Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 98 (2021) 235–240

www.elsevier.com/locate/procedia

28th CIRP Conference on Life Cycle Engineering

Comparative LCA of Municipal Solid Waste Collection and Sorting Schemes Considering Regional Variability

Selin Erkisi-Arici[a]*, Johanna Hagen[a], Felipe Cerdas[a], Christoph Herrmann[a]

[a]*Chair of Sustainable Manufacturing & Life Cycle Engineering, Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig, Langer Kamp 19b, 38106 Braunschweig, Germany*

* Corresponding author. Tel.: +49-531-391-7602; fax: +49-391-5842. *E-mail address:* s.erkisi@tu-braunschweig.de

---

Abstract

Plastic packaging brings safety, hygiene, and comfort to the consumers; however, they also bring a massive problem to the society and to the environment – plastic waste streams. Approximately only one-third of plastic waste is transformed into new recycled goods whereas the rest is incinerated, sent to landfills or, end up in the environment. Therefore, proper management of plastic waste streams has great importance from social, political, and environmental perspectives. Recycling is promoted among the solid waste hierarchy as the most preferred option after waste prevention and reduction. However, only a holistic approach can reveal the advantages, the disadvantages and the hotspots of the waste management structures. Life cycