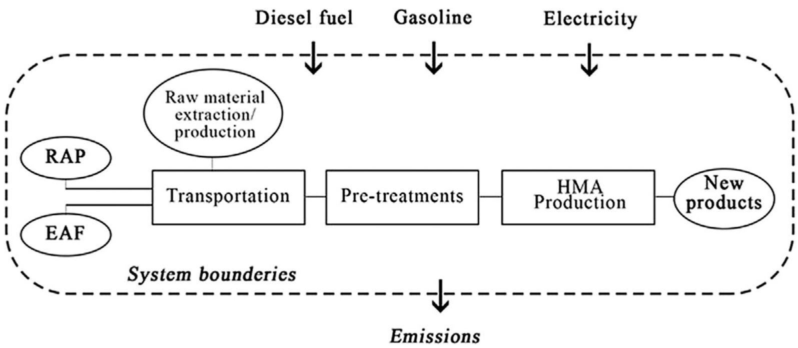


**FIGURE 5 |** Diagram flow of recycling reclaimed asphalt pavement (RAP) and electric arc furnace (EAF) in the CTI batch plant.

provide recommendations to the CTI for the improvement of technologies and regulations, based on environmental considerations. The functional unit (FU) of LCA is 1 km of secondary suburban road (with a width of 10.5 m, and a thickness of 4 cm for the wearing course, and 6 cm for the binder course). The system boundary includes all the treatment processes, starting from virgin material mining, and secondary and virgin materials entering the CTI batch plant (diesel, electricity), until when they leave the plant as an (solid, liquid, or gaseous) emission or as a new material. The final disposal or recycling processes are out of the boundary. Hence, this LCA is a cradle-to-gate analysis. As depicted in **Figure 5**, the system and processes involved in the present study are:

- The raw material transportation from the mining site/quarry to the CTI plant;
- The RAP transportation from road worksites to the CTI plant;
- The RAP pre-processing, which includes crushing and screening;
- The avoided production and transportation of natural aggregates (replaced by recycled aggregates), including extraction, processing, and transportation to the CTI batch plant;
- The avoided production and transportation of virgin bitumen (replaced by recycled bitumen).

The geographical scope is local. The study focuses on the conditions and CTI technologies used in 2018. The potential environmental impacts were evaluated using the software SimaPro®. This analytical tool works in accordance with the ISO 14040 standard (ISO, 2006a). The impact assessment baseline, performed by the Institute of Environmental Sciences of the Leiden University (CML) in version 3.05, was selected as a method for the environmental impact assessment, using the LCI “Ecoinvent 3.5” and “Europe & Denmark input output” databases. The following impact categories were evaluated: abiotic depletion, acidification, eutrophication, global warming potential, ozone layer depletion, and photochemical oxidation.

## Inventory Analysis

Data regarding the core processes, i.e., transportation, hot recycling, and energy consumption, are primary data. For analyzing the CTI HMA batch plant, data were collected directly from the CTI company. Data related to other foreground processes, i.e., bitumen production, extraction of natural mineral resources, and pre-processes of waste asphalt, were instead taken from the LCA software SimaPro databases (Ecoinvent and Europe & Denmark databases). Therefore, the avoided impacts, due to the avoided consumption of natural virgin aggregates because of the EAF steel slags and RAP addition into hot mixes, are modelled using secondary data on quarry activities in Europe.

Inventory data about the transportation of the raw materials, asphalt waste, and bitumen are modelled using the primary data on CTI transports, as shown in **Table 2**. **Table 3** shows the inventory data on energy consumption in the CTI batch plant.

## Impact Assessment

In the LCIA, the CML impact assessment baseline calculation method was adopted. The consumption of materials and energy as well as the emissions to air, water, and soil were gathered according to the effects they can have on the environment. According to ISO 14044 (2006b), the LCIA consists of classifications into impact categories, normalization, and the weighting of impacts. In this standard, a distinction between mandatory elements (classification and characterization) and optional elements (normalization, grouping, ranking, and weighting) was pointed out. In the current LCA study, classification and characterization were performed to assess the environmental impacts of MixW1 compared to MixW0 and of MixB1 compared to MixB0. No optional elements were evaluated.

Therefore, this methodology aims to assess the environmental impacts of the processes identified in the inventory analysis. Hence, all substances were measured and assigned to an impact category. The results are represented by single midpoints.

**TABLE 2 |** Inventory data about the transportation of the asphalt waste, the by-products, and the primary materials to the plant.

| Material | Transport distance (km) | Description | Lorry type | Source |
|---|---|---|---|---|
| EAF slags | 150 | Road distance between company – CTI batch plant | 32 metric tons, EURO 6 | Ecoinvent 3.5 |
| Asphalt waste | 40 | Road distance between RAP site – CTI batch plant | 32 metric tons, EURO 6 | Ecoinvent 3.5 |
| Natural aggregates | 190 | Road distances between quarry site – CTI batch plant | 32 metric tons, EURO 6 | Ecoinvent 3.5 |
| Virgin bitumen | 230 | Road distances between bitumen plants – CTI batch plant | 28 metric tons, EURO 6 | Ecoinvent 3.5 |

**TABLE 3 |** Inventory data about the energy consumption in the CTI batch plant.

| Processes | Energy type | Energy consumption/ton (kWh/ton) | Methane ($m^3$) | Source |
|---|---|---|---|---|
| Line 0 | Electricity | 6131 | 8.5 | Ecoinvent 3.5 |
| Line 1 | Electricity | 273 | 8.5 | Ecoinvent 3.5 |

**TABLE 4 |** Environmental impacts related to MixW1 and MixB1.

| Impact categories | Unit | Total | |
|---|---|---|---|
| | | MixW1 | MixB1 |
| Global warming potential | kg $CO_2$ eq. | 4.60E + 04 | 5.80E + 04 |
| Human toxicity | kg 1.4 - DB eq. | 1.82E + 04 | 2.62E + 04 |
| Acidification | kg. $SO_2$ eq. | 3.09E + 02 | 3.35E + 02 |
| Eutrophication | kg $PO_4$ eq. | 8.31E + 01 | 1.09E + 02 |
| Ecotoxicity | kg 1.4 - DB eq. | 1.53E + 03 | 1.55E + 03 |
| Photochemical oxidation | kg $C_2H_4$ | 1.53E + 01 | 1.72E + 01 |
| Ozone layer depletion | kg CFC - 11 eq. | 3.18E − 02 | 3.39E − 02 |
| Abiotic depletion | kg Sb eq. | 1.45E − 01 | 1.49E − 01 |
| Abiotic depletion fossil fuels | MJ | 2.52E + 06 | 2.73E + 06 |

# RESULTS

## Standard Characterization Test Results: Performances of the MixW1 and MixB1 Mixtures

In order to evaluate the physical and mechanical performances of the mixtures incorporating different recycled aggregate percentages for the wearing and binder courses, MixW1 and MixB1 were characterized in terms of air void content (v), indirect tensile strength (ITS), indirect tensile stiffness modulus (ITSM), and indirect tensile strength ratio (ITSR).

The determination of the air void content of MixW1 and MixB1 can be found in the **Supplementary Material** as well as the results of the determination of ITS, ITSR, and ITSM of MixW1 and of MixB1, respectively. According to the UNI EN 12 697 – 12 standard, the ITSR value represents the ratio of the indirect tensile strength of wet (water conditioned) specimens to that of dry specimens expressed as percentages, calculated by using the following equation (**Eq. 5**):

$$ITSR = 100 \cdot \frac{ITS_w}{ITS_d} \tag{5}$$

Where: $ITS_w$ is the indirect tensile strength of wet (water conditioned) specimens; $ITS_d$ is the indirect tensile strength of dry specimens.

**TABLE 5 |** Mechanical and volumetric properties of MixW1 and MixW0.

| Specimen | Avg. ITS (MPa) | Avg. void (%) | | |
|---|---|---|---|---|
| | | 10 | 120 | 210 (v) |
| MixW1 | 2.68 | 11.2 | 2.7 | 1.8 |
| MixW0 | 1.19 | 13.2 | 4.0 | 2.5 |

**TABLE 6 |** Mechanical and volumetric properties of MixB1 and MixB0.

| Specimen | ITS (MPa) | Void (%) | | |
|---|---|---|---|---|
| | | 10 | 100 | 180 |
| MixB1 | 1.88 | 9.6 | 4.6 | 1.6 |
| MixB0 | 1.35 | 13.6 | 4.9 | 2.9 |

## Life Cycle Assessment Results: Performances of the MixW1 and MixB1 Mixtures

The LCA was chosen to evaluate the environmental impacts that affect the designed road life cycle (production and treatment processes and transportation of the involved materials). The overall environmental impacts related to the production of asphalt mixtures MixW1 and MixB1 in the CTI batch plant are shown in **Table 4**. The analysis was supported by the LCA in compliance with the ISO 14040 standard and the ISO 14044 standard.

# DISCUSSION OF STANDARD CHARACTERIZATION OF MIXTURES AND LIFE CYCLE ASSESSMENT

To discuss the results of the standard characterization of the designed mixtures, a comparison of the performances of the designed mixtures and control mixtures was first performed.

**Tables 5**, **6** show the results for the four mixtures, in terms of average indirect tensile strength (ITS) and average air void percentages.

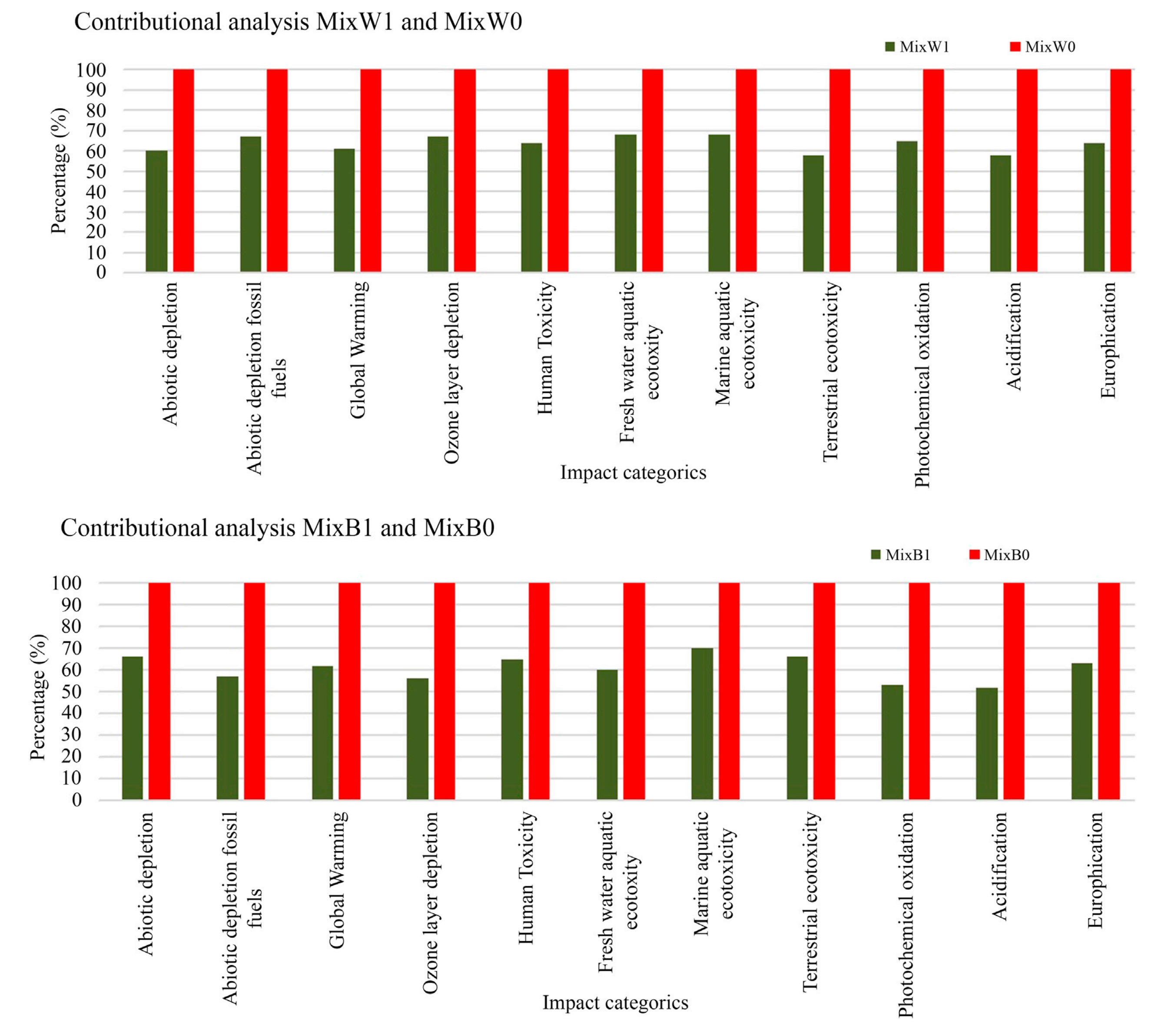


**FIGURE 6 |** Contribution analysis related to recycling of RAP and EAF slags in CTI batch plant for wearing course **(above)** and for binder course **(below)**.

The mechanical analysis was supported by the ITS test in compliance with the EN 12697-23 standard. For each mixture, three samples were prepared with a gyratory compactor (180 and 210 times) and then conditioned at 25°C for 4 h before testing. According to the scientific literature, an ITS test is generally used to assess the level of tenacity of the aggregate-filler-bitumen bond (Sangiorgi et al., 2019) and the ITS value strongly depends on the medium-high amount of aggregates, bitumen, and recycled materials. From the analysis of data, there was a difference in terms of indirect tensile resistance between the two experimental mixtures (MixW1 and MixB1) compared to the control ones (MixW0 and MixB0). It could be argued that the results indicate a hardening of the composite blend caused by the presence of the aged bitumen. Therefore, the two mixtures show different air void contents.

To note, the average value of ITS recorded for both experimental mixtures was considerably higher than the limit suggested by the Italian technical specifications (ANAS, 2019), which ranges between 0.72 and 1.60 MPa per wearing course, and between 0.72 and 1.40 MPa per binder course.

Similarly, if the Italian technical specification is taken into account, the air void content (v) was lower than the suggested one, which ranges between 3 and 8%.

The standard characterization of the mixtures evaluated the hardening effect of the old bitumen on the content blend. According to Noferini et al. (2018), the hardening effect becomes relevant when the RAP binder content is above 20% by weight of the mixture. In particular, the new bituminous mixtures per binder and wearing course (MixB1 and MixW1)

**TABLE 7 |** Environmental impacts related to MixW0 and MixW1, MixB0 and MixB1.

| Impact categories | Unit | Total | | | |
|---|---|---|---|---|---|
| | | MixW0 | MixW1 | MixB0 | MixB1 |
| Global warming potential | kg $CO_2$ eq. | 7.51E + 04 | 4.60E + 04 | 9.37E + 04 | 5.80E + 04 |
| Human toxicity | kg 1.4 - DB eq. | 2.86E + 04 | 1.82E + 04 | 4.02E + 04 | 2.62E + 04 |
| Acidification | kg. $SO_2$ eq. | 5.30E + 02 | 3.09E + 02 | 6.36E + 02 | 3.35E + 02 |
| Eutrophication | kg $PO_4$ eq. | 1.30E + 02 | 8.31E + 01 | 1.73E + 02 | 1.09E + 02 |
| Ecotoxicity | kg 1.4 - DB eq. | 2.30E + 03 | 1.53E + 03 | 2.33E + 03 | 1.55E + 03 |
| Photochemical oxidation | kg $C_2H_4$ | 2.61E + 01 | 1.53E + 01 | 3.25E + 01 | 1.72E + 01 |
| Ozone layer depletion | kg CFC - 11 eq. | 4.74E − 02 | 3.18E − 02 | 5.97E − 02 | 3.39E − 02 |
| Abiotic depletion | kg Sb eq. | 2.44E − 01 | 1.45E − 01 | 2.23E − 01 | 1.49E − 01 |
| Abiotic depletion fossil fuels | MJ | 3.74E + 06 | 2.52E + 06 | 4.73E + 06 | 2.73E + 06 |

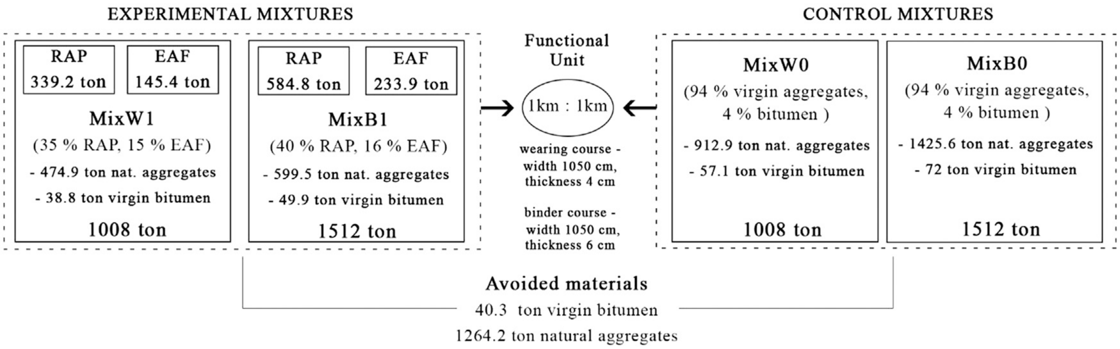


**FIGURE 7 |** Diagram flow of recycling RAP and EAF in the CTI batch plant for hot-mix asphalt, with the inclusion of the avoided products for wearing course (MixW0 and MixW1) and binder course (MixB0 and MixB1).

were more rigid than the traditional ones (MixB0 and MixW0), but they were not excessively thickened because the final void value was less than 2%. Hence, the final void content of the two new mixtures was optimal.

Moreover, as the stiffness and the fatigue performance were not tested, further research might investigate these aspects.

Secondly, a comparison of LCA results between the two mixtures for the wearing course (MixW0 and MixW1) and the two mixtures for the binder course (MixB0 and MixB1) was performed. Hence, **Figure 6** and **Table 7** show the results of the contribution analysis related to the recycling of RAP and EAF slags in the CTI batch plant. Interestingly, significant differences were found between MixW0 and MixW1, and between MixB0 and MixB1. LCA allows the authors to evaluate the environmental benefits related to the use of recycled aggregates. Due to the reduction of emissions and natural resources used, MixW1 and MixB1 provide environmental benefits in all impact categories (abiotic depletion, abiotic depletion fossil fuels, global warming potential, ozone layer depletion, human toxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication). The avoided impacts associated with the use of recycled material and with the reduction in the consumption of bitumen and aggregates overcome the impacts related to the waste transportation and the pre-treatment processes, resulting in a total reduction in environmental impact. Hence, it can be argued that recycling RAP and EAF steel slags in the CTI batch plant provides environmental benefits, besides reducing the consumption of virgin bitumen and natural aggregates.

These results are supported by the ones obtained in a preliminary and more general study, previously undertaken (Degli Esposti et al., 2020), showing that the experimental mixtures have fewer environmental impacts than the control ones. According to the LCA results, a reduction in all impact categories occurred, and mainly in human toxicity (−30.5%) and eutrophication (−24%), related to the intensive energy consumption and the utilization of non-renewable sources, during both the extraction and transportation phases. In particular, a robust reduction in $CO_{2eq}$ emissions was demonstrated by the better performance of the category global warming potential (−21%), as it was estimated at 46 tons of $CO_{2eq}$ for the experimental mixtures (MixW1 and MixB1) and at 58 tons of $CO_{2eq}$ for the control mixtures (Mix W0 and MixB0). To summarize, the use of RAP and EAF steel slags in 1 km of suburban road allows the CTI to reduce the content of virgin bitumen by weight of the total mixture by 2.15% (by total weight) for the wearing course and by 1.70% (by total weight) for the binder course. Moreover, the use of recycled materials in 1 km of suburban road allows the company to save 438.0 tons of natural aggregates and 18.2 tons of virgin bitumen for the wearing course, 826.2 tons of natural aggregates and 22.1 tons of virgin bitumen for the binder course, as shown in **Figure 7**.

## CONCLUSION

The inert nature of RAP, and the excellent mechanical properties of the EAF slags make them two potentially useful materials in a wide variety of applications, including re-use or recycling in new asphalt pavements. This case study demonstrates the high potential for recycling RAP and EAF steel slags in the road construction sector, as a secondary raw material and a by-product, respectively.

As a result of testing the use of EAF steel slags and RAP in new bituminous mixtures, the physical and mechanical properties as well as the environmental performances of the two mixtures have been evaluated for wearing and binder courses, respectively. In order to maximize the environmental sustainability of the road pavement, the use of RAP and EAF steel slags can be recommended.

Moreover, the authors believe that LCA results and indicators are appropriate tools to compare and communicate the environmental performances of different asphalt mixtures in road construction.

By reducing the global environmental impact and recycling by-products, the CTI and the co-located companies are a real case study of industrial symbiosis at the meso-level.

The authors believe that the development of industrial symbiosis projects provides the opportunity to promote waste reduction, reuse, and recycling, while reducing the environmental impacts, as well as increasing companies' competitiveness, in particular in countries like Italy, where there are already several large industrial clusters. Moreover, information sharing among stakeholders would facilitate the development of industrial symbiosis networks.

Future research efforts could focus on investigating other recycled materials, for the same applications as virgin ones, with the purpose of reaching the same quality level and performances. In this issue, no economic evaluation was carried out. As a future research direction, the economic sustainability will be evaluated.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

## AUTHOR CONTRIBUTIONS

AB and AE designed the study. AE collected information and materials from the company. AB and AE conceived and planned the experiments for the characterization of asphalt mixtures. AE carried out the experiment. All the authors contributed to the interpretation of the results. AE and CM designed the LCA model and analysed the data. All the authors contributed to the interpretation of the LCA results. AB took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript.

## ACKNOWLEDGMENTS

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmats.2020.572955/full#supplementary-material.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## 4.2. Paper 2. A framework for sustainability assessment and prioritisation of urban waste prevention measures (Magrini et al., 2021)

### Brief introduction

The aim of this paper is to propose a framework for the sustainability assessment, the evaluation of success, and the prioritisation of Waste Prevention Measures at consumption level. Firstly, relevant project categories are selected, by verifying the fulfillment of specific conditions. Adopting a life-cycle perspective, the environmental, economic, and social consequences of Waste Prevention Measures within the selected categories are assessed. Then, a set of indicators for the evaluation of effectiveness and efficiency of the projects is defined, as well as an algorithm to support the identification of a priority order for the project categories. The model is described through its application to the significant case of the Emilia-Romagna Region, in Italy. The Region has a population of 4.471.485 inhabitants (2019), with a production of urban waste equal to 3.011.354 tons in 2018. Some ongoing prevention projects implemented by Municipalities in the Region are analysed as replicable case studies.

### Study findings

In this research study waste prevention is investigated within the framework of sustainability, in accordance with the SDG 12 of United Nation Agenda 2030, by focusing on Waste Prevention Measures promoting sustainable consumption. In compliance with the definition of strategic waste prevention, a framework for the assessment of waste prevention measures implemented by Municipalities is proposed, to evaluate their success and support the financing choices of public decision-makers. The designed framework evaluates impacts, effectiveness, and efficiency of some selected prevention measures. The framework designed by authors was tested on three categories of projects: as a case study, the impacts of 17 projects already ongoing in the Emilia- Romagna Region were assessed. As an outcome, a priority order for future allocation of financial resources can be defined. Moreover, the contribution of waste prevention measures to the achievement of waste prevention targets and sustainable development is quantified. In the present study environmental considerations are complemented by an evaluation of economic and social impacts. Life Cycle Assessment and Life Cycle Cost methodologies have been applied, limiting the explored system to the phases of consumption and Waste Management. The three types of projects (water dispensers in towns/cities, water dispensers in schools and reduction in consumption of disposable products) is compared, for each aspect analysed (environmental, economic, and social), by assessing the average value of selected indicators. Hence, the results are shown in Table 3. Each indicator was normalized (see Section 5 of Appendix A). Then, the average value for each aspect was calculated. Table 4 shows the results: the total score for each project category is calculated as the average of the scores in each sustainability pillar. The total score is a result of the environmental, economic, and social contributions. The water dispenser project category whose total score is 0,4265 ranks first, resulting in the best one, whereas the water dispenser in schools and the replacement of disposable goods in school canteens get an approximately equal total score.

This study gives a contribution in the waste prevention field. Literature highlighted the need of developing reliable methods to monitor, measure and evaluate benefits of waste prevention, as means to overcome potential barriers to the spread and to the success of waste prevention measures.

**Conclusion**

I. No general methodology for the assessment of prevention initiatives does exist yet;

II. Environmental, economic, and social sustainability in a life cycle perspective are used for the evaluation of the Impacts, effectiveness, and efficiency of 17 waste prevention projects are assessed;

III. An algorithm for prioritisation is proposed for monitoring waste prevention activities in decision-making processes;

IV. The analysis and discussion of results gives a valuable contribution to the formulation and promotion of Waste Prevention strategies at different geographical levels.

**Author contributions**

Chiara Magrini: Conceptualization, Methodology, Validation, Formal analysis, Data curation,Writing – original draft, Writing – review & editing, Visualization.

**Anna Degli Esposti**: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. Elena De Marco: Conceptualization, Validation, Investigation, Writing – original draft.

Alessandra Bonoli: Conceptualization, Validation, Writing – review & editing, Supervision.

**Table 4.2**. Overview of the second manuscript (Magrini et al., 2021).

| | |
|---|---|
| Title | A framework for sustainability assessment and prioritisation of urban waste prevention measures |
| Status | Published |
| Keywords | Waste prevention, Waste reduction, Sustainability, Environmental assessment, Economic assessment, Social assessment |
| Journal | Science of the total environment, 776, 1 – 12 |
| Abstract | Waste prevention (WP) can play a significant role in pursuing both sustainable development and decarbonization. Nevertheless, a general method to monitor and evaluate WP does not exist yet. This study proposes a framework for the sustainability assessment and prioritisation of waste prevention measures (WPMs), at consumption level. Firstly, some WPMs are selected, based on relevant criteria. Secondly, their impacts are assessed, in terms of environmental, economic, and social sustainability, in a life-cycle perspective. Then, a set of significant effectiveness and efficiency indicators are chosen and calculated. Finally, an algorithm for the prioritisation is proposed. The designed framework has been applied to 17 projects implemented by Municipalities in the Emilia-Romagna Region (Italy), as case study. The projects, whose aim is the reduction of waste from plastic disposable goods, can be grouped in three different categories: i)drinking water dispensers in towns/cities, ii) drinking water dispensers in schools and iii)replacement of disposable goods in school canteens. The project category of drinking water dispensers in towns proved to be the most sustainable one, achieving a score of 0,4265, while the other categories scored around 0,28. |
| Credit authorship | Chiara Magrini: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Anna Degli Esposti**: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. Elena De Marco: Conceptualization, Validation, Investigation, Writing – original draft. Alessandra Bonoli: Conceptualization, Validation, Writing – review & editing, Supervision. |
| Annex | 2 |

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# A framework for sustainability assessment and prioritisation of urban waste prevention measures

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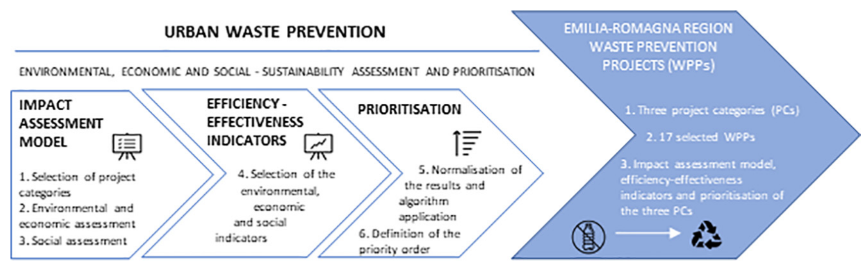
## HIGHLIGHTS

- No general methodology for the assessment of prevention initiatives exist.
- Environmental, economic, and social sustainability in a life cycle perspective.
- Impacts, effectiveness, and efficiency of 17 waste prevention projects are assessed.
- An algorithm for prioritisation is proposed.
- Monitoring waste prevention activities is crucial for decision-making.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Waste prevention (WP) can play a significant role in pursuing both sustainable development and decarbonization. Nevertheless, a general method to monitor and evaluate WP does not exist yet. This study proposes a framework for the sustainability assessment and prioritisation of waste prevention measures (WPMs), at consumption level. Firstly, some WPMs are selected, based on relevant criteria. Secondly, their impacts are assessed, in terms of environmental, economic, and social sustainability, in a life-cycle perspective. Then, a set of significant effectiveness and efficiency indicators are chosen and calculated. Finally, an algorithm for the prioritisation is proposed. This methodological approach might be useful to guide the financing choices of the public decision-makers, to assess and promote WPMs, and to develop WP strategies. Moreover, the results can be used in waste management planning and to motivate local actors through benchmarking.

The designed framework has been applied to 17 projects implemented by Municipalities in the Emilia-Romagna Region (Italy), as case study. The projects, whose aim is the reduction of waste from plastic disposable goods, can be grouped in three different categories: i) drinking water dispensers in towns/cities, ii) drinking water dispensers in schools and iii) replacement of disposable goods in school canteens. The project category of drinking water dispensers in towns proved to be the most sustainable one, achieving a score of 0,4265, while the other categories scored around 0,28.

The study confirms that WP should be promoted, despite being very difficult to monitor. The political institutions should invest in implementing a specific monitoring system, also able to reveal potential integration of WP strategies with other policy areas. Finally, an improved institutional framework might help the Municipalities in overcoming barriers to the identification and implementation of WPMs, by allowing for coordination and networking of individual projects and by encouraging the spread of good practices.



## 1. Introduction

Waste prevention (WP) is an important element within the paradigm of sustainable development: in the frame of United Nations

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Agenda 2030, sustainable development goal (SDG) 12 (Ensure sustainable consumption and production patterns) includes targets focused on environmentally sound management of all waste through prevention, reduction, recycling, and reuse (targets 12.4 and 12.5) and reduction of food waste (target 12.3) (United Nations, 2015). At global level, WP is particularly important in urban areas, where the population is increasing, and waste generation is higher. Accordingly, the SDG 11 (Make cities and human settlements inclusive, safe, resilient, and sustainable) aims to "reduce the adverse per capita environmental impact of cities, including special attention to air quality and municipal and other waste management", and the New Urban Agenda (United Nations, 2017) commits to "environmentally sound management and minimization of all waste" too.

WP could play a significant role in emission reduction and more specifically in climate change mitigation, if implemented globally (Gentil et al., 2011): the potential greenhouse gases (GHG) savings from WP and minimisation could greatly exceed the savings that can be achieved by advanced technologies managing post-consumer waste (ISWA, 2010). In Europe, waste management (WM) sector represents the fourth largest source of GHG emissions, accounting for 3% of total greenhouse gas emissions in 2017 (Eurostat, 2020): the implementation of best practices might boost the achievement of the 2050 European climate-neutrality target, or the intermediate goal envisaging at least −55% net GHG emissions by 2030, as stated by the European Green Deal (European Commission, 2020).

The European waste hierarchy places the greatest preference on WP, which is the most favourable WM option, above reuse, recycling, and recovery (Directive 2008/98/EC (EU European Union, 2008), Article 4, as amended by Directive (EU) 2018/851 (EU European Union, 2018)). Nevertheless, over the time frame between 2013 and 2018, an increase in per capita generation of municipal solid waste (MSW) occurred in the European Union.

Although the political commitment to this topic, according to literature very little is understood about how to monitor and evaluate WP particularly among local authority waste managers who are most likely to implement intervention campaigns (Sharp et al., 2010; Corsini et al., 2018; Gusmerotti et al., 2019). So far, there is no general method to monitor and evaluate the effects of waste prevention measures (WPMs) (Zorpas and Lasaridi, 2013; Zacho and Mosgaard, 2016; Yano and Sakai, 2016; Matsuda et al., 2018; Hutner et al., 2018) and only a few studies have focused on waste prevention systems (Laurent et al., 2014; Hutner et al., 2018). The success of a WP action cannot be assessed with an analysis of the evolution of waste, since waste generation depends on many factors whose effect is difficult to assess. Therefore, a completely different approach has to be led, focusing on the actual action (Bel, 2010; Hutner et al., 2018).

As Abeliotis et al. (2013) state, WP includes a variety of different actions, such as: i) reducing or even eliminating the consumption and therefore the production of certain goods; ii) substitution of products by others; iii) extending the utilization phase for items. A more detailed classification of WPMs was proposed by Nessi et al. (2013) (see Section 2 of Appendix A): the focus is on the environmental consequences of the implementation of waste prevention activities (i.e., the environmental impacts related to substitutive goods/packaging or to the usage phase).

Considering the increasing demand for broader sustainability assessments, where the environment, society and the economy are integrated (Hellweg and Canals, 2014), it might be stated that the impacts of WPMs have to be assessed by including also economic and social domains, given that a partial approach often delivers misleading messages for policy- and decision makers. Moreover, this conforms with Article 4 of the Waste Framework Directive (EU European Union, 2008) which establishes "economic viability" and "economic and social impacts" as decisive criteria for the implementation of the waste hierarchy.

Results of a literature review show that only one study has assessed waste prevention activities according to the so-called three pillars of sustainability: Bergström et al. (2020) applied Environmental Life-Cycle Assessment, Life-Cycle Costing and Social Life-Cycle Assessment to some food waste prevention activities (see Section 1 of Appendix A for details on the literature review performed by the authors). To the best of the authors' knowledge, no studies exist about the sustainability assessment of prevention activities aiming at the reduction of other waste streams. Moreover, the study by Bergström et al. (2020) does not provide the readers with indicators assessing the success of WPMs analysed.

Thus, the aim of this paper is to propose a framework for the sustainability assessment, the evaluation of success, and the prioritisation of WPMs at consumption level. Firstly, relevant project categories are selected, by verifying the fulfilment of specific conditions. Adopting a life-cycle perspective, the environmental, economic, and social consequences of WPMs within the selected categories are assessed. Then, a set of indicators for the evaluation of effectiveness and efficiency of the projects is defined, as well as an algorithm to support the identification of a priority order for the project categories. The specific objectives are: i) to support the decision-makers in the prioritisation of publicly funded projects, which aim at WP by acting at consumption level; ii) to assess the already implemented projects, in a preliminary manner, by providing insights on their success. The analysis and discussion of results gives a valuable contribution to the formulation and promotion of WP strategies, at different geographical levels.

The model is described through its application to the significant case of the Emilia-Romagna Region, in Italy. The Region has a population of 4.471.485 inhabitants (2019), with a production of urban waste equal to 3.011.354 ton in 2018. Some ongoing prevention projects implemented by Municipalities in the Region are analysed, as replicable case study.

## 2. Materials and method

Strategic Waste Prevention is defined as "*a long-term policy concept that concretely situates waste prevention within a longer-term resource management and sustainable development perspective. Strategic Waste Prevention works toward the reduction of absolute waste amounts, hazards and risks, and it is characterised by at least four aspects* (…)*: a life-cycle perspective, a material-differentiated approach, integration of social and economic aspects into environmental policy discussions, and facilitating co-operation across traditional institutional structures for overall policy synergy*" (OECD, 2000). This definition is the base for the design of the framework described in this study.

WP needs actions both at production and consumption level. According to Boulanger and Mainguy (2010) "path towards dematerialized and detoxified goods and services can be summarized by 4Rs; significant benefits in Reducing, Reusing, Recycling and Repairing will not result from changes at the production level only, but from inescapable changes in consumption practices and institutions": this study focuses on this second kind of changes, enabled by the implementation of specific projects at municipal level.

Fig. 1 depicts a graphical representation of the stages of the designed framework. The framework is described in detail in the next paragraphs, after an introductive description of the Emilia-Romagna case study.

### 2.1. The case study of the Emilia-Romagna Region

In Italy, urban WM involves a system articulated between State, regional, provincial, and municipal competences. While the State is in charge of defining the general criteria for WM (Legislative Decree 152/2006 art.195 (Italian Government, 2006)), the Regions are responsible for planning activities (Legislative Decree 152/2006 art.196 (Italian Government, 2006)).

The Emilia-Romagna Region is committed to WP: after the approval of the Italian national waste prevention program in 2013, the Emilia-Romagna Region Council approved in 2016 the "Emilia-Romagna

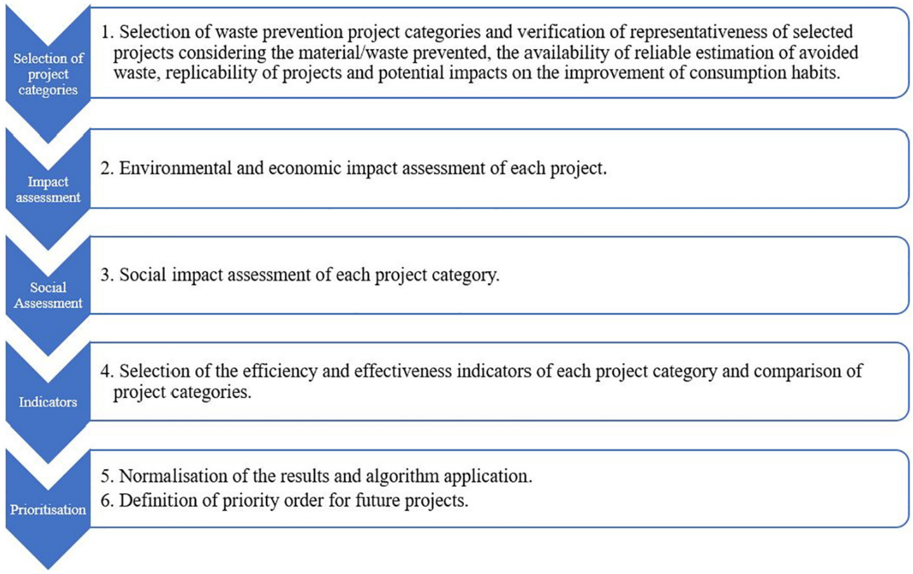


**Fig. 1.** Graphical representation of the stages of the proposed framework.

Region waste management plan" which defines the regional waste prevention program (chapter 17, part IV), over a time frame of 7 years (2013—2020). The plan includes some prevention measures; each measure is divided in related actions, which have impact on different product life stages (see Section 2 of Appendix A for details). The target is to reach 20–25% reduction of per capita urban waste production by 2020, compared to 2014.

Since the implementation of a municipal WP program can be a complex process, requiring important investments and the involvement of many actors, potentially belonging to the whole supply chain of goods and services (Nessi et al., 2015), the Region established a fund to promote prevention and reduction of waste among the Municipalities (Emilia-Romagna Region, 2015). This conforms to European Directive 851/2018, which suggests the application of economic incentives for regional and local authorities, in particular, to promote WP and intensify separate collection schemes (see annex IVa, titled "Examples of economic instruments and other measures to provide incentives for the application of the waste hierarchy"). The regional fund aims at: i) reducing the cost of WM for the citizens of the Municipalities which achieved the best results in reducing production of non-recyclable waste; ii) reducing the costs of changing the collection system, to implement a pay-as-you-throw scheme; iii) financing the creation of municipal reuse centres and municipal projects promoting reduction in waste generation. This study focuses on the third point, analysing the projects promoting waste reduction. The regional fund is managed by ATERSIR, the Emilia-Romagna territorial agency for water and waste services, which defines the criteria to allocate economic resources. Starting from 2016, every year a call for grants for the implementation of municipal waste reduction projects has been published. Section 2.1 of Appendix A provide further information, showing a classification of the 89 waste reduction projects funded from 2016 to 2018 in Emilia-Romagna.

Since the total cost of WM system in the Emilia-Romagna Region for the 3 years (2016–18) was around 2.248 million €, the investments in waste reduction projects represent around 0,05% of this value. As for now, 81 Municipalities out of 331 Municipalities have received funds for at least one project.

### 2.2. First stage: selection of the project categories and verification of representativeness of the selected projects

The first stage of the designed framework aims at the selection of project categories to be considered and of representative projects within each of them. Selection criteria ensure the reliability of the analysis and the comparability among the selected project categories. This framework was designed to analyse and compare only projects which prevent the same waste materials. Besides that, other selection criteria are the availability of reliable estimation of avoided waste imputable to projects, the replicability of projects within the territory, and their potential impacts on the improvement of consumption habits. After the selection of project categories, the representativeness of projects within each category has to be verified.

In the present case study, this results in selecting three categories of projects: i) installation of water dispensers in towns/cities (the so-called "water houses"), including 12 projects; ii) installation of water dispensers in schools, including 2 projects; iii) replacement of disposable goods in school canteens, including 3 projects.

Firstly, since plastic was defined as a priority waste stream both at European and regional level, projects tackling plastic pollution has been selected. A focus on single-use plastic waste prevention through the reduction of disposable plastic products consumption is maintained. Over the past few years, plastic has been object of specific policies, both at European and regional level, i.e., the European Union (EU) plastic strategy (COM/2018/028), the so-called "Single-use plastic products (SUPP) Directive" (Directive 2019/904) and the related "Emilia-Romagna Regional strategy for reducing the impact of plastics on the environment" (Emilia-Romagna Region, 2019). Social commitment on this problem has increased as well. For example, a recent survey shows that a major part of Italian citizens (94%) are willing to stop buying plastic bottles (EIB, 2020).

The second selection criterion verifies the feasibility of a reliable estimation of avoided waste for project categories object of analysis. In this case, the availability of the involved stakeholders to provide real data has been an essential condition.

Thirdly, all the selected project categories have high replicability potential, meaning that their replication is theoretically feasible in each Municipality and each school of the Region, as they do not have specific requirements (e.g., in terms of place, because they are implemented in public spaces).

Additionally, potential impacts on the improvement of consumption habits have been considered. Italy is the first Country in Europe for per capita consumption of bottled water (BW): in 2018 the average value was 221 l/year, while in 1980 it was only 47 l/year (Bevitalia, 2019). Considering packaging, in 2018, the majority consisted of single-serve polyethylene terephthalate (PET) BW, which represents the 82% of total water consumption, while the 16% consists of glass bottles (Bevitalia, 2019). This implies that wide margins of improvement exist in BW consumption habits. The same considerations are valid for single-use tableware: in Italy, around 114.200 t of single-use tableware are sold every year, used both in big events and in public or private canteens (Eco dalle città, 2010). In Italy, 432,3 million of meals in school canteens were consumed in 2016 (ORICON, 2017). Assuming that half of them is served in disposable tableware whose weight is 200 g, 43.230 t of waste would be generated every year.

Finally, the representativeness of projects within each project category has to be guaranteed. To check that, the average and the standard deviation of the population of Municipalities implementing projects in category 1 has been calculated and compared to the average and standard deviation of the population for all the Municipalities in the Region. Results show that the values are acceptable. The schools involved in projects within category 2 are representative of schools in the Region as far as the number of potential users is concerned. As a matter of fact, the average number of scholars in each school in the Region is equal to 1024 (School office of the Emilia-Romagna Region, 2020), a value close to the average number of students involved in the selected projects. Moreover, since a specific group of citizens is targeted, the average usage rate can be assumed as more uniform, with the variation of the school. On the other hand, the three projects within category 3 are representative of a small, medium, and large school canteens, respectively.

### 2.3. Second stage: impact assessment methodology and system boundary

According to the "European better regulation guidelines" (EC, 2017), the impact assessment (IA) process is about gathering and analysing evidence to support policymaking as well as the advantages and disadvantages of available solutions. Hence, the IAs must compare the policy options on the basis of their economic, social, and environmental impacts (quantified costs and benefits whenever possible). Thus, the second stage of the framework aims to assess the environmental and economic impacts of each project.

Environmental benefits of waste prevention activities may not be simply considered as proportional to the amount of waste prevented (Nessi et al., 2013). The assessment of environmental impacts of WPMs is complex, as it requires determining the environmental impact of: i) the avoided production of the material that becomes waste; ii) the avoided or additional upstream life-cycle stages that are affected by the prevention measure; iii) the avoided WM (JRC, 2011).

Considering the classification of WPMs by Nessi et al. (2013) (reported in Section 2 of SM), the analysed projects can be included in the typology "Development and/or use of less-waste-generating goods or services to provide a given function", as they imply the "development and/or use of a reusable good or of a good provided in a reusable packaging instead of a disposable good or of a good provided in a disposable packaging". Therefore, the substitutive goods generated as additional MSW to be managed and the increase of impacts in the usage phase have also been assessed, in order to include the rebound effects generated by WPMs (Hertwich, 2008).

The same considerations are valid when other dimensions of sustainability are considered. For this reason, the system boundaries set by the design framework are in common to environmental, economic, and social analyses. The geographical boundaries are regional.

The system object of the analysis includes all the activities starting from the purchase of single-use products and substitutive products to their end of life (e.g., the consumption of oil in the production of plastic bottles and the emissions to air from the vehicles that transport single-use bottles are not included). It should be noted that production, placement, and end of life of water dispensers and dishwashers are out of system boundaries, such as the life-cycle of preliminary water purifying and distribution systems. Even if the projects have a multi-year life-cycle, the assessment has been limited to the first year of project life.

Table 1 shows a brief overview of the impacts evaluated, split into: i) avoided impacts; ii) impacts related to substitutive goods and additional MSW; iii) additional impact of usage stage. Categories 1 and 2 are merged, as they are modelled in the same way.

#### 2.3.1. Life-Cycle Assessment and Life-Cycle Costing

Life-cycle assessment (LCA) methodology has been used to evaluate environmental sustainability of waste prevention activities, since it is a well-established methodology for this purpose (Cleary, 2010; Gentil et al., 2011; Nessi et al., 2012).

Environmental consequences have been assessed in terms of Global Warming Potential (GWP), according to the Intergovernmental Panel on Climate Change (IPCC) values for a 100-year time horizon (IPCC, 2014). The amount of carbon dioxide equivalent ($CO_2$-eq) imputable to each project of the selected categories (drinking water dispensers

**Table 1**
Impacts considered for each project category.

| Project category | Object of analysis | Avoided impacts | Impacts related to substitutive goods and additional MSW | Additional impact of usage stage |
|---|---|---|---|---|
| Drinking water dispensers in towns/cities and schools (Categories 1 and 2) | Products | PET bottles (primary packaging, secondary packaging, transport packaging) | Glass bottles, aluminium bottles and water dispensers | |
| | Environmental impacts | Transport, waste management of bottles, starting from the purchase, over one year. | Transport, waste management of reusable bottles, starting from the purchase, over one year. | Energy consumption of drinking water dispenser.<br>Energy, detergent, and water consumption to hand-wash reusable bottles, over one year. |
| | Economic impacts | Avoided cost for the waste management of disposable bottles, over one year. | Annual cost of substitutive goods (dispensers, glass bottles and aluminium bottles). Annual cost for additional waste management. | Cost for annual energy consumption of drinking water dispenser.<br>Annual cost paid by citizens for supplied water.<br>Annual cost for energy, detergent, and water consumption to wash reusable bottles. |
| | Social impacts | Included | – | Included |
| Replacement of disposable goods in school canteens (Category 3) | Products | Disposable plates/glasses | Multi-use plates/glasses and dishwashers | |
| | Environmental impacts | Waste management of plastic plates and glasses, starting from the purchasing, over one year. | Waste management of reusable plates/glasses, starting from the purchase, over one year. | Energy, detergent, and water consumption to wash reusable dishes/glasses (in the dishwasher). |
| | Economic impacts | Avoided cost for the waste management of disposable goods, over one year. | Annual cost of substitutive goods (dishwashers, multi-use plates and glasses). Annual cost for additional waste management. | Annual cost for energy, detergent, and water consumption to wash reusable dishes/glasses (in the dishwasher). Annual cost of labour. |
| | Social impacts | Included | – | Included |

in towns/cities and schools, replacement of disposable goods in school canteens) has been calculated, considering a time frame of one year.

In accordance with ISO 14040 standard (ISO 14040:2006), the LCA methodology and the impact assessment baseline performed by the Institute of Environmental Sciences of the Leiden University (CML) in version 3.05 have been applied.

Hence, for the impact assessment phase, primary data have been provided by ATERSIR, coming from the financing requests and the project descriptions elaborated by the Municipalities themselves; other information has been gathered by directly contacting the Municipalities, the water providers, the schools, or the waste collection providers involved in the projects.

To make the assumptions on the amount of waste which would have been generated without the WPM as plausible as possible, data about litres of water delivered have been gathered for the first two categories of projects, while for the last one the amount of waste prevented is foreseeable to a good approximation before the operational phase. As far as the projects of drinking water dispensers installed in the towns/cities and in schools are concerned, the Municipalities or the water providers and the schools have been asked for information about litres of water delivered by each dispenser, in a specified period. Analysing the projects of replacement of disposable goods in school canteens, the Municipalities have been asked for information about the number of meals in one school year, the number of plastic plates and glasses used in every meal and the weight of disposable products. Furthermore, the avoided impacts, due to the avoided WM and transport of single-use products have been modelled by using secondary data gathered from the Emilia-Romagna Region WM plan, as well as the WM of substitutive goods. Material composition and life expectation of reusable solutions have been assumed by the authors, in case information on that was not available in the project descriptions. The additional impacts related to energy consumption of drinking water dispenser, and energy, detergent, as well as water consumption to wash reusable have been modelled.

The source of data related to the impacts of transportation, energy, water, and detergent is the "Ecoinvent 3.5" database. Further details on the assumptions can be found in Section 3 of Appendix A.

The potential environmental impacts have been evaluated using the software SimaPro® 8.

Economic impacts have been assessed by applying Life-Cycle Cost (LCC) methodology. LCC can be considered as a useful complement to LCA: it exceeds the ordinary costs calculation of a process, summarizing all costs associated to each phase in the whole life-cycle (e.g., raw materials and energy supply, production, use and end-of-life). The costs must be related to money flows, i.e., investment costs, operating costs, and hidden costs (Kloepffer, 2008).

For all projects, ATERSIR have been asked for some information about investment costs sustained by the Municipalities and about funds allocated to each project. For the first two project categories, investment costs include the purchase and installation of water dispensers, and potentially cost for communication campaigns (up to 10% of the total cost). Moreover, investment cost of the second project category includes the costs for the purchase of reusable aluminium bottles, which are provided for free to the students, while for the first category of projects, the costs related to substitutive goods have been estimated, since they are covered by users and therefore not directly available. For the third project category, investment costs include the purchase of dishwashers and of reusable tableware.

In the first project category, information on the cost paid by users for water supplied by the dispensers were gathered, in order to include this cost item in the assessment.

Additional costs related to the WM of substitutive goods and to the usage phase (i.e., cost of energy consumption of water dispensers, cost of washing reusables covered by users) have been estimated. Avoided cost for SUPP purchase have also been considered.

Moreover, reducing the quantities of waste produced means that it should be possible to reduce the budget required for the collection, transportation, and treatment of waste products (Zorpas et al., 2017). Therefore, avoided cost for WM of SUPP has been calculated, considering the average cost in the Emilia-Romagna Region. Other externalities were not included in the LCC, to avoid the risk of double-counting. Further details on the assumptions can be found in Section 3 of Appendix A.

### 2.4. Third stage: social impact assessment methodology

The third stage of the framework aims at assessing the social impacts of WPMs. Given the availability of information, the social analysis has been carried out by category of project (water dispensers in towns/cities, water dispensers in schools and replacement of disposable products in school canteens) and not for each single project.

For the design of the social impact analysis, the "Product Social Assessment Methodology Report 2018" (Goedkoop et al., 2018) has been used as inspiration as it is in consonance with the SDGs, agreed upon by 193 Countries in 2015. The Product Social Impact Assessment method described in the manual includes four key parameters: i) stakeholder groups (small entrepreneurs, workers, users, and local communities); ii) social topics; iii) performance indicators; iv) reference scales to assess the impact. Social topics for users and related indicators are of interest to the authors because the stakeholder group considered in the study are the users, i.e., the citizens, who benefit from the use of the infrastructures installed thanks to these projects. All citizens are potential users of projects implemented within category 1, while projects within categories 2 and 3 target specific users, i.e., the students at the involved schools. Thus, the indirect effects on other stakeholders associated with the consumption reduced/induced by the different projects have not been analysed.

Hence, social sustainability has been evaluated based on the following social topics: health, safety, responsible communication, privacy, inclusiveness, effectiveness and comfort. One indicator per topic was evaluated, using reference scale with relative scores (from −2 to +2).

"Health" indicator is meant to assess the extent to which the project maintains or improves the health status of the users. "Safety" indicator considers the extent to which the project maintains or improves safety of the users. "Responsible communication" assesses the extent to which transparency enables users to make informed choices. The fourth indicator concerns the extent to which a project respects and protects users` privacy. "Inclusiveness" is defined as the extent to which the project affects affordability and accessibility of products or services to different groups of people (e.g., disabled persons, the elderly, persons with low income). Finally, "effectiveness and comfort" of projects aims to evaluate the extent to which the projects affect the efficiency and comfort of users.

### 2.5. Fourth stage: waste prevention observation, identification and selection of indicators

Waste prevention observation consists in setting up indicators describing and monitoring the resources allocated to the action or policy, the results of this action or policy, and to assess its efficiency regarding sustainable development (Bel, 2010).

In the fourth stage of the framework, impact-oriented and result-oriented indicators have been assessed with the aim to monitor both effectiveness and efficiency of the selected project categories in a life-cycle perspective. Facing the huge number of possible prevention measures that theoretically could be taken by the public sector, and, taking into account limited financial resources and also organizational capacities, indicators allow comparison of the effectiveness of different measures, and thus to select and prioritise (Wilts, 2012).

In collaboration with ATERSIR, some indicators to perform the analysis have been identified, starting from the results of the environmental, economic, and social assessment. The focus was not on the monitoring of every single project, but on the analysis of the project categories, in order to assign priority order for future allocation.

As far as the environmental aspect is concerned, some waste reduction indicators have been assessed, as well as some impact indicators, which stem from the LCA assessment. Waste reduction indicators always include the estimations of additional waste from substitutive goods. Besides indicators assessing the total avoided waste and total avoided $CO_2$-eq emissions, the indicators "per capita avoided waste" and "per capita avoided $CO_2$-eq emissions" have been calculated, by applying two different methodologies for the estimation of users. The first one considers the diffusion factor (DF), defined as the percentage of population/producers that effectively changes its consumption behaviour as a consequence of the prevention policy (JRC, 2011), while the second one considers all the potential users. The indicators calculated with the first methodology are part of the final set of indicators, as they are more representative of reality. Moreover, they are constant within each project category. Further details about the DF for each project category are provided in Section 3 of Appendix A.

As far as the economic aspect is concerned, the economic impact resulting from the LCC assessment has been parametrized to avoided waste and avoided $CO_2$-eq emissions. Moreover, a comparison between the funds allocated by ATERSIR and the economic impact has been performed, together with an analysis of the grant received by each project in function of the avoided waste. Nevertheless, the indicators referring to the grant have been excluded from the final set, to guarantee the objectivity of the analysis. As the decision on the fund's allocation is notified by ATERSIR to the Municipalities after the start of projects, it is assumed that the economic efficiency is not influenced by the grant amount. Moreover, the payback period of each investment has been calculated, considering all the additional and avoided costs for the society: this indicator has not been included in the final set, because the time required to recoup the funds expended is not considered relevant.

The indicators finally selected include five environmental indicators, three economic indicators and one social indicator. In particular, the environmental indicators encompass two waste reduction indicators: i) "Avoided waste" [kg/year] and ii) "Per capita avoided waste, considering DF" [kg/(user year)], and three LCA indicators: i) "Total avoided $CO_2$-eq emissions" [kg $CO_2$-eq/year], ii) "Per capita avoided $CO_2$-eq emissions, considering DF" [kg $CO_2$-eq/(user year)], and iii) "Avoided $CO_2$-eq emissions per avoided waste" [kg $CO_2$-eq/(kg year)]. They are complemented by three economic indicators: i) "Economic impact" [€], ii) "Economic impact per avoided waste" [€/(kg year)] and iii) "Economic impact per avoided $CO_2$-eq emissions" [€/kg $CO_2$-eq], and one social indicator, the sustainability assessment score resulting from the social impact assessment. While some indicators can only be calculated by experts or researchers (e.g., LCA indicators, economic impact per avoided $CO_2$-eq), the waste reduction indicators as well as the social indicator do not require the same experience. Hence, the local administrators might be always able to evaluate the majority of the indicators.

### 2.6. Fifth and sixth stages: normalization and definition of the priority order

After the calculation of the indicators, the results have been normalized. This normalization step is usually regarded as a sensible matter which requires careful judgement based on experience (Rigamonti et al., 2016; Wilson et al., 2015). Following Fernández-Braña et al. (2019), for the sake of simplicity, in this analysis it was decided to give the same weight to each indicator as a first assessment, leaving the question of a more accurate weighing procedure for future studies. The following mathematical formulae were applied to calculate the final score of each project category:

$$Normalised\ value_{ijp} = \frac{ind_{ijp}}{\sum_{j=1}^{3} ind_{ijp}}$$

$$Average\ of\ normalised\ value_{jp} = \frac{\sum_{i=1}^{n} Normalised\ value_{ijp}}{n}$$

$$Total\ score_{j} = \frac{\sum_{p=1}^{3} Average\ of\ normalised\ value_{jp}}{3}$$

where:

$j$ represents the project category (from 1 to 3, indicating installation of water dispensers in towns/cities, installation of water dispensers in schools, replacement of disposable goods in school canteens); p represents the sustainability pillar (from 1 to 3, indicating environment, economic and social aspects); $ind_{ijp}$ is an effectiveness and/or efficiency indicator i, for the project category j, referred to the sustainability aspect p.

As final result, a priority order for the analysed project categories is extrapolated.

## 3. Results and discussion

### 3.1. Results of the environmental, economic, and social impact assessment

Table 2 shows a comparison of the total impacts related to the drinking water dispensers in towns/cities, drinking water dispensers in schools and replacement of disposable goods in school canteens, considering environmental, economic, and social aspects. Section 4 of Appendix A shows the detailed results of LCA and LCC, for each project; additionally, it describes the reasons of the scores, for each social indicator and for each project category.

As far as environmental impacts are concerned, interestingly no significant differences can be found between the three categories: the avoided impacts associated with the use of disposable goods overcome the impacts related to the additional WM and the additional consumption of energy, water, and detergent, resulting in an overall negative environmental impact. Therefore, the additional energy consumption item has the highest environmental impact.

From an economic perspective, the investment cost is the highest cost item for the categories 1 and 2, while for category 3 the cost for washing reusables is the most significant one. Consequently, for categories 1 and 2 the economic impact is lower than the total cost of the projects, while for category 3 this does not happen. As far as avoided costs are concerned, for all the categories the avoided expense for SUPP purchase is the most relevant economic benefit.

The social impact assessment has resulted from evaluations made by the authors. In three out of six social topics, each project category gets the same score. The third project category has no impact on safety and on inclusiveness, while the first two categories have a positive impact on these topics, since they offer an essential goods, in a safe manner and at very low costs. Moreover, the effectiveness of the second and third project categories is increased by the fact that they are implemented in schools, given that education plays an important role in generating the awareness essential to effectively promote WPMs.

### 3.2. Effectiveness and efficiency indicators

As far as the environmental aspects are concerned, the waste reduction indicators (i.e., the average per project avoided waste and the average per capita avoided waste) for each project category are shown in Fig. 2. LCA indicators, i.e., the average values of both total environmental impact and per inhabitant impact in terms of avoided $CO_2$-eq emissions for each category, are shown in Fig. 3, together with the avoided $CO_2$-eq emissions per kg of avoided waste. This last indicator links the two classes of indicators. Section 5 of Appendix A shows the values of indicators for each single project.

On the base of waste reduction indicators, the first category (water dispensers in towns/cities) is the most effective one in terms of WP: the total annual amount of avoided waste is around six times bigger if

**Table 2**
Results of IA. Total impacts for each project category.

| | Drinking water dispensers in towns/cities | Drinking water dispensers in schools | Replacement of disposable goods in school canteens |
|---|---|---|---|
| Environmental items | Environmental impacts [kg $CO_2$-eq.] | | |
| Avoided waste management | −109.000 | −3.090 | −14.800 |
| Additional waste management | 429 | 189 | 139 |
| Additional energy consumption for washing reusables and for water dispensers | 39.500 | 266 | 3.890 |
| Additional water and detergent consumptions for washing reusables | 35.500 | 233 | 2.160 |
| **Total environmental impact** | **−33.571** | **−2.402** | **−8.611** |
| Cost items | Economic impacts [€] | | |
| Investment cost (covered by municipalities) | 357.655 | 37.931 | 57.259 |
| Cost paid by users (for water supplied by the dispensers) | 22.520 | – | – |
| Cost of energy consumption (water dispensers) | 1.088 | 21 | – |
| Cost of substitutive goods (covered by users) | 79.286 | (Included in investment cost) | (Included in investment cost) |
| Cost of washing reusables | 46.904 | 265 | 57.664 |
| Additional cost for WM of substitutive goods | 1.159 | 14 | 2,68 |
| Avoided cost for SUPP purchase | −428.316 | −11.139 | −11.381 |
| Avoided cost for SUPP WM | −22.747 | −572 | −1.070 |
| **Total economic impact** | **57.548** | **26.520** | **102.474** |
| Social topics and indicators | Score | | |
| Health | 1 | 1 | 1 |
| Safety | 1 | 1 | 0 |
| Responsible communication | 2 | 2 | 2 |
| Privacy | 0 | 0 | 0 |
| Inclusiveness | 2 | 1 | 0 |
| Effectiveness and comfort | 0 | 1 | 2 |
| **Total social impact** | **6** | **6** | **5** |

compared to the same indicator for categories 2 and 3. Nevertheless, per capita avoided waste is higher for category 3 (replacement of disposable goods in school canteens): this is due to the fact that in this case the diffusion factor is equal to 100%, as the application of this prevention measure does not depend on consumer choices. The same consideration is valid as far as per capita avoided $CO_2$-eq emissions are concerned. Hence, the category 3 has the least per capita environmental impacts, in terms of $CO_2$-eq emissions. The third category performs better than the others also in: i) the average value of total avoided $CO_2$-eq emissions, since it reaches a value slightly higher than the first category; ii) the amount of avoided $CO_2$-eq emissions per kg of avoided waste.

It should be considered that waste reduction indicators and LCA indicators do not result in the same ranking of project categories, both taking into account the total and the per capita indicators. Thus, it was decided to maintain a double focus by selecting indicators of both classes, in order to mirror the targets set by legislation.

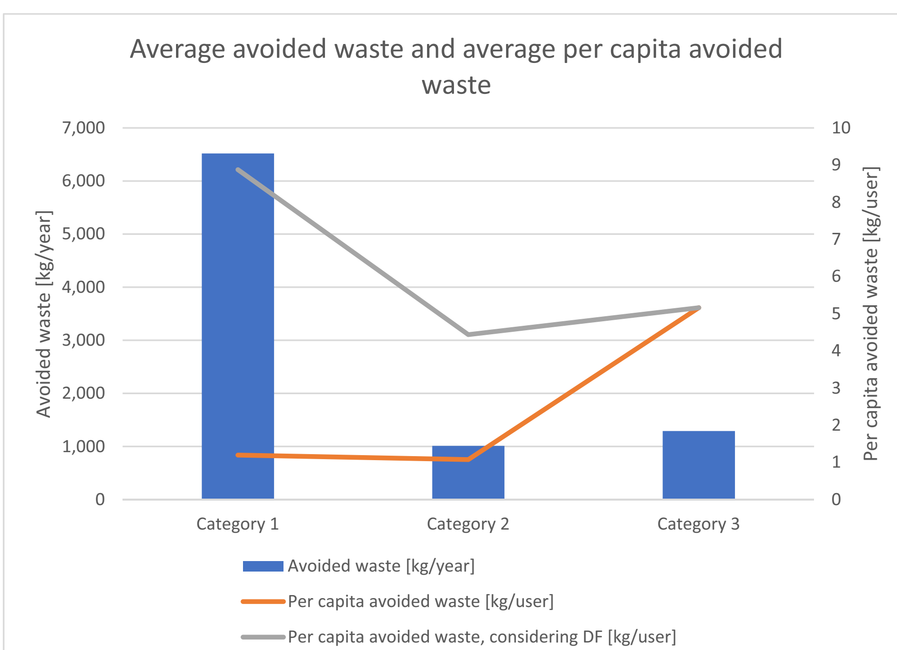


**Fig. 2.** Average values of environmental indicators in terms of avoided waste for each project category.

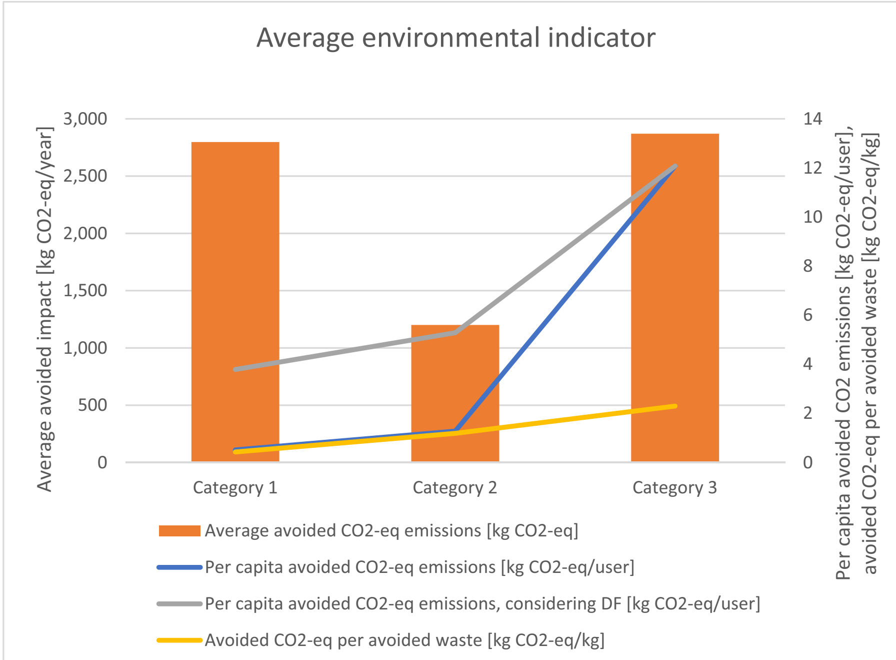


**Fig. 3.** Average values of environmental indicators (in terms of avoided $CO_2$-eq emissions) for each project category.

As far as the economic aspects are concerned, Fig. 4 shows the average indicators for each category, while Section 5 of Appendix A shows the values of indicators for each single project.

Overall, these results indicate that the third category of project reports in the first year an average economic impact which is much higher than the grant received by ATERSIR: the reason can be found in the high value of operating costs associated to dishwashing of reusable dishes/glasses. The opposite can be said of the first category: in this case, the cost item “Savings for citizens for not buying BW” has a big relevance: thus, the grant received by ATERSIR covers just a small portion of the economic impact in the first year.

The third category has the highest cost per kg of avoided waste, resulting in a value almost seven times bigger than category 1. The gap between categories decreases when the cost per avoided $CO_2$-eq emissions is assessed.

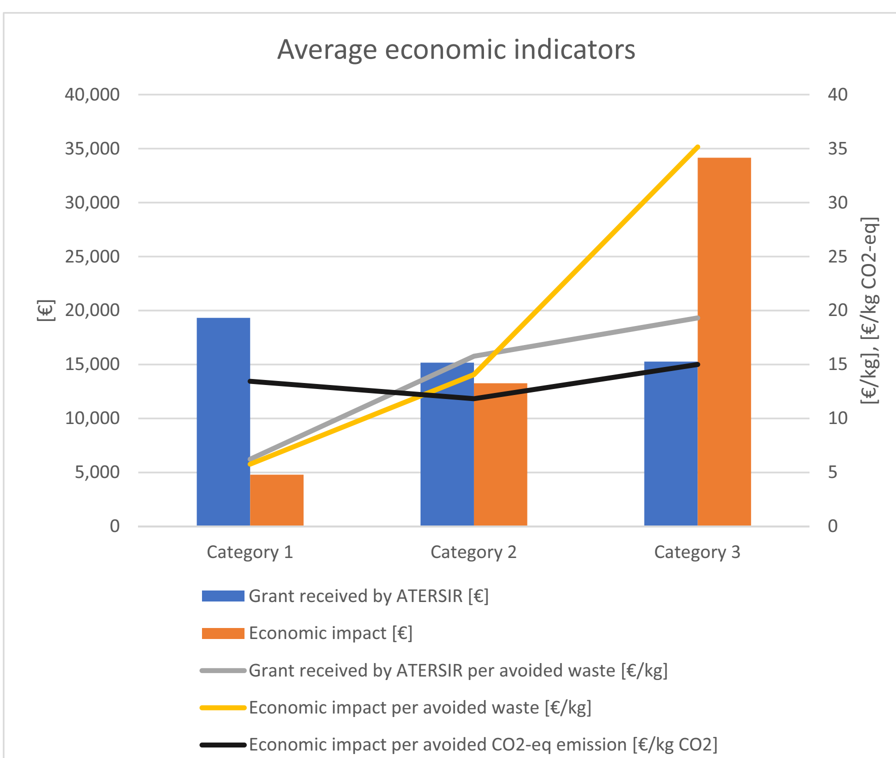


**Fig. 4.** Average values of economic indicators for each project category.

**Table 3**
Comparison of average values of the selected indicators, for each project category.

| Project category | Number of projects | Environmental analysis | | | | | Economic analysis | | | Social analysis |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Average "avoided waste" [kg/year] | Average "avoided $CO_2$-eq emissions" [kg $CO_2$-eq/year] | Average "Per capita avoided waste, considering DF" [kg/user] | Average "per capita avoided $CO_2$-eq considering DF" [kg $CO_2$-eq/user] | Average "avoided $CO_2$-eq per avoided waste" [kg $CO_2$-eq/kg] | Average "economic impact" [€] | Average "economic impact per avoided waste" [€/kg] | Average "economic impact per avoided $CO_2$-eq emissions" [€/kg $CO_2$-eq] | Sustainability assessment score |
| Water dispenser in towns/cities | 12 | 6.518 | −2.798 | 8877 | −3,79 | −0,429 | 4.796 | 5,77 | 13,45 | 6 |
| Water dispenser in schools | 2 | 1.011 | −1.201 | 4436 | −5,29 | −1189 | 13.260 | 14,07 | 11,83 | 6 |
| Replacement of disposable goods in school canteens | 3 | 1.290 | −2.870 | 5162 | −12,08 | −2300 | 34.158 | 35,15 | 15 | 5 |

Finally, the payback period was calculated (in Section 5 of Appendix A, the average values for each category is shown). It should be noticed that the first 2 categories of projects have a pay-back period, while the third category prove to be not profitable.

### 3.3. Selected indicators and comparison of project categories

The three types of projects (water dispensers in towns/cities, water dispensers in schools and reduction in consumption of disposable products) have been compared, for each aspect analysed (environmental, economic, and social), by assessing the average value of selected indicators. Hence, the results are shown in Table 3.

Each indicator was normalized (see Section 5 of Appendix A). Then, the average value for each aspect was calculated. Table 4 shows the results: the total score for each project category is calculated as the average of the scores in each sustainability pillar.

The total score is a result of the environmental, economic, and social contributions. The water dispenser project category whose total score is 0,4265 ranks first, resulting the best one, whereas the water dispenser in schools and the replacement of disposable goods in school canteens get an approximately equal total score.

### 3.4. Discussion and considerations

The application of the designed framework to the case study allowed the comparison of three different categories of project. The first two categories (i.e., water dispensers in towns/cities, water dispensers in schools) aim to promote sustainable consumption practices. With a strategy of de-commoditization, they both pursue at decreasing the influence of goods and products and, more generally, of the market institution in the way in which people satisfy their needs and desires (Boulanger and Mainguy, 2010). The third measure (i.e the replacement of disposable goods in school canteens) represents a procurement decision made by the public sector.

The criteria of selection guarantee the comparability of the different project categories and the reliability of the result.

**Table 4**
Final results.

| Project category | Environmental analysis | Economic analysis | Social analysis | Total score |
|---|---|---|---|---|
| Water dispenser in towns/cities | 0,383 | 0,544 | 0,353 | 0,4265 |
| Water dispenser in schools | 0,217 | 0,292 | 0,353 | 0,2872 |
| Replacement of disposable goods in school canteens | 0,400 | 0,164 | 0,294 | 0,2863 |

Starting from the results of the environmental, economic, and social assessment, the proposed algorithm for the prioritisation allows the decision-maker to objectively evaluate the project categories. The analysis is also strongly supported by the effectiveness and efficiency indicators, selected in collaboration with the public decision-maker.

As preliminary evaluation after one-year from the project start date, the total amount of avoided waste thanks to the implementation of the 17 analysed projects has been estimated as approximately equal to 88 tons: this accounts for the 0,03% of the total plastic waste production in the Region in 2018 (ARPAE, 2020). Even if this value seems low, it should not be neglected that only few projects, demanding limited economic resources, have been analysed: the investment cost for the implementation of these projects is equal to the 0,873% of the WM cost paid by the involved Municipalities in 2018. Thus, increasing the investments for WP might allow one to unlock the high potential of replicability of the selected projects.

Considering the impact assessment phase, the geographical boundaries of the system coincide to the regional ones: this implies that the analysis is limited to the purchase, the use and the WM of avoided single-use products and related substitutive goods. Furthermore, another limitation of the analysis is the fact that only projects in an initial stage of their life-cycle are considered. An evaluation of success in the long-term could benefit, as it is crucial that WP behaviour are sustained beyond cessation of the active campaign (Cox et al., 2010). Moreover, it should be considered that the unsuccessful projects were excluded from the analysis. Further research might investigate the reasons of their failure, to develop a learning process.

A careful analysis of the single projects can be the starting point to identify the success factors within each project category. For example, within the first project category, the smallest Municipality is the one that achieves the best performance in terms of per capita avoided impacts: a more detailed analysis of the specific characteristics of each Municipality should be performed to understand if the Municipality size has indeed influence on the success of this kind of projects.

Thus, future research might focus on an accurate assessment of the impacts of every single WP project, in a particular geographical context, with a lower number of assumptions. Furthermore, a sensitivity analysis might be performed. Economic analysis might also be enlarged, by considering the monetization of externalities. Moreover, the social assessment might be performed at project level, allowing a more detailed analysis of impacts (e.g., water quality can vary from a Municipality to another), on a larger number of stakeholders. The use of a life-cycle approach might allow designers to identify any critical points of a WPM, possible improvements, and the way a WPM can be best designed and implemented in a particular geographical context to achieve the expected benefits (Nessi et al., 2014; Magrini et al., 2020).

Monitoring prevention and re-use activities is crucial for policy and decision-makers.

To effectively allocate financial resources, the results of this study should be integrated with an analysis of waste generation patterns in the regional territory, in order to promote and implement WPMs where per capita waste generation and/or littering rate (if available, both limited to the waste stream tackled by the WPMs) are high. Moreover, the framework should be applied to projects which target other waste streams: the comparison of the results can provide policy and decision-makers with a more complete picture.

The Emilia-Romagna Region has not implemented a specific monitoring system for prevention activities yet. The annual monitoring of WM plan does not evaluate the success of waste prevention activities, but it only considers the quantity of waste generated. Indeed, the LCA study of regional WM plan considers WP only for the definition of the functional unit, as waste in input (Magrini and Bonoli, 2019). The monitoring system should oversee WPMs implemented in the territory, not only at consumption level, but also at other stages of the value chain, promoting synergies to pursue strategic waste prevention.

If the monitoring activity is complemented by an improvement of coordination and networking of individual projects, good practices could spread and learning effects regarding innovation approaches could realize (Wilts et al., 2013). Additionally, benchmarking between different spatial entities motivates local actors to invest more time, effort, and responsibility in the objectives (OECD, 2004; Wilts, 2012).

Furthermore, the analysis of the indicators assessing the average environmental impact (both in terms of amount of avoided waste and in terms of avoided $CO_2$-eq emissions) and the economic impact might be useful in planning activities, as in the definition of a waste prevention program or in making projection about waste composition in the future years.

On the one hand, the indicators can provide a benchmark value for ATERSIR, in the phase of screening of the funding requests, in order to validate the projections on waste reduction and the economic estimations made by Municipalities; on the other hand, they might be useful for Municipalities, for an ex-ante assessment of the environmental and economic benefits related to specific WPMs.

Moreover, social impact assessment helps in evaluating the achievement of long-term sustainability goals: education and knowledge are considered to be one of the most powerful, well-known, and proven drivers for sustainable development and behavioural change must be done starting from young ages to move the agenda forward on prevention (Zorpas et al., 2016).

To effectively promote WP, its potential integration with other policy areas should be considered. Thus, institutional mechanisms can help in linking efforts to promote sustainability in various issue areas, thus representing one crucial element of an integrated approach to sustainable development (Spangenberg et al., 2002).

Hence, policies must have a systemic perspective, including considerations on life-cycle perspective, production systems and raw material in use, consumer behaviour, direct and indirect environmental impacts as well as economic and social ones, trade-offs between environmental, economic, and social sustainability. In this sense, the use of indicators can facilitate cooperation across traditional institutional structures.

The analysis indicated that till now few Municipalities of the region have presented fund requests for the implementation of WPMs: an improved institutional framework might help the Municipalities in overcoming barriers to the identification and implementation of WPMs.

Financial incentives offered by the region can cover the investment costs for the implementation of WPMs. Nevertheless, in some cases, the need for additional longer-term incentives arises, in view of the high operating costs (e.g., category 3).

As far as the participation of citizens is concerned, it should be noticed that the first category of project has an average DF equal to 13%, while the second category scores 24%. Certainly, there can be several different drivers to determine the social approval of a WP action. In promoting the participation of citizens, it should be considered that citizens all over the world, regardless of what category their countries are (low or high incomes), need motivation (mainly less taxes or to receive extra money somehow) to react to anything and specially to participate in environmental performances actions (Zorpas et al., 2017). As example, in case of project category 1, the price for water supply paid by users can influence the success of these projects.

Moreover, as barriers to engaging householders include both modern consumer culture and a genuine confusion that WP is equivalent to recycling (Cox et al., 2010), communication campaigns are fundamental.

## 4. Conclusions

In this research study, waste prevention is investigated within the framework of sustainability, in accordance with the SDG 12 of UN Agenda 2030, by focusing on WPMs promoting sustainable consumption.

In compliance with the definition of strategic waste prevention, a framework for the assessment of WPMs implemented by Municipalities is proposed, to evaluate their success and support the financing choices of public decision-makers. The designed framework evaluates impacts, effectiveness, and efficiency of some selected WPMs. The framework designed by authors was tested on three categories of projects: as case study, the impacts of 17 projects already ongoing in the Emilia-Romagna Region were assessed. As outcome, a priority order for future allocation of financial resources can be defined. Moreover, the contribution of WPMs to the achievement of waste prevention targets and sustainable development is quantified.

In the present study environmental considerations are complemented by an evaluation of economic and social impacts. LCA and LCC methodologies have been applied, limiting the explored system to the phases of consumption and WM.

This study has the ambition to give a contribution in waste prevention field. Literature highlighted the need of developing reliable methods to monitor, measure and evaluate benefits of waste prevention, as means to overcome potential barriers to the spread and to the success of WPMs. Moreover, monitoring the effects of waste prevention is a mean to integrate the evaluation into environmental policy strategies, thereby mainstreaming sustainability into policymaking.

As above discussed, the study confirms that institutional mechanisms, such as action and economic leverage, are fundamental for channelling the behaviour of individuals and the actions implemented by Municipalities towards WP, contributing to the evolution of societies towards sustainable development.

## CRediT authorship contribution statement

**Chiara Magrini:** Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Anna Degli Esposti:** Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Elena De Marco:** Conceptualization, Validation, Investigation, Writing – original draft. **Alessandra Bonoli:** Conceptualization, Validation, Writing – review & editing, Supervision.

## 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.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.145773.

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## 4.3. Paper 3. Municipal solid waste collection systems: An indicator to assess the reusability of products (Degli Esposti et al., 2021)

**Brief introduction**

The aim of this research study is to define a comprehensive indicator to evaluate the social, economic and environmental sustainability of Preparation for Reuse, coupled with potential for reuse at product category level. This paper aims to contribute to research on reuse and Preparation for Reuse by assuming the perspective of waste collection operators. Consequently, the role of the waste collection operators in facilitating reuse is often neglected, despite being the collection mode and storage method two drivers of reuse.

**Study findings**

The main contribution of this paper is in proposing a framework of assessing a model for selecting and prioritizing performance indicators to evaluate the reusability of products. Indicators to evaluate the reusability of product categories do not exist yet. A reusability indicator is proposed, which includes one coefficient (i.e. the reusability coefficient) and three indicators: the first one (i.e. the Social Indicator) for the assessment of social performances, the second one (i.e. Environmental Indicator) for the assessment of environmental performances and the third one (i.e. Economic Indicator) for the assessment of economic performances. The reusability indicator allows waste collection operators to evaluate the potential impacts of the reuse strategy on their Municipal Solid Waste collection system for each product category. Moreover, the designed framework allows them to monitor and disclose to the public the impacts related to reuse activities, thus promoting a change of perception of the waste itself. Preparation for Reuse can have benefits not only for waste collectors but also for local authorities and managers.

**Conclusion**

I. No general indicator for the assessment of preparation for reuse does exist yet;

II. Environmental, economic, and social sustainability in a life cycle perspective are used for the evaluation of the implications on preparation for reuse;

III. The reusability indicator can have benefits not only for waste collectors but also for local authorities and managers.

**Table 4.3**. Overview of the third manuscript (Degli Esposti et al., 2021).

| | |
|---|---|
| Title | Municipal solid waste collection systems: An indicator to assess the reusability of products |
| Status | Published |
| Keywords | Municipal solid waste, reuse, reusability, life cycle assessment, life cycle cost, waste collection |
| Journal | Waste management and research, 39, 1200 – 1209 |
| Abstract | The paper illustrates a model to support waste management (WM) operators of municipal solid waste (MSW) services. This study proposes a framework to evaluate the potential of preparation for reuse (PfR) as a strategy to jointly decrease social, environmental and economic impacts and meet the legal targets on waste management. As general indicators to evaluate the reusability of products do not exist yet, the aim of this study is the definition of a comprehensive indicator, which may be calculated for each product category by waste collection operators. The proposed reusability indicator includes one coefficient evaluating the potential for reuse, and three impact indicators for the assessment of social, environmental and economic performances. The indicator can be calculated by using real data, gathered by the waste collection operators in collaboration with reuse centers and referred to previous years. Hence, the proposed methodology allows waste collection operators to evaluate the potential consequences of the reuse strategy on their MSW collection system to monitor and disclose to public the impacts related to reuse activities, facilitating the achievement of sustainability in the WM sector. |
| Annex | 3 |

*Original Article*

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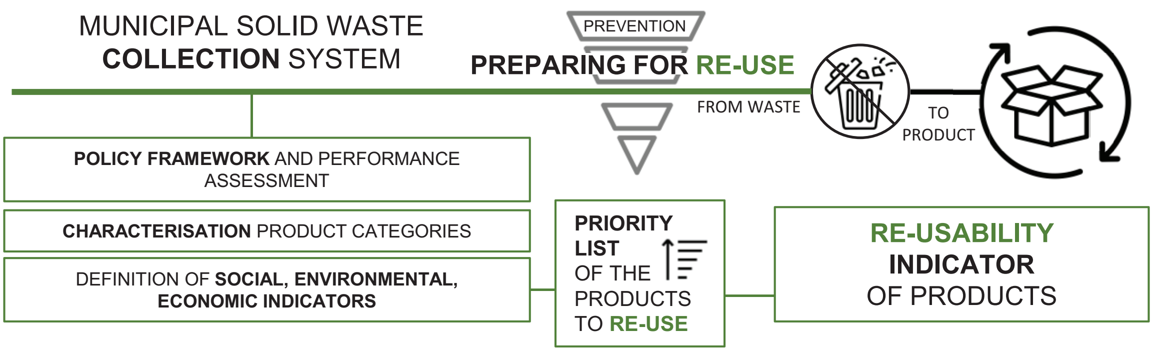
# Municipal solid waste collection systems: An indicator to assess the reusability of products

**Anna Degli Esposti, Chiara Magrini and Alessandra Bonoli**


## Abstract

The paper illustrates a model to support waste management (WM) operators of municipal solid waste (MSW) services. This study proposes a framework to evaluate the potential of preparation for reuse (PfR) as strategy to jointly decrease social, environmental and economic impacts and meet the legal targets on waste management. As general indicators to evaluate the reusability of products do not exist yet, the aim of this study is the definition of a comprehensive indicator, which may be calculated for each product category by waste collection operators. The proposed reusability indicator includes one coefficient evaluating the potential for reuse, and three impact indicators for the assessment of social, environmental and economic performances. The indicator can be calculated by using real data, gathered by the waste collection operators in collaboration with reuse centres and referred to previous years. Hence, the proposed methodology allows waste collection operators to evaluate the potential consequences of the reuse strategy on their MSW collection system to monitor and disclose to public the impacts related to reuse activities, facilitating the achievement of sustainability in the WM sector.


## Graphical abstract




**Keywords**

Municipal solid waste, reuse, reusability, life cycle assessment, life cycle cost, waste collection

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## Introduction

Municipal solid waste (MSW) management includes the collection, transfer, resource recovery, recycling and treatment of waste. As a public service, MSW collection is the first step of waste management (WM), and it is one of the key levers for city authorities to achieve the targets on waste set by the legislation. The main target of MSW collection is to protect the population health, promote environmental quality, provide support to economic productivity and develop sustainability. In this context, WM is a complex and multifaceted problem, involving environmental, social, economic, political and local issues, and its sustainability assessment cannot be fully addressed without the quantification of at least environmental, economic and social consequences (Di Maria et al., 2020;

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Morrissey and Browne, 2004; Rodrigues et al., 2018; Singh et al., 2012). The public administration agenda considers sustainability as a key success factor, and new technologies are enabling the development and the provision of sustainable public services (Deslatte et al., 2017; Gnan et al., 2013; Homsy and Warner, 2015; Rodrigues et al., 2018).

Since an integrated WM is defined by United Nations Environmental Programme (UNEP, 1996) as a framework of reference for designing and implementing new waste management systems (WMSs) and for analysing and optimising existing systems', the optimal integrated WM reduces waste production, social and environmental problems associated with waste and increases energy production and useful materials (Yousefloo and Babazadeh, 2020). According to Cobo et al. (2018), if an integrated waste management system (IWMS) is to be studied from the perspective of a circular economy (CE) and waste prevention, the actual definition of IWMS is incomplete. Thus, the authors proposed the expansion of the typical IWMS boundaries to include the upstream subsystems that reflect the transformation of resources and its interconnections with the WM subsystems.

For waste managers, CE perspective on value implies a shift from a focus on cost-effectiveness in waste collection and management to a focus on creating value from waste (Stahel, 2016). Indeed, the WMS can contribute to create value from discarded product and according to the definition of Cobo et al. (2018), the sustainable and circular IWMS can contribute to achieve the maximum economic profit and benefits for society at the expense of the minimum environmental impacts and consumption of natural resources.

From a CE perspective, reuse directly contributes to waste prevention and reduces the demand for waste treatment and disposal, while indirectly reducing the demand for new items. Within the framework of CE, much attention is devoted to manufacturing-centred reuse systems (e.g. take-back systems) and related enabling business models (e.g. product service system), while neglecting that the material collection system in place is WM (Gusmerotti et al., 2019). On the other hand, according to a recent review performed by Campitelli and Schebek (2020), who reviewed 366 articles, which assessed the WMS of cities or countries focusing on MSW, only 25 analysed waste collection and transport together with prevention and reuse; only four out of these 25 applied life cycle approaches. None of these investigates reuse centres' systems nor mentions preparation for reuse (PfR) as strategy to select products that are likely to be reused and that may be prevented from being waste through recovery operations.

Despite the importance of PfR in terms of contribution to waste prevention goals and the wide range of potential addressed products, this stage is not frequently discussed in literature and most of the case studies focus on PfR of electric and electronic equipment (Boldoczki et al., 2020; Bovea et al., 2016, 2018; Coughlan and Fitzpatrick, 2020; Johnson et al., 2020; Pini et al., 2019; Zacho et al., 2018a), whereas other studies analyse textile waste (Muthu, 2015). However, PfR is of interest for such municipal waste fractions as clothing and textiles, furniture, bicycles, paint, mattresses, toys, books, etc. whose end-of-waste criteria can be achieved through sorting, checking and testing, transporting, cleaning or repairing, storing, moving and pricing operations, which in turn should be justified by actual reuse (Gusmerotti et al., 2019). Moreover, despite the existence of many waste-related metrics, most of them capture the extent to which waste is generated and the fraction of waste that is already used as a resource, while not directly indicating limitations or possibilities for the use of waste as a resource (Van Ewijk and Stegemann, 2020). The waste and material statistics, currently collected to support waste policy implementation, are volume based rather than value based (Hollins et al., 2017).

In this context, this research main thesis is that PfR is contingent to public services sustainability, and its development is pivotal for waste collection systems, since it is a strategy to retain the value, in compliance with CE principles. Thus, the aim of this study is to support urban waste operators in boosting sustainable WMSs, as strategy to jointly decrease environmental, economic and social negative impacts and meet the legal targets on WM. This study provides a discussion on the role of PfR, within the background of European regulations and waste hierarchy, and an indicator to assess the potential for reuse and the reusability of products is developed, assuming the perspective of waste collection operators. The challenge is to define a comprehensive indicator that can be calculated by the waste operators in charge of waste collection service based on some metrics extracted from literature review and waste collection experts involved in.

Literature provides the conceptual framework where PfR or reusability could be identified, as well as aspects and metrics involved in managing waste collection systems. The idea to measure the potential of reuse and reusability of products is not new in the literature: the definition of potential for reuse or reusability has been debated in literature, and some tools to assess them have been proposed.

According to StEP (2009), five dimensions can be distinguished in the definition and assessment of potential for reuse: (i) technologic, (ii) economic, (iii) ecologic, (iv) social and cultural and (v) legal aspects.

From a mathematical perspective, the reusability of a product can be defined as a probability that a product and/or component having been used for a time period $t$ ends its life in the following unit time (i.e. in the interval between $t$ and $t + 1$), but the product and/or component is reusable (Murayama et al., 2004). This definition considers only the functionalities of the product and/or component. According to Kissling et al. (2012), reusability (or potential for reuse) can be defined as the ecologic, economic and social advantageousness of reuse compared to direct product recycling and disposal. This definition recognises the fact that reuse does not always constitute the optimal solution at a product's end of life (EoL) as the product type, the product condition, the energy efficiency of comparable new substitute products and other contextual factors impact the reuse potential.

Bovea et al. (2016) defined a general methodology for assessing and estimating the potential reuse of small waste electrical and electronic equipment, focusing on devices classified as domestic appliances; the methodology can be used by reuse enterprise as protocol, since it includes specific tests for visual inspection, function and safety for 10 different types of household appliances; therefore, only technical aspects are considered. A tool to help industries in the evaluation of the potential reusability of a product was proposed by Anityasari et al. (2005); the model incorporates quality or technical aspect of products after the first lifetime and economic aspect of reuse strategy, including the environmental cost.

Theoretically, according to Lu et al. (2014) the reusability of products and components is basically determined by the physical situation as an internal factor, and the technology development as the external factor, whereas in practice, it is always the economic cost that mainly affects the products reusability. Nevertheless, the authors claim that, from the point of sustainability view, reusability of products and components should also be evaluated based on environmental and social factors. Therefore, they evaluated reusability via the environmental, economic and social advantageousness of reuse compared to other EoL strategies, including materials recovery and disposal, by applying Life Cycle Sustainability Assessment (LCSA) to help waste recycling practitioners measure reusability of typical electrical and electronic products and components. Thus, the system boundary considered by the authors includes the collection, disassembly, shredding, sorting, materials recovery, components reuse and final disposal stages.

Van Ewijk and Stegemann (2020) proposed to introduce a legal requirement to recognise the potential of waste to be used: the waste use potential complement the legal definition of waste, reinforces and goes beyond the waste hierarchy by providing material-specific and context-specific information and by directly challenging the discarding of materials that could be used instead.

As far as assessment tools are concerned, Park and Chertow (2014) designed a quantitative tool, 'reuse potential indicator', to be calculated at waste material level. The aim is to aid management decision-making about waste based not on perception but more objectively on the technical ability of the materials to be reused in commerce. The tool adopts a resource-based paradigm, based on the view that what we formerly perceived as wastes should instead considered to be potential resources until determined otherwise. Nevertheless, as already claimed by Van Ewijk and Stegemann (2020), Park and Chertow (2014) used the term 'reuse' in a way which is not consistent with the European legislation since their analysis focuses on the USA.

A system to assist managers in determining WM options for all types of wastes from one or more industrial plants is proposed by Boyle and Baetz (1998). The system is developed to determine the potentials for reuse and recycling, and all possible treatment for the selected waste as well as the data on the secondary masses from treatments are determined.

Unarguably, from the literature review, there are no indicators similar to the one that the authors propose below. None of these investigates MSW management activities considering the inherent particularities of the context where the activities themselves are developed. The proposed indicator evaluates the potential for reuse considering not only the economic, environmental and social dimensions of sustainability but also the point of view of the potential 'user' to be considered as possible post-consumer waste user. In this context, considering the thesis that animates this study on PfR, this paper intends to provide waste collection operators an instrument for establishing measurement metrics to assess sustainable performance of their MSW strategies. As reuse does not always constitute the optimal solution at a product's EoL as the product type, the proposed 'reusability indicator' will allow waste collection operators to compare different reusable products in an objective way and to monitor the performance of the collection system over the years, with the aim to select products that are likely to be reused and that may be either prevented from being waste by preparing them for reuse, through recovery operations.

For this purpose, in the section 'Materials and method', the authors introduce the reusability indicator and define the specific indicators that constitute it, based on European current regulation and literature review on preparing for reuse, and the metrics extracted from literature, and experts' considerations. The section 'Results and discussion' discusses the definition of the reusability indicator, and in the section 'Conclusion', the authors report the conclusions of the study.

## Materials and method

### *Current regulation and literature discussion on preparing for reuse*

According with European and national regulations, solid waste can be classified in: (i) MSW and (ii) industrial waste (IW) resulting from the production of goods and products. The classification of waste is based on the European List of Waste (LoW) and on the Annex III to Directive 2008/98/EC (European Union (EU), 2008). The harmonised LoW established by the European Commission Decision (European Commission (EC), 2000) is regularly revised based on new knowledge (EU, 2014). As at European level MSW and IW are identified with an appropriate and hierarchical waste codes, the different types of waste in the harmonised list are fully defined by six-digit code and the respective two-digit and four-digit chapter headings. Moreover, the LoW provides a common Europe terminology for waste classification to an easier WM, including the activity of waste collection.

Over the past few decades, the European Commission has encouraged Member States to separately collect at least paper, metal, plastic and glass waste, and, by 1 January 2025, textiles waste. Similarly, to move towards a European recycling society, ambitious targets have been set for the amount of waste to be prepared for reuse and/or recycled (50%, 55%, 60% and 65% by

2020, 2025, 2030 and 2035, respectively). Consequently, the Directive 2018/850/EU (EU, 2018a) introduced the rate of 10% as maximum amount of urban waste landfilled by 2035. Moreover, the European waste hierarchy lists the actions and goals in WM in order of hierarchical importance: prevention, reuse or PfR, recycling, recovery of energy and recovery of material, disposal.

According with the EU-common definition of waste, once the holder of an item discards it or intends to discard it, the product passes the waste threshold and turns into waste. According to the European waste hierarchy, beyond the waste threshold, PfR is the preferred WM option. Preparing for reuse is defined as 'checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be reused without any other pre-processing' (EU, 2008). Thus, materials that are likely to be reused may be either prevented from being waste by preparing them for reuse, through recovery operations. According to the Commission Decision 2011/753/EU (EU, 2011), four methods for the calculation of the share of MSW, which is prepared for reuse, recycled or has undergone other material recovery are listed: (i) the PfR and the recycling of paper, metal, plastic and glass household waste; (ii) the PfR and the recycling of paper, metal, plastic, glass household waste and other single types of household waste or of similar waste from other origins; (iii) the PfR and the recycling of household waste and (iv) the PfR and the recycling of MSW. Consequently, the achievement of the target on preparing for recycling and reuse depends on the calculation method applied. Even if the Directive 851/2018/EU (EU, 2018b) defines a new measurement methodology for preparing for reuse, separate to that for preparing for recycling, a binding target at European level is not set yet. Moreover, the monitoring framework on the CE set-up by the European Commission includes the assessment of recycling rate, while neglecting reuse and PfR.

Some authors addressed challenges that currently hinder the PfR and restrict the access to sufficient volumes of reusable goods. The unpredictability in supply and demand, the lack of global reuse standards and improper communication and information to consumers, which still see used product as low-quality products, are some of the raised issues (EC, 2015). Moreover, lack of qualification of employees at recovery centres, the considerable time demand, as well as an insufficient infrastructure are all barriers for PfR (EC, 2015; Messmann et al., 2019). Improvements in legislation are needed to effectively enable and promote these activities (Messmann et al., 2019).

Many authors agree on the importance of the role of mode of collection as driver for PfR. The waste arriving at collection points has the highest potential for the PfR compared to wastes collected by the pick-up system or public containers: this was observed in Germany (Messmann et al., 2019), Denmark (Parajuly and Wenzel, 2017) and England (Curran et al., 2007; WRAP, 2012). The storage method is also recognised as critical to the potential end use of an item (RX3, 2013). Moreover, the role of waste handlers-local authorities is pivotal to implement the logistical, and in some cases financial, solutions that are required to increase recovery and subsequent reuse (Curran et al., 2007). In many countries like Italy, reuse centres' operators are in charge of receiving, preparing for reuse and distributing goods, thus extending product lifetime and promoting a CE vision. Moreover, a recent study performed in Italy (Rigamonti et al., 2020) estimated that preparing for reuse and/or recycling bulky items separately collected and disposed at 16 Italian collection points would increase of 3 percentage points the 'rate of preparing for reuse and recycling' EU-common indicator. Furthermore, these centres are often managed by social enterprises or third-sector organisations with a strong embeddedness in local communities (e.g. social cooperatives or charities), and whose primary goals are to reduce local and global environmental impacts of consumerist approaches to WM and to integrate disadvantaged people into society via the labour market (Kissling et al., 2012; Pansera and Rizzi, 2020; Rizzi et al., 2020). Thus, they are a powerful vehicle to promote qualitative growth, help develop human capital and strengthen social cohesion. Some social and economic benefits derive, which range from providing employment and training opportunities for people with disabilities or the long-term unemployed to providing access to good equipment for people on low incomes in both the developed and the developing world (Gusmerotti et al., 2019; Kissling et al., 2012).

As shown by literature, there is significant potential for increasing reuse operations in collection and recycling centres, but to be economically profitable it is important to identify the most suitable material fractions (or product groups) and engage in strategic partnerships that will allow more effective organisation of reuse processes (Milios and Dalhammar, 2020).

## Assessment model development

Literature provides the conceptual framework where PfR or reusability can be identified, as well as aspects and metrics involved in managing waste collection systems. A critical analysis of the literature allowed the authors to identify the potentials and the limitations of the existent models.

The concerns and the objectives inherent to the research main thesis are structured in Table 1, which shows the categorisation of the metrics, according to their origin and representativeness in the local context. The metrics of the literature review are incorporated with some other relevant metrics suggested by experts who have analysed the concerns of the studied problem and the context. Thus, the collaboration with them is pivotal in all the stages of the framework. Following Zacho et al. (2018b) and Milios and Dalhammar (2020), the analysis of reuse potential was carried out at product level, since that allows better understanding of where and when reuse is feasible.

Based on the investigated metrics, a model to assess the performance of waste collection system is suggested, with the aim to select products that are more likely to be prepared for reuse. The steps of the designed framework are depicted in Figure 1.

**Table 1.** Metrics: Categorisation of metrics extracted from literature and experts involved in local waste collection service.

| Category and objective/source of metrics | Literature | Experts |
|---|---|---|
| Technologic aspect | | |
| Assure quality and technical aspects of products and/or components (e.g. functionality, safety) | | |
| Visual inspection | x | x |
| Importance of collection system (e.g. reuse potential increases in collection and recycling centres) | x | x |
| Importance of storage method of waste | x | |
| Economic aspect | | |
| Create value from waste and achieve the maximum economic profit | | |
| Economic cost related to products reusability (e.g. physical situation, technology development) and potential incomes from the reuse activities | x | x |
| Strategic partnerships to effectively organise reuse processes | x | x |
| Environmental cost | x | |
| Social and legal aspects | | |
| Achieve the maximum benefits for society | | |
| Reuse system networks | x | x |
| Distance to meet the legal targets on waste management | x | x |
| Social advantageousness of reuse (e.g. social cohesion) | x | x |
| Employment and training opportunities | x | x |
| Regulation and procedures to test products intended to be reused | | x |
| Ecologic and environmental aspects | | |
| Reduce waste production and environmental impacts related to consumption of natural resources | | |
| Ecologic and environmental advantageousness of reuse | x | |

Source: Elaborated by the authors.

Firstly, the policy framework on MSW prevention, collection and treatment is analysed at different institutional levels (i.e. European, national and regional level), with focus on quantitative legal targets in the different stages of waste cycle. An example of table to be used for this assessment is showed in Supplemental Appendix (see Table S1).

Then, for the local area object of analysis, the current performances in terms of separate collection rate (SC), rate of waste prepared to reuse and/or recycle (PRR) and rate of landfilled waste (LF) are assessed. Eventually, the actual gaps to be close to meet the legal quantitative targets are calculated, for the analysed local area. Following Di Maria et al. (2020), these gaps can provide a measure of social sustainability of the waste operator, considering governments as stakeholders.

Thus, considering the absolute value of the distance from the target and the number of months within which the target must be reach, the following variables are calculated according with equations (1), (2) and (3):

$$gap\,SC = distance\ to\ SC\ target\left[\%\right] / \ months \tag{1}$$

$$gap\,SRR = distance\ to\ SRR\ target\left[\%\right] / \ months \tag{2}$$

$$gap\,LF = distance\ to\ LF\ target\left[\%\right] / \ months \tag{3}$$

Secondly, the product categories, which can be prepared to reuse centres, are listed, and their weight and composition are estimated.

Every product category is then related to the European codes it generates when it becomes waste. To link products to the waste flows and to estimate weights and compositions, a sample analysis offers information about the composition of products and might be performed by the waste collection operator at collection points; this might also help in estimating the total amount of collected waste per year, for each product category. This can be a critical step, as the waste operator usually monitors waste flows, while not collecting data by product category. For all these reasons, data availability can be a criterion for the selection of relevant product categories. The product-specific analysis considers all influencing factors to determine whether reuse is advantageous to recovery alternatives.

Then, the reusability indicator of each product category is calculated as explained in the following paragraphs.

## The reusability indicator

The proposed reusability indicator aims to assess the possibilities as well as the limitations for the PfR of each product category. The indicator considers three aspects: (i) the reusability coefficient of each product category, (ii) the distance from targets set by the legislation (e.g. rate of separate collection, preparing for reuse and recycling target, rate of landfilled waste) and the potential contribution to their achievement provided by each product category, (iii) the environmental as well as economic impacts of the collection and treatment of product categories, assessed by life cycle assessment (LCA)-based and life cycle costing

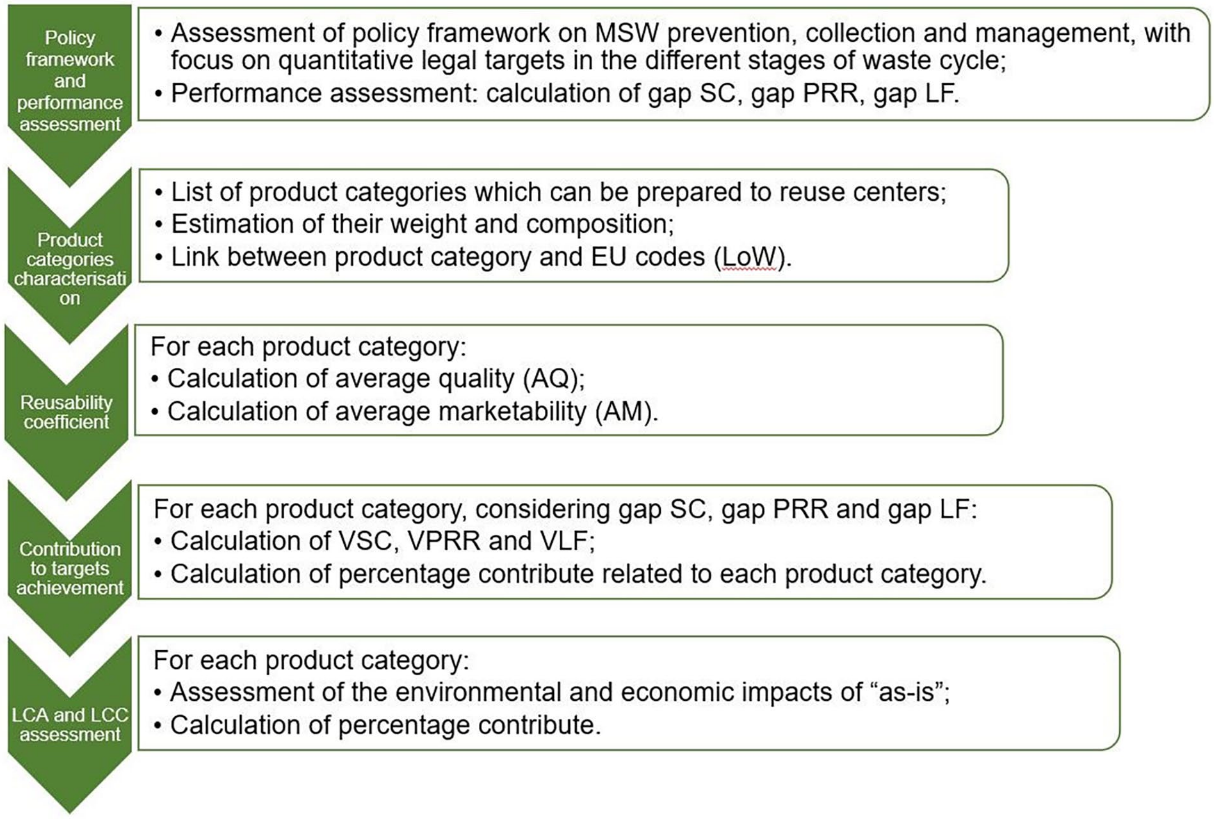


**Figure 1.** Methodology: Graphical representation of the steps of the proposed framework.

(LCC)-based indicators. Unarguably, in recent years life cycle thinking (LCT) has taken a more prominent role in environmental and sustainable decision-making, becoming essential for public services management. In this context, LCA is increasingly used in WM sector, since it provides useful support to decision- and policy-makers to identify strategies that prevent or minimise negative impacts on ecosystems, human health or natural resources (Laurent et al., 2014). For this purpose, LCA and LCC methodologies can be combined to analyse the environmental and the economic drivers in several MSW management alternatives. Thus, the reusability indicator evaluates environmental and economic sustainability of the choice to prepare a product for reuse, by calculating the avoided impacts.

*Reusability coefficient.* The reusability coefficient ($RC_i$) includes two different contributions. Using data collected by the waste operator, the average quality ($AQ_i$) of each product category is calculated as the percentage of products collected by the waste collection operator which meet the requirements to be prepared to reuse. The average marketability ($AM_i$) estimates how much a product category is easy to sell, being calculated as the percentage of sold products out of the quantity of products prepared to reuse. The final coefficient conceptually represents the reusability potential of each product category in term of quality and market demand. Equation (4) shows the formula to calculate $RC_i$ [%]:

$$RC_i[\%] = (AQ_i + AM_i)/2 \tag{4}$$

where the subscript $i = 1, \ldots n$ represents the considered product category.

*Social indicator.* The potential contribution of each product category to the achievement of quantitative legal targets is defined as the ratio between the potential variation of the analysed target and the distance from the target set by the legislation, by calculating the following variables:

$$VSC_i = potential\ variation\ of\ SC\ rate\ due\ to\ i[\%] / gap\ SC, if\ gap\ SC > 0 \tag{5}$$

$$VPRR_i = potential\ variation\ of\ PRR\ rate\ due\ to\ i[\%] / gap\ PRR, if\ gap\ PRR > 0 \tag{6}$$

$$VLF_i = potential\ variation\ of\ VLF\ rate\ due\ to\ i[\%] / gap\ VLF, if\ gap\ VLF > 0 \tag{7}$$

where the subscript $i = 1, \ldots n$ represents the considered product category; $VSC_i$ is the variation of product category $i$ rate related to the achievement of SC targets; $VPRR_i$ is the variation of product category $i$ rate related to the achievement of waste PRR targets and $VLF_i$ is the variation of product category $i$ rate related to the achievement of LF targets.

The potential variations of both SC and PRR rates are calculated on the total amount of waste generated by the product category over the analysed year.

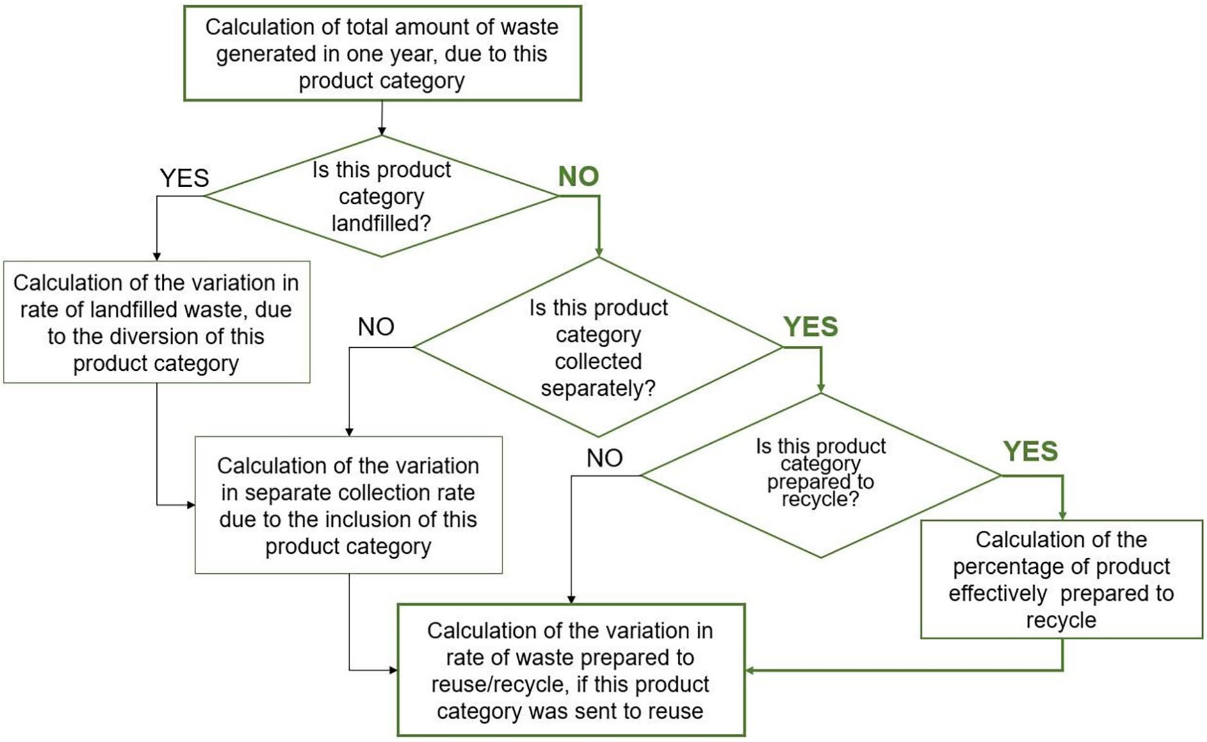


**Figure 2.** Logical flow of thoughts. Step-by-step process to evaluate the variation of LF (VLF), variation of SC (VSC) and variation of PRR (VPRR) for each product category.

As local government and waste operators should be guided in planning their daily activities, the authors suggest a method to guide them.

The flow of thoughts to be followed for each product category is graphically showed in Figure 2.

The percentage contribution of each product is then calculated:

$$VSC_i[\%]=(VSC_i)/(\sum_{i=1}^{n} VSC_i) \quad (8)$$

$$VPRR_i[\%]=(VPRR_i)/(\sum_{i=1}^{n} VPRR_i) \quad (9)$$

$$VLF_i[\%]=(VLF_i)/(\sum_{i=1}^{n} VLF_i) \quad (10)$$

Finally, the contribution to targets achievement ($I_{Si}$) is defined as follow, and it is calculated according to equation (11):

$$I_{Si} = VLSC_i[\%]+VSRR_i[\%]+VLF_i[\%] \quad (11)$$

*Environmental and economic indicators.* LCA and LCC are applied to assess the environmental and economic impacts of the actual urban WM. Some tables, which can help in the LCA and LCC, are reported in Supplemental Appendix (see Tables S5 and S6).

For both the assessments, the functional unit is the management of the annual amount of waste generated, for each product category and for the related European codes. The system boundaries include the collection and treatment of waste. It is worth noticed that the geographical boundaries of these analyses can be even smaller the whole area in charge to the waste collection operator.

In the Life Cycle Impact Assessment (LCIA), after classification, characterisation and normalisation, weighting is performed by multiplying the normalised results of each of the impact categories with a weighting factor that expresses the relative importance of the impact category. In this case, an equal weight for each impact category is assumed. The total environmental impact for each product category is calculated ($I_{ENi}$).

As far as the economic assessment is concerned, the cost items related to waste collection and treatment are considered to evaluate the total economic impact for each product category ($I_{ECi}$).

To make the different product categories comparable, the contribution of each product is then calculated:

$$I_{ENi} = (I_{ENi})/(\sum_{i=1}^{n} I_{ENi}) \quad (12)$$

$$I_{ECi} = (I_{ECi})/(\sum_{i=1}^{n} I_{ECi}) \quad (13)$$

## Results and discussion

The framework designed by the authors provide waste operators with a reusability indicator for each product category. Thus, it is mathematically calculated as follow:

$$RI_i = RC_i[\%]*(I_{Si} + I_{ENi} + I_{ECi}) \quad (14)$$

The actual social performances in terms of SC, PRR, LF, environmental and economic impacts are calculated without assessing the effective fate of goods. Thus, $RC_i$ multiplies the other indicators to consider the potential failure of reuse activities.

As outcome, a priority list of the products to be prepared to reuse can be derived.

It is worth noting that geographical scope influences not only the results of LCA and LCC but also the assessment of the distance from legislative targets.

A barrier to the application of this framework might be data availability: waste service operators should put effort in collecting data grouped by product category, and not by waste flow. This is a prerequisite for the calculation of environmental and economic impacts, which would be avoided, thanks to PfR. Moreover, only when final data on effective reuse are available, the average quality and marketability of each product category can be inferred. Therefore, the collaboration with reuse centres is pivotal to gather this information.

Moreover, a crucial decision is the granularity level of the analysis, that is, the level of detail in the definition of product categories.

As far as the targets set by policies are concerned, the lack of quantitative binding targets at European level on waste prevention and reuse is highlighted. The scarcity of targets on reuse may reflect a culture attentive to the production of new goods, but it can also due to the difficulties in framing the problem (Morseletto, 2020).

The analysis suggests that the achievement of target on separate waste collection might go to the detriment of waste prevention and reuse. From the perspective of the waste collection operator, the final formula (equation (14)) highlights that the achievement of the targets on separate collection, PfR and/or recycling and landfill disposal have the same weight. Thus, the final rank of products is equally influenced by all these aspects. This suggests that waste operators should be incentivised in the implementation of reuse and PfR strategies, considering that PfR requires a high-quality collection phase (Parajuly and Wenzel, 2017). Moreover, setting a separate target for preparing for reuse would encourage stakeholders in the recycling and preparing for reuse value chain to collaborate and create partnerships in order to grant access to reuseable goods, which have ended up in the waste stream (RREUSE, 2018).

As claimed by Zacho et al. (2018b), the value added by the citizens is largely unrecognised in the assessment of WMS: the sorting done by citizens is a prerequisite for the system to function, and their sorting actions can be regarded as the first value-adding input in the recovery process, particularly when it comes to PfR. Thus, the collaboration with the user is pivotal for developing a sustainable collection system.

The authors believe that the designed model would allow waste collection operators to evaluate and disclose to public the impacts related to their day-to-day service. This could increase the awareness and the participation in decision-making of urban waste providers, public administration and citizens together, that is vital for achieving a sustainable WM.

Hence, this study can provide useful insights to policy-maker, since institutional strategic planning of public solid WM needs to assure alignment with their operators in order to guarantee sustainability policies realisation (Hazlett et al., 2013; Machado et al., 2017; Rodrigues et al., 2018).

Finally, considering the importance of monitoring prevention and reuse activities (Magrini et al., 2021), this framework can help in designing effective incentives for waste operators to boost PfR. In particular, the authors believe that the framework is suitable to be applied to product categories usually included in bulky waste items (i.e. discarded furniture) and textiles. In a future perspective, the evaluation might be extended to include other waste fraction such as waste from electric and electronic equipment, as in this case further investigation would be required to understand the effective benefits of reuse.

## Conclusion

The aim of this research study is to define a comprehensive indicator to evaluate the social, economic and environmental sustainability of PfR, coupled with potential for reuse at product category level. This paper aims to contribute to research on reuse and PfR by assuming the perspective of waste collection operators. Indeed, their role in facilitate reuse is often neglected, despite being the collection mode and storage method two drivers of reuse. The main contribution of this paper is in proposing a framework of assessing a model for selecting and prioritising performance indicators to evaluate the reusability of products. Indicators to evaluate the reusability of product categories do not exist yet. A reusability indicator is proposed, which includes one coefficient (i.e. the reusability coefficient) and three indicators: the first one (i.e. the Social Indicator – $I_s$) for the assessment of social performances, the second one (i.e. Environmental Indicator – $I_{EN}$) for the assessment of environmental performances and the third one (i.e. Economic Indicator – $I_{EC}$) for the assessment of economic performances. Further indicators that evaluate the social aspects might be investigated in future research to include all the aspects of social sustainability on waste collection system (e.g. health and safety, job creation potential).

The reusability indicator allows waste collection operators to evaluate the potential impacts of the reuse strategy on their MSW collection system for each product category. Moreover, the designed framework allows them to monitor and disclose to public the impacts related to reuse activities, thus promoting a change of perception the waste itself.

As PfR can have benefits not only for waste collectors but also for local authorities and managers, future research study is needed to simplify and testing the reusability indicator in a first stage of assessment and when researchers or LCT experts are not present.

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## Supplemental material

Supplemental material for this article is available online.

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## 4.4. Paper 4. Door-to-door waste collection: a framework for the socio – economic evaluation and ergonomics optimisation (Degli Esposti et al., 2022)

**Brief introduction**

This study aims to quantify the impact of the Door - To - Door collection system on the health and safety of the workers involved in waste collection and to support waste collection operators in boosting the sustainable design of its service. A framework to evaluate the sustainability of the service through the identification of the technical and economic factors, as well as the social impacts, is described. A technical intervention in a Door - To - Door collection scheme of paper waste was selected as a case study to provide indications to the operators on how the load carried by workers can be minimised and to improve the design as well as the sustainability of the paper waste collection system. The methodological approach used criteria indicating the ergo-quality level and technical, economic, and social performances of the selected collection systems (i.e., 40-litres and 120-litres capacity bins).

**Study findings**

The interest raised in waste collection is widely debated in several publications. The research study aims to shed light on designing efficient and effective collection schemes required to boost high-quality performances, particularly as regards separate waste collection. Waste collection characteristics impact the daily workers' exposure to the Manual Material Handling of waste containers. In this context, ergonomics interventions are needed to reduce the risk of developing Musculoskeletal Disorders. This study gives a contribution to the waste collection field, quantifying the risk factors that might affect the health and safety of the workers involved in DTD waste collection, particularly considering its workloads and high repetitive tasks. The literature highlighted that the risk factors vary depending on waste collection services (e.g., waste collection containers, collection frequency, collection rounds, collection vehicle) and on the postural assessment of the workers. Now, more than ever, social and economic sustainability is a critical part of our thinking, and targets on waste collection set by the European and national legislation are crucial. An evaluation of social impacts complements technical and economic considerations to boost the sustainability of waste collection. social Life Cycle Assessment methodologies have been applied, limiting the considered stakeholders to the workers. To evaluate the potential impacts on the improvement of the selected scenarios, in the assessment of technical and economic implications, some criteria have been selected to ensure the reliability of the analysis and the comparability among the selected collection system. This case study demonstrates that using 120-litres capacity bins would improve the ergo-quality level of paper waste collection. As a result of the ergonomic risk assessment, it can be stated that using the 2-wheeled bins minimises the operator workload. Thus, the study confirms a cost and ergonomic optimisation in modifying the characteristics of the collection service by reducing the number of manual handling operations, such as lifting and carrying. Future research studies might focus on other ergonomics aspects (e.g., high repetitive tasks, collection frequency, job rotations), environmental influencing factors (i.e., transportation, waste collection vehicles), socio-economic impacts on the users (e.g., household), and the applicability of the designed framework on other waste fraction as well as other bins typology (e.g., 240, 360, 4-wheeled). The application of the designed framework to different case studies (e.g., non-urban areas) will allow the authors to test and refine the process. A collaboration with other urban waste operators is encouraged to be disclosed, whereas the conversations with some waste operators confirmed that the analysis was not routinely used but might be helpful to decision-making in designing waste collection services (e.g., paper, glass, plastic).

**Conclusion**

I. Waste collection characteristics impact workers' health and safety;

II. The selected case study of a technical intervention in a door-to-door collection scheme is used for the development of a theoretical framework for increasing sustainability,

III. Ergonomics evaluation is not widely implemented for evaluating the implications of the waste collection systems.

IV. Ergonomics intervention on wheeled containers reduces the musculoskeletal disorders.

**Table 4.4**. Overview of the fifth manuscript (Degli Esposti et al., 2022).

| | |
|---|---|
| Title | Door-to-door waste collection: a framework for the socio – economic evaluation and ergonomics optimisation |
| Status | Published |
| Keywords | Municipal solid waste, musculoskeletal disorder, paper waste collection, cost-optimisation, Social life cycle assessment |
| Journal | Waste management, 156, 130-138 |
| Abstract | Waste collection is the first step of waste management, and its characteristics impact workers' health and safety. Arising out of the challenge for waste collection operators to design sustainable systems of work, the authors review the literature on ergonomics and socio-economic sustainability and design a theoretical framework for assessing the sustainability of waste collection. The framework quantitatively assesses the impact of the door-to-door collection system on the health and safety of the workers to provide indications to waste collection operators on how the load carried by workers can be minimized and the economic and social sustainability can be improved. As a case study, this paper investigates the musculoskeletal disorders derived from the manual material handling of waste containers affecting the workers in charge of door-to-door sorted collection of paper waste with the goal of optimizing the workers well-being and overall waste collection system performance The research study was conducted in collaboration with a company which operates in the solid waste collection for Italian municipalities. For this purpose, the ergo-quality level of two paper waste collection systems is evaluated. For each system, ten scenarios of door-to-door paper waste collection are considered. The analysis is complemented by an economic analysis, which estimates the costs associated with the collection system under consideration, and a social life-cycle assessment. Results suggest that using 120-litres capacity bins would effectively improve ergonomics and optimise the costs of the investigated activity. More specifically, due to mechanised collection, the more limited number of lifting and carrying operations would expose the workers to lower ergonomic risk. |
| Annex | 4 |

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# Door-to-door waste collection: A framework for the socio – Economic evaluation and ergonomics optimisation

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A R T I C L E I N F O

*Keywords:*
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Musculoskeletal disorder
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A B S T R A C T

Waste collection is the first step of waste management, and its characteristics impact workers' health and safety. Arising out of the challenge for waste collection operators to design sustainable systems of work, the authors review the literature on ergonomics and socio-economic sustainability and design a theoretical framework for assessing the sustainability of waste collection. The framework quantitatively assess the impact of the door-to-door collection system on the health and safety of the workers to provide indications to waste collection operators on how the load carried by workers can be minimised and the economic and social sustainability can be improved. As a case study, this paper investigates the musculoskeletal disorders derived from the manual material handling of waste containers affecting the workers in charge of door-to-door sorted collection of paper waste with the goal of optimizing the workers well-being and overall waste collection system performance The research study was conducted in collaboration with a company which operates in solid waste collection for Italian municipalities. For this purpose, the ergo-quality level of two paper waste collection systems is evaluated. For each system, ten scenarios of door-to-door paper waste collection are considered. The analysis is complemented by an economic analysis, which estimates the costs associated with the collection system under consideration, and a social life-cycle assessment. Results suggest that using 120-litres capacity bins would effectively improve ergonomics and optimise the costs of the investigated activity. More specifically, due to mechanised collection, the more limited number of lifting and carrying operations would expose the workers to lower ergonomic risk.

## 1. Introduction

Municipal waste management (WM) is among the most complex systems to manage, and its characteristics impact the environment and human health (Eu, 2018a). Waste collection is the first step of WM, and source-separated waste collection has proved to be the most efficient method for returning high-quality materials suitable for high recycling efficiency (Di Maria et al., 2020, Laurieri et al., 2020) and a key success factor for enabling reuse and preparation for reuse (Degli Esposti et al., 2021). WM at the municipal level includes collection, transportation, treatment, and disposal of urban waste, and it involves legislative, urban planning and human aspects as well as the environmental, social, and economic dimensions of sustainability (Bamonti, 2012, Rodrigues et al., 2018).

In recent years, municipal solid waste management (MSWM) systems have been widely debated in several publications concerning the organization, planning, administration, engineering, financial, environmental and health aspects. They were lately reviewed particularly regarding the safety of the workers involved in managing of waste potentially contaminated by COVID-19 (Behera, 2021, Yousefloo and Babazadeh, 2020), and the effect of the COVID-19 pandemic on urban planning and management (Sharifi and Khavarian-Garmsir, 2020, Madsen et al., 2021). Together with street cleaning, waste collection is the most important service provided at the municipal level in terms of economic and environmental impacts on public health and citizens' quality of life and it is essential for achieving sustainable solid waste systems (Hannan et al., 2020, Benito et al., 2021). In this context, improper waste collection may lead to ineffective waste management:

*Abbreviations:* CR, Collection Route; DTD, Door To Door; LCA, Life Cycle Assessment; LI, Lifting Index; MMH, Manual Material Handling; MSD, Musculoskeletal Disorder; MSWM, Municipal Solid Waste Management; NIOSH, National Institute of Occupational Safety and Health; OD, Occupational Disease; RC, Reduction of Cost; sLCA, Social Life Cycle Assessment; SM, Sustainability Metric; WSL, Work Shift Length; WM, Waste Management.

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an improved approach to integrating social, economic, institutional, legal, technical, and environmental aspects is essential for planning the sustainable management of solid waste (Das et al., 2019). Although the literature is mainly focused on WM of specific waste streams (e.g., plastic, organic waste, waste from electrical and electronic equipment), with particular emphasis on public–private comparisons of efficiency in WM services (e.g., waste collection) (Bel and Warner, 2008, Bel, 2010), some authors also evaluate the performance of waste collection in terms of quality of the service (Bel and Sebo, 2021). In line with that, Bel and Sebo (2020) argue that evidence available on service quality is much scarcer than on other aspects, mainly due to the fact that measuring and monitoring quality is difficult and costly (Shrestha and Feiock, 2011).

Significant health issues also characterise the waste sector since its work activity involves, among other risk factors (e.g., weather, air, noise exposure), the manual material handling (MMH) of loads, i.e., receptacles: this can potentially cause musculoskeletal disorders (MSDs) (Thomas et al., 2021) which is defined by the International Encyclopedia of Public Health as a disease span, a range of ailments affecting the soft tissues of the musculoskeletal systems, including tendons, ligaments, cartilage, muscles, and nerves (Dennerlein, 2008).

Despite being a relatively small sector in terms of employment, waste collection records a significant fatal injury rate and its characteristics impact workers' exposure to non-fatal injuries due to the MMH of waste containers, and mainly the risk of developing work-related MSDs (Battini et al. 2018, Botti et al. 2020). A recent review on ergonomic interventions among waste collection workers cites 15 studies on occupational health developed in Europe (Emmatty et al., 2019). Specifically, questionnaires and medical examinations have globally reported MSDs and other diseases (liver disorders, Hepatitis A, Hepatitis B, respiratory problems, and cardiovascular diseases) (Engkvist et al., 2011, Jozwiak et al., 2013, Emmatty et al., 2019). National data from Italy show that MSDs are the main type of recognised Occupational Disease, and they have stabilised since 2012, after growing continuously over years (EASHW, 2019).

To the best of the authors' knowledge, a very limited number of studies focused on ergonomics to improve waste collection. None of these evaluates the ergo-quality aspects, along with the economic and social implications of a waste collection system. Regarding ergonomics, Botti et al. (2020) report very high ergonomics risk due to MMH when waste collectors empty the waste containers into the collection vehicle, suggesting some critical areas of improvement (e.g., avoiding torsion and awkward postures). Moreover, the same authors demonstrate that 2-wheeled containers with a capacity bigger than or equal to 120 L are safer and preferable than small standardized containers (with a capacity equal to 25 L). Similarly, Thomas et al., 2021 demonstrate that collection services using wheeled bins have lower MSD-related absence rates than those requiring bending and lifting operations. Thus, from an epidemiological perspective, the study's results identify a correlation between the collection methods and the prevalence of MSDs, concluding that systems comprising 4-wheeled and 2-wheeled bins appear to be consistently less hazardous for workers when compared to systems using sacks and boxes.

Only a few studies evaluated the socio-economic impacts of waste collection. Likewise, some studies are focused on the costs and the efficiency of local governments in managing waste collection (Benito et al., 2021), while others on the economic regulation of waste collection (Di Foggia and Beccarello, 2018, Magrini et al., 2021b). According to Campitelli and Schebek (2020), who reviewed 366 studies on waste management systems of cities or countries and focused on municipal solid waste, only 89 studies consider at least one social aspect. However, Mohsenizadeh et al. (2020) argue that some studies on MSWM incorporate the social dimension of sustainability, considering methods such as social life cycle assessment (sLCA), and social indicators (e.g., creation of job opportunities, visual pollution, amount of reused waste). Moreover, a recent review conducted by Hannan et al. (2020) shows that only 6 out of 21 studies on solid waste collection considered the social dimension of sustainability. Specifically, reviewing 162 selected papers, the authors conclude that there are ten most common constraints in sustainable waste collection. Narrowing down to the optimization constraints of the sustainable waste collection, the results show that only 2 out of those 6 studies evaluate the "labour constraint" in terms of human labour and job opportunities (Heidari et al., 2019, Hannan et al., 2020) and indirect social benefits in improving quality of life and human health (Mohsenizadeh et al. 2020, Hannan et al. 2020). As for "social and non-negative constraints", the authors consider the involvement of various stakeholder groups in the decision-making process and the impacts of social capital parameters (e.g., social network, social trust, social learning). Moreover, in designing a waste collection route (CR), the company in charge of waste collection service should consider both socio-economic implications and ergonomics aspects. In this context, the UK Health and Safety Executive has identified that the provision of appropriate guidance and tools represents a useful means of assisting Local Authorities, or organisations (including community organisations) that are responsible for delivering waste management services, to select the most appropriate systems to ensure that environmental targets are met with the least possible health and safety risk (Turner et al., 2008).

Thus, in this study, a technical-ergonomic evaluation complements a socio-economic analysis, which is not widely implemented for waste collection systems.

This study aims to quantify the impact of the DTD collection system on the health and safety of the workers involved in waste collection and to support waste collection operators in boosting the sustainable design of its service. For this purpose, firstly, a methodology for the assessment is proposed. Secondly, a framework to evaluate the sustainability of the service through the identification of the technical and economic factors, as well as the social impacts, is described. Finally, the designed framework is applied to the case study of DTD paper waste collection in an Italian Municipality to evaluate throughout the designed framework the ergonomic, technical, and socio-economic sustainability of a waste collection system from the workers' perspective. A technical intervention in a DTD collection scheme of paper waste was selected as a case study to provide indications to the operators on how the load carried by workers can be minimised and to improve the design as well as the sustainability of the paper waste collection system. The methodological approach used criteria indicating the ergo-quality level and technical, economic, and social performances of the selected collection systems (i.e., 40-litres and 120-litres capacity bins). The conversations with some waste operators confirmed that the analysis was not routinely used but might be helpful to decision-making in designing waste collection services (e.g., paper, glass, plastic).

The paper is structured in four sections. In Section 2, the authors describe the system and introduce the formulation of the mathematical modelling. Section 3 presents the case study. Section 4 discusses the results of the case study, while in Section 5, the authors draw some conclusions.

## 2. Materials and method

In this section, the authors detail the system of the study. Then, the method to calculate the sustainability metrics (SMs) and the mathematical modelling are described. Thus, the model used in section 3 to analyse the effects of socio-economic and ergonomics variables on the efficiency of waste collection is provided.

### 2.1. System description and sustainability metrics

The literature agrees on selecting as indicators to monitor waste collection systems: i) the cost of the service, ii) the tons of waste collected in the municipality, iii) the number of containers per collection route (CR), iv) the frequency of collection (Emmatty et al., 2019, Botti et al., 2020, Benito et al., 2021). Therefore, the literature highlighted that the following aspects were globally considered to improve the sustainability of waste collection service: operating costs and collection time (Pires et al., 2019, Hannan et al., 2020).

This study proposes three sustainability metrics (SMs) for evaluating the sustainability of DTD waste collection service, based on the literature review described in Annex 1. Table 1 shows a brief overview of the designed system (i.e., object of the analysis, impacts, involved stakeholders and selected indicator) split into: i) technical and ergonomic, ii) economic, and iii) social aspects.

Once the three indicators for waste collection have been selected, within the designed framework, the authors explained the mathematical modelling to calculate the SMs using the method in Section 2.2.

### 2.2. Mathematical modelling

As depicted in Fig. 1, the authors designed a mathematical model to analyse and compare different collection systems in five steps with the following algorithm.

#### 2.2.1. Step 0: Selection of the collection systems and identification of the scenarios

Before evaluating the different collection systems, some selection criteria should be considered, to identify the most appropriate scenarios. Selection criteria are necessary to ensure the reliability of the analysis and the comparability among the collection systems. The authors designed a framework to analyse and compare collection systems which collect the same waste flow with the same frequency, operators, and vehicles. Besides that, other selection criteria are the applicability of the systems within the territory, their potential impacts on improving collection habits and the result of the ergonomics evaluation. According to Botti et al., (2020), Rossi et al., (2022), it is suggested conducting the ergonomics risk assessment using the NIOSH Lifting Equation, developed by the National Institute for Occupational Safety and Health of the USA (NIOSH, 1994). The selected scenarios should all have the same risk value ("low-risk related work"). Consequently, the selection criterion is the ergonomics evaluation, which classifies the collection system selected for the analysis as a "low-risk related work".

#### 2.2.2. Step 1: Evaluation of the technical end ergonomics aspects

Technical and ergonomics analyses should focus on the feasibility and ergo-quality level of the waste collection service from the perspective of the waste operators and the workers in charge of waste collection.

The number of **manual handling operations (MHO)** includes the number of containers, as well as the load carried by the workers for each CR, and it can be calculated as follows (Equation (1)):

$$MHO = c \times u \quad (1)$$

**Table 1**
Overview of the technical and ergonomics, economic, and social aspects of the designed system.

| Aspects | Technical and ergonomic aspects | Economic aspect | Social aspect |
|---|---|---|---|
| **Object of the analysis** | Technical implications of reducing MMH of waste containers | Economic evaluation of the service | Social analysis of the collection workers |
| **Impacts** | Feasibility and ergo-quality level of the waste collection service | Cost of the service | Positive and negative impacts associated with the waste collection operators |
| **Stakeholders involved** | Workers<br>Waste operators | Inhabitants<br>Waste operators | Workers |
| **Selected indicators** | **Manual handling operations** as the number of operations needed to collect waste | **Reduction of cost** of the service | **Indicators included in the subcategory "workers** "(UNEP, 2011) |

Where:

c is the coefficient that represents the average number of collected bins per CR;

u is the user as the number of households which produce waste;

It was assumed that each user has got one bin which requires one MHO for waste operator. More specifically, given the deep complexity that characterizes the analysis - due to both multi-parameters' assessments and to varying urban management settings – the coefficient "c" represents the uncertainty about the number of collected bins which is not always equal to the actual overall of the bins under study.

Where the coefficient c is calculated as follows (Equation (2)):

$$c = \frac{s_p \times k_b \times w}{l \times CR} \quad (2)$$

Where:

$s_p$ is the specific weight of collected waste (kg/litre)

$K_b$ represents correction coefficient for the cost unit (€/kg) and the generation of waste (kg/yr), which means that the generation of waste depends on the number of the members of each family under study (ARERA, 2020).

l is the litres capacity of the waste container

w is the amount of waste produced per year per household (kg/household)

CR represents the frequency of each collection route, which represents a parameter defined by the waste operator. It depends on several factors (e.g., the waste collection flow, the amount of waste generation, the population density).

#### 2.2.3. Step 2: Evaluation of the economic aspect

According to the literature, waste collection costs include the cost required to collect bins and containers for each CR. The potential **reduction of costs (RC)** considers the cost per inhabitant, and it can be calculated through Eq. (3):

$$RC(€/inhab.) = \frac{C}{u} \quad (3)$$

Where:

Costs (C) are calculated through Eq.4:

$$C(€/min) = \frac{cost}{wsl} \quad (4)$$

Where:

cost is intended to be the cost to collect the bins daily (€/day)

wsl is the work-shift length that includes the time required to collect each bin (t) multiplied by the number of containers for each CR (u), and it can be calculated as follows:

$$wsl(min/day) = t \times u \quad (5)$$

The purpose of the RC indicator is to communicate to all the citizens of the city the economic value of the reduction of cost refers to the waste collection service with a communicative approach based on easily understandable indicators (De Feo et al., 2019, Meriläinen and Tukiainen, 2020).

#### 2.2.4. Step 3: Evaluation of the social aspect

According to the literature, information on waste collection's socio-economic aspects and waste collectors' social performances has to be considered for decision-making. For this purpose, positive and negative impacts associated with the waste collection operator across the life cycle of its service should be assessed from the workers' perspective. Likewise, social topics for workers are of interest to the authors because waste collection operators are the stakeholder group considered in the study.

For the design of the social analysis, the Social Life Cycle Analysis (sLCA) methodology is considered a useful tool to evaluate the social impacts of the selected waste collection system. According to Magrini

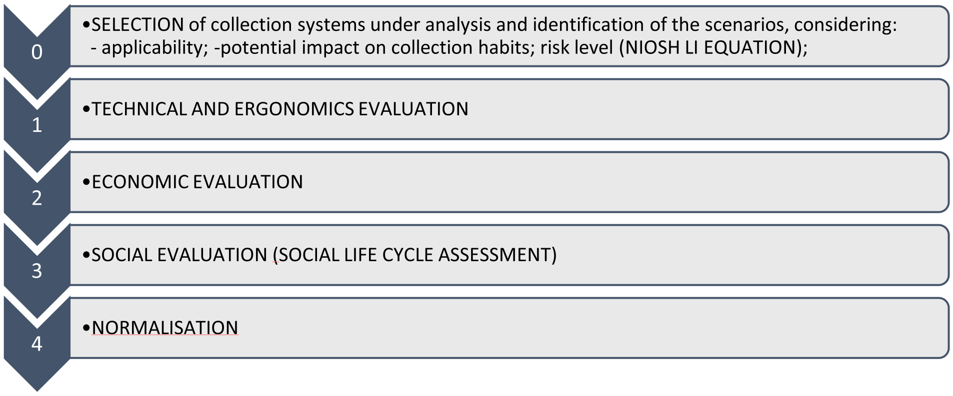


**Fig. 1.** Overview of the four steps of the designed framework.

et al. (2021a), the "Guidelines for Social Life Cycle Assessment of Products and Organizations 2020" (UNEP, 2020) should be used because they position sLCA in consonance with the SDGs and capture methodological developments lately implemented by the methodological sheets (UNEP, 2021). In this context, the Social Impact Assessment method described in the guidelines includes the following steps: i) selection of an impact assessment approach (i.e., reference scale, impact pathway); ii) definition of the social topics (stakeholder categories, children, and subcategories and/or impact categories); iii) identification of the reference scale to assess the impact; iv) possibly, choice of a weighting approach. Specifically, the stakeholder categories are the workers, the local community, the value chain actors, the consumers, the society, and the children. Hence, social sustainability has been evaluated based on the "workers" category and the following subcategories: i) freedom of association and collective bargaining, ii) fair salary, iii) working hours, iv) equal opportunities/discrimination, v) health and safety, vi) social benefits/social security. It should be noted that the subcategories "sexual harassment", "small holder including farmers", and "social benefits and/or social security" were not considered in this study, mainly due to the fact that they were out of the objectives of the study. Annex 1 details the assessment of the social analysis. The weighting approach was not applied in this study.

The "reference scale" for Social -Life Cycle Impact Assessment ranging from negative to positive performance is selected with only two scale levels (from $-2$ to $+2$). Eq. 6 shows the final value of the indicator WS: $\sum_{1}^{3} ws_i$ (Eq. 6)

Where:

$ws_i$ are the scores ranging from $-2$ to $+2$ per each selected subcategory i of the category "workers".

See **Annex 1** for more information about subcategories.

#### 2.2.5. Step 4: Normalization of the results

The fourth step refers to the normalization of the results, which were calculated through equations (1), (3), and 6. Driven by the experiences of Rigamonti et al. (2016), Wilson et al. (2015), Fernández-Braña et al. (2019), and Magrini et al. (2021a), as a first assessment, the present analysis is characterized by the same weight for each SM. The following mathematical formulae were applied to calculate the final score of each scenario:

$$Normalised\ value_{ijs} = \frac{SM_{ijs}}{\sum_{1}^{3} SM_{ijs}}$$

$$Total\ score_j = \sum_{j=1}^{3} SM_{ijs}$$

Where:

$j$ represents the scenario (from 1 to 10);

$s$ represents the sustainability pillar (from 1 to 3, indicating ergonomics, economic and social aspects);

$SM_{ijs}$ is a sustainability indicator $i$, for scenario j, referred to the sustainability aspect $s$.

## 3. Case study

The research study focuses on DTD paper waste collection of small waste containers in an Italian Municipality (Argelato, Emilia-Romagna Region). Emilia-Romagna is a region in Northern Italy that extends inland westward from the Adriatic coast. The population of the Region is 4.459.477 inhabitants (2019), while the urban waste service is managed by 11 different providers (2019) (Magrini et al., 2021b). The street bin collection is the most common separated collection method in the Region: 33% of sorted waste is collected this way, while the DTD collection system covers 19% of separate collection waste. However, its diffusion rate has been growing for the past few years (ARPAE, 2019), and the municipalities have been promptly achieving the targets for separate collection of waste set by the European and national legislation (EU, 2011, Emilia-Romagna Region, 2015, EC, 2018a, EC 2018b). Moreover, in 2015 the Region established a fund to promote waste prevention and reduction among the Municipalities: the fund also aims to reduce the costs of changing the collection system for those Municipalities which want to implement a DTD collection system, including at least unsorted waste and biowaste (Magrini et al., 2021a; Emilia-Romagna Region, 2015). In this context, the DTD paper waste collection in Emilia-Romagna Region is mainly performed with bags and small standard waste containers, e.g. 40-litres capacity bins. Thus, it often requires MMH of bins and bags as lifting, pushing, and pulling operations.

The research study is divided into three phases: firstly, the ergonomics risk of two different DTD collection systems is evaluated by using the NIOSH Lifting Equation, developed by the National Institute for Occupational Safety and Health of the USA; secondly, ten scenarios for the DTD paper waste collection are considered. Further details on the relationship between the two different DTD collection systems are provided in Annex 2.

By considering the Municipality of Argelato, a situation in which paper waste collection is completely performed with 40-litre capacity bins (baseline scenario); a situation in which paper waste collection is completely performed with 120-litre capacity bins; 9 scenarios in which 40 L are partially substituted by 120 L. Finally, technical, economic, and social implications of the improved DTD paper collection system are provided. Further details on the ten scenarios are provided in Annex 2 and Annex 3.

### 3.1. Step 0: Selection of the collection systems and identification of the scenarios

As mentioned above, the preliminary step of the algorithm is the selection of the systems under analysis, based on the result of the ergonomics analysis and on other section criteria.

*3.1.1. Ergonomics analysis*

DTD waste collection activities include emptying bins and driving vehicles. As regards emptying bins, several risk factors affect the health and safety of waste collectors, such as lifting and carrying, pulling heavy loads, repetitive tasks, and long working hours. In that sense, these activities might cause work-related MSDs and might result in chronic injuries and ODs.

The ergonomics study focuses on the MSDs derived from MMH of waste containers in a DTD collection of paper waste. Data refer to urban waste collection performed by an Italian waste management operator reviewing its collection system in collaboration with the municipalities in the Emilia-Romagna Region. The ergonomics risk assessment includes the NIOSH Lifting Equation, developed by the National Institute for Occupational Safety and Health of the USA in 1994, to evaluate the risk of lifting and carrying, pushing, and pulling the selected waste containers (i.e., typology A and typology B). According to Thomas et al. (2021), each collection system has its specific combination of manual handling risks. In this context, paper waste is collected manually (in the case of 40-litre bins) and/or semi-mechanically (in the case of 120, 240, 360 L). As for the 40-litre capacity bins, the operator directly lifts small bins from the ground. Then, the operator lifts, carries and empty the bins into the vehicle hopper; and lowers the bins to the ground. Differently, for 120-litre and 360-litre bins, the workers pull and hook the 2-wheel containers to the vehicle. While pushing and pulling wheeled bins (120 – 360 L) affects the shoulders, elbows and back, handling baskets (30 – 45 L) affects the neck, shoulders, elbows and back (Thomas, 2005, Thomas et al., 2021).

As far as the ergonomics analysis of typology A is concerned, the analysis was conducted according to ISO 11228–1 standard (ISO 11228-1:2007). Considering typology B, the ergonomics analysis was performed by adopting wheeled containers for the DTD collection of paper waste. The methodology detailed in the ISO 11228–2 standard was applied to investigate the pushing and pulling forces during the manual handling of the 2-wheel containers, full of paper waste. The maximum capacity of the container is 120 L. Handles were positioned at 95 cm from the ground. Six pushing and pulling trials were performed. Trials consisted in pushing the container for 7.5 m, with a frequency of 1 push every two minutes. A digital force gauge equipped with two handles was used to measure the pushing force.

Table 2 shows the input data of the reference ergonomics study.

Table 3 shows the results of the NIOSH Lifting Index (LI). The green colour indicates the low-risk range (LI 0.85), the yellow the moderate risk range (LI > 0.85 and LI < 1), while the red one indicates the high-risk range (LI 2) and the purple the highest risk range (LI3). The LI was calculated for male workers since this type of works is expected to be performed only by them.

More details on the ergonomic risk assessment conducted by the NIOSH LI equation are shown in **Annex 4**.

*3.1.2. Selection of the scenarios*

Based on the results provided by the NIOSH LI, which has classified both the selected typologies as "low-risk related work" (section 2.3), an in-depth analysis was carried out of ten scenarios of DTD paper waste collection to evaluate the technical, economic and social benefits of the selected systems, in which the 40-litre containers (typology A) are totally or partially substituted with 120-litre bins (typology B).

The analysis of the ten scenarios was conducted according to technical, economic, and social indicators described in section 2.2. These indicators will assess the ergo-quality level related to the selected waste collection systems, the efficiency related to the organisation of the systems, socio-economic correlations, and effective implementations related to the improved scenarios.

**Table 2**
Characteristics of waste collection in an Italian non-urban area. Average value of 5 rounds for typology A and 2 rounds for typology B.

| Parameter / Typology of Bin | Unit | Typology A | Typology B |
|---|---|---|---|
| WSL | [min/day] | 480 | 440 |
| Breaks per day | [min/day] | 30 | 30 |
| Time to unload vehicle | [min/day] | 15 | 15 |
| Time to collect bins | [min/day] | 73 | 83 |
| Bin weight | [kg] | 5.67 | 17 |
| N. bins collected per day | [-] | 219 | 125 |
| Frequency of MMH operations | [-] | 0,5 | 0,5 |
| Total waste collected / worker | [kg] | 1,24 | 2,13 |

**Table 3**
NIOSH LI for each risk range related to the whole waste collection activity (Lifting, transport, pushing and pulling) of containers typology A and typology B.

| NIOSH results | Bins typology | |
|---|---|---|
| | Typology A | Typology B |
| Lifting operation | 0,59*<br>0,74** | – |
| Carrying operations | 0,42 | – |
| Pulling and pushing operations | – | 0.65*<br>0.79** |
| Colour indexing | GREEN | GREEN |

*male workers 18–45 years old **male workers < 18 or > 45 years old.

*3.2. Step 1, 2 and 3: Evaluation of the technical, ergonomics, economic, and social aspects*

The third phase of the research study aims to assess the scenarios' ergonomics, technical, economic, and social implications. The objective of the analysis was to support the waste collection operator in boosting its service's sustainable design by identifying the technical and economic factors and social impacts of the DTD paper waste collection systems.

Technical implications were evaluated based on the local context where the waste management operator provides its service. In that sense, the study involved many stakeholders, mainly the waste collection operator and its workers, the municipality of Argelato and its local authorities. In this context, the paper waste collection consists of two main tasks: emptying the bins and driving the vehicle to the transfer station, storage or sorting facility or recycling plant. The first task requires the workers to drive the waste collection vehicle to the bins and empty them into the vehicle hopper. The waste operator in charge of paper waste collection separately collects the containers on a tri-weekly arrangement using waste collection vehicles. In the early morning, waste collectors start the first CR. The work shift finishes at around 13, with a 30-minutes break per day. The kerbside collection requires about 80% of the total CR, while the average time to unload the collection vehicle at the recycling plant is about 75 min per day. Hence, the average time of MMH of waste containers is about 400 min per day. Both services are provided by a single crew which costs 0.89 €/min.

In the present case study, the assessment of technical implications was based on primary data on: i) specific characteristics of the collection system (e.g., local context, frequency, CRs), ii) analysis of paper waste (e.g., amount per inhabitants, quality of paper waste), and iii) inhabitants characteristics (e.g., number of users) and users' habits (e.g., typology of waste containers, production of paper waste). Considering paper waste generation (equal to 38.43 kg/cap/yr), paper waste weight (equal to 0.13 kg/l) and the number of household users, data are necessary to evaluate the feasibility and the design of the service (i.e., collection frequency, CRs, number of bins per round). As the collection frequency is 1/21 (time/day), the number of CRs per year is 16.

Table 4 shows the selected parameters for the collection systems.

As far as the economic assessment is concerned, the costs of the selected scenarios have been evaluated based on the cost of 0.89 Euro/min per day for each CR (Table 4)

**Table 4**
Description of the selected parameters of each collection system.

| Parameter | Scenario | | | |
|---|---|---|---|---|
| | **Unit** | **Scenario 0** | **Scenario 10** | **Scenario 5** |
| Average time to collect bin | [min/day] | 1 | 2 | 1 for 40-litre<br>2 for 120-litre |
| N. 40 L capacity bins | [-] | 313 | 0 | 157 |
| N. 120 L capacity bins | [-] | 0 | 313 | 157 |
| N. household users with 40 L | [-] | 727 | 0 | 367 |
| N. household users with 120 L | [-] | 0 | 727 | 367 |
| WSL | [min/day] | 437 | 403 | 420 |
| Cost | [Euro/min/CR] | 389 | 359 | 374 |

As for the assessment of social sustainability, the “reference scale” was selected as the impact assessment approach for sLCIA, ranging from negative performance to positive performance was selected with only two scale levels (from −2 to + 2).

## 4. Results and discussion

The present study evaluated the ergonomics and technical implications, as well as the economic factors related to the DTD collection of paper waste. Social sustainability was also assessed to identify the negative and positive impacts on collection workers, as a meaningful complement to the ergonomics case study.

Results show that the use of 120-litre capacity bins would significantly improve the ergonomics of the investigated activity (Table 4). The ergonomics study on 120-litre showed that the resulting pushing force was 15 kg and the pulling force was 11 kg. The ergonomics study on 360-litre showed that the pushing force was 17 kg and the pulling force was 13 kg. Hence, both observed values are lower than the limits for pushing force (23 kg) and pulling force (14 kg) suggested in ISO 11228–2 (International Standard Organization, 2007b). According to Battini et al. (2018), the main risk factor is due to the horizontal distance between the hand and the body of the worker as well as the vertical distance between the hands and the ground, and it impacts on the final risk index. Therefore, according to the authors lifting and pulling frequencies greatly impact the NIOSH LI. In this context, the use of typology B containers in scenarios 1 and 2 reduces the number of lifting and carrying operations. More specifically, due to the development of the semi-mechanised collection, the more limited number of lifting and carrying operations would expose the workers to less ergonomic risk in scenario 10. Scenario 5 gets a number of total ergonomic operations equal to 125, 94 of which are lifting, whereas 75 are pulling operations. Hence, the total amount of lifting and carrying operations is effectively reduced if compared to scenario 0 (235).

Therefore, the average work time of the improved mechanised collection (40 s per operation) is found to be higher than in the case of paper waste collection performed with the 40 L waste bins which require less time-consuming lifting operations (20 s). In that sense, while the average time of each bin is found to be twice for 120 L, the effective time of paper waste collection performed by 40 L for each CR is found to be the highest (Scenario 0). Interestingly, using 2-wheeled 120 L capacity bins reduce at the same time the MMH of loads and the effective time of the collection service. Hence, the best scenario with less lifting and carrying operations is the first one in which 120 L capacity bins completely substitute the 40 L bins. It should be noted that Scenario 5 shows the actual number of users with 120-litres capacity bins (60% of the users). Accordingly, 50% of the users did not have 120-litre bins by changing their habits.

Consequently, the costs of Scenario 1 and Scenario 5 were significantly reduced (see Table 4). Hence, by multiplying the cost of the service and the work shift length (see Table 3), the total costs of the services are an average of 6,220 €, 5,737 €, and 5,930 € for Scenario 0 and Scenario 10. The municipality accounts for an average of 7% of the total expenditure per year for paper waste collection. The results in Fig. 2 show that using 120-litres capacity bins would effectively reduce the total cost of the service for the citizens.

As for the social analysis, the sLCA results are shown in Table 5.

In six out of seven social topics, each scenario gets the same score. Since the collection service is managed by the same company (Brodolini, 2021), no significant differences have been evaluated for workers (Table 5). Scenario 0 was considered as the baseline scenario for the evaluation of the health and safety category, while scenario 10 has a positive impact on these topics based on the results of the ergonomic risk assessment. As a matter of fact, even if the NIOSH analysis evaluated the use of 40-litres and 120-litres capacity bins as “low risk related work”, scenario 10 results in an ergonomic improvement for the workers when compared to the baseline scenario (scenario 0). More specifically, the safety of scenario 10 is increased by the fact that the MMH of loads would be significantly reduced, given that ergonomic interventions play an important role in developing waste collection services.

Moreover, the SMs have been evaluated for ten scenarios ranging from Scenario 0 to Scenario 10. Due to the semi-mechanised waste collection systems, It has been demonstrated that the MMH of waste containers has been significantly reduced, whereas the RC has been increasing due to the reduction of RC (Fig. 2). Consequently, the use of 120-litres capacity bins would expose the waste collection operators to fewer ergonomics risks, and the waste operators would undercharge households by 1.55 Euro for paper waste collection services. Social Life Cycle Assessment shows that the best scenarios in terms of social impact are scenarios 8, 9, and 10, whit a total score of 13 points (see Annex 5).

Finally, each SM was normalized (see Annex 5). Then, the total score of each scenario was calculated. Fig. 3 shows the results: the total score for each scenario is calculated as the sum of the scores of the sustainability dimensions. The total score results from the ergonomics, technical, economic, and social contributions. Scenario 10, whose total score is 45, ranks first.

## 5. Conclusions

The interest raised in waste collection is widely debated in several publications. The research study aims to shed light on designing efficient and effective collection schemes required to boost high-quality performances, particularly as regards separate waste collection. Waste collection characteristics impact the daily workers’ exposure to the MMH of waste containers. In this context, ergonomics interventions are needed to reduce the risk of developing MSDs.

This study has the ambition to give a contribution to the waste collection field, quantifying the risk factors that might affect the health and safety of the workers involved in DTD waste collection, particularly considering its workloads and high repetitive tasks.

The literature highlighted that the risk factors vary depending on waste collection services (e.g., waste collection containers, collection frequency, collection rounds, collection vehicle) and on the postural assessment of the workers. Now, more than ever, social and economic sustainability is a critical part of our thinking, and targets on waste collection set by the European and national legislation are crucial.

An evaluation of social impacts complements technical and economic considerations to boost the sustainability of waste collection. sLCA methodologies have been applied, limiting the considered stakeholders to the workers. To evaluate the potential impacts on the improvement of the selected scenarios, in the assessment of technical and economic implications, some criteria have been selected to ensure the reliability of the analysis and the comparability among the selected collection system.

This case study demonstrates that using 120-litres capacity bins

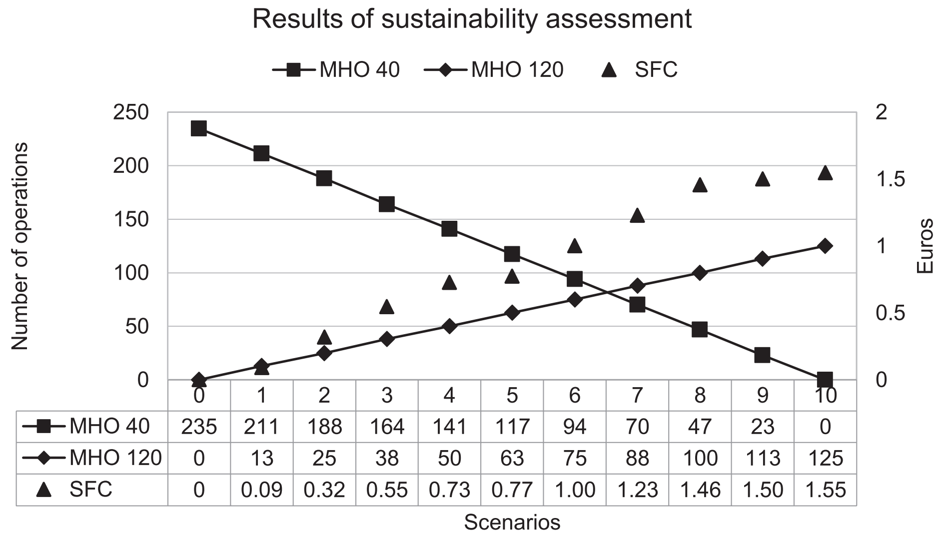


**Fig. 2.** Results of the technical and economic analysis for ten scenarios.

**Table 5**
Results of sLCA in terms of workers subcategory for ten scenarios.

| **Total sLCIA** | 11 | 11 | 11 | 11 | 12 | 12 | 12 | 12 | 13 | 13 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Scenarios | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

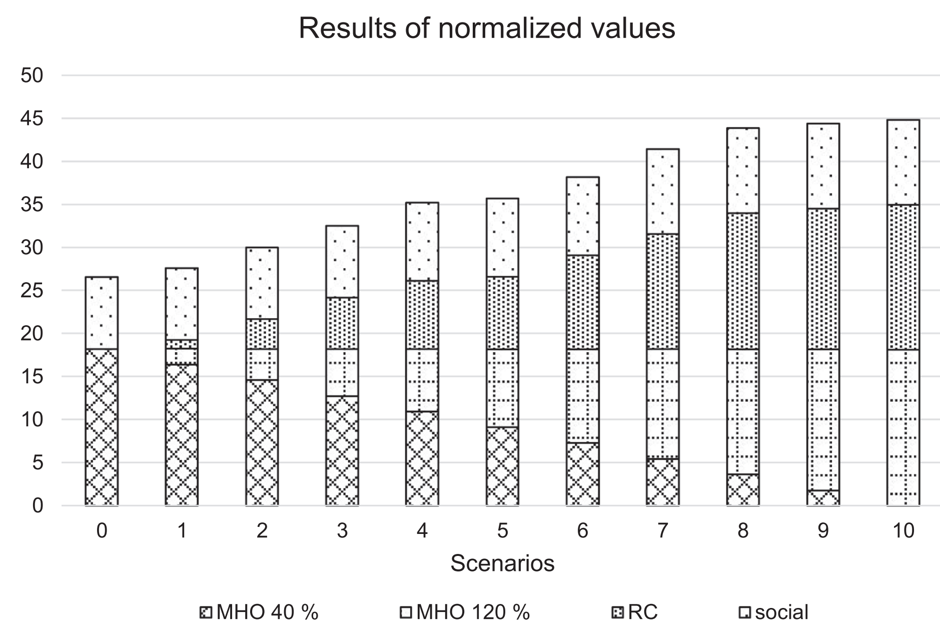


**Fig. 3.** Results of the normalized values of technical, economic, and s - LCA analysis for ten scenarios.

would improve the ergo-quality level of paper waste collection. As a result of the ergonomic risk assessment, it can be stated that using the 2-wheeled bins minimises the operator workload. Thus, the study confirms a cost and ergonomic optimisation in modifying the characteristics of the collection service by reducing the number of manual handling operations, such as lifting and carrying.

Future research studies might focus on other ergonomics aspects (e.g., high repetitive tasks, collection frequency, job rotations), environmental influencing factors (i.e., transportation, waste collection vehicles), socio-economic impacts on the users (e.g., household), and the applicability of the designed framework on other waste fraction as well as other bins typology (e.g., 240, 360, 4-wheeled). The application of the designed framework to different case studies (e.g., non-urban areas) will allow the authors to test and refine the process. A collaboration with other urban waste operators is encouraged to be disclosed.

## 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

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2022.11.024.

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# CONCLUSIONS

*Look up at the stars and not down at your feet. Try to make sense of what you see And wonder about what makes the universe exist. Be curious.*
*(Stephen Hawking)*

In this thesis, some recent advances in the waste management sector have been presented. Specifically, this thesis attempted to fill the gap in the following open issues which arise when dealing with the sustainability of the waste management systems and building infrastructures: (i) How to monitor the collection and generation of waste?; (ii) How can the effects of a waste collection system be measured considering the pillars of sustainability?; (iii) Can environmental and social analysis support design of buildings and waste management systems?; (iv) What is the role of waste collection in boosting sustainable systems of waste management?; (v) How can ergonomics impacts of waste collection be assessed and compared?.

Essentially, the advancements pursued in the framework of the industrial symbiosis, waste prevention, preparation for reuse and reusability, the door – to – door collection system, and the Italian waste management plans have been shown and discussed. In such a framework, to fill the afore-mentioned gaps the author proposes some new metrics for the evaluation of the sustainability in the waste sector.

Although apparently disconnected, the different advances achieved in this thesis can be combined to provide a framework for the assessment of the sustainability of waste management. Basically, the principle of the Life Cycle Thinking, Sustainable Development Goals, and Industrial Symbiosis concepts described in Chapter 3 might be jointly applied within the evaluation of the sustainability of the waste management impacts proposed in this thesis, as shown in Chapter 4. In other words, the thesis proposed four case studies which aim to investigate the above – mentioned concepts within the assessment of the environmental, economic, social, and ergonomics' impacts of the waste sector.

The first case study has demonstrated the high potential for recycling the Reclaimed Asphalt Pavement and the steel slags in the road construction sector, as a secondary raw material and a by-product, respectively. The authors have also demonstrated that the LCA is an appropriate tool to compare and to communicate the environmental performances of different asphalt mixtures in road constructions. By reducing the global environmental impact and recycling by products, the firm and the co-located companies which have been considered in the study are a case study of industrial symbiosis at the meso-level.

In the second case study the authors gave a valuable contribution to the formulation and promotion of waste prevention strategies, at different geographical levels. The authors have proposed a methodology to monitor waste generation and waste service costs at the municipal level: an algorithm to support the identification of a priority order for three project categories was provided (i.e., drinking water dispenser in town/city, drinking water dispenser in school, replacement of disposable goods in school canteens). By considering the user categories which live in a city or take advantage of its services, a framework for the sustainability assessment and the evaluation of the prioritisation of waste prevention measures was assessed. More specifically, by adopting a life-cycle perspective, the environmental, economic, and social consequences of waste prevention measures within the selected categories were assessed. Thus, a set of indicators for the evaluation of the effectiveness and the efficiency of the projects was defined.

The third case study has demonstrated the high potential for preparing for reuse and reusability within the municipal solid waste collection system. The authors have proposed a model to support waste management operators of municipal solid waste services: a framework to evaluate the potential of preparation for reuse as a strategy to jointly decrease social, environmental, and economic impacts and meet the legal targets on waste management was proposed. The proposed reusability indicator includes one coefficient evaluating the potential for reuse, and three impact indicators for the assessment of social, environmental, and economic performances. The indicator can be calculated by using real data, gathered by the waste collection operators in collaboration with reuse centers and referred to previous years.

The fourth case study has the ambition to shed light on the ergonomics' impacts of door – to – door collection systems: a theoretical framework for assessing the sustainability of the waste collection in a life cycle perspective has been provided. The framework has quantitatively assessed the impact of the door-to-door collection system on the health and safety of the workers, and it has provided indications to waste collection operators on how the load carried by workers can be minimized, and the economic and social sustainability can be improved. The analysis is complemented by an economic analysis, which estimates the costs associated with the collection system under consideration, and by a social life-cycle assessment. The authors have demonstrated that the use of 120-liters capacity bins would effectively improve the ergonomics and optimize the costs of the investigated activity. More specifically, due to the use of mechanized collection, the more limited number of lifting and carrying operations would expose the workers to a lower ergonomic risk.

Future developments of the waste management analysis presented in this thesis should include:

- The analysis presented in Annex 1 could be easily extended not only to the analysis of other case studies of industrial symbiosis in collaboration with the Italian SUN Network, but also to mixes containing concrete made with RAP (RAP – CON). This type of analysis will be carried out in the framework of the research project granted by Fondazione Cariplo (i.e., circular economy for a sustainable future, call 2019) entitled "Sustainable concrete made with recycled asphalt pavement" (RAP CON 2020 – 2023);

- The algorithm of prioritization of waste prevention projects (Annex 2) should be promoted and the political institutions should invest in implanting a specific monitoring system, also able to reveal potential integration of WP strategies with other policy areas. Despite being very difficult to monitor, the waste prevention should be also promoted within national and regional waste management plans. This type of analysis should be carried out in collaboration with the Italian LCA Network and the working group – “Gestione e Trattamento dei rifiuti”;

- The implementation of the re - usability indicator (Annex 3) within the framework of the waste management plan, which means that policy - makers could monitor not only the potential impacts of the waste collection and recycling strategies, but also the potential impacts of the reuse strategy on the municipal solid waste management system. As preparation for reuse can have benefits not only for waste collectors but also for local authorities and managers, future research study is needed to simplify and test the reusability indicator in a first stage of assessment and when researchers or Life cycle thinking experts are not present. This type of analysis should be carried out in collaboration with the Italian LCA Network and the working group – “Gestione e Trattamento dei rifiuti;

- The analysis presented in Annex .4 of Chapter 4 could be easily extended not only to the analysis of other ergonomics aspects (e.g., high repetitive tasks, collection frequency, job rotations) but also to the analysis of the environmental influencing factors such as transportation, and waste collection vehicles in a life cycle perspective. The Life Cycle Assessment tool could evaluate the environmental impacts of the waste collection system coupled by the socio-economic analysis of the impacts on the users e.g., household. This type of analysis will be evaluated in collaboration with the Geovest firm.

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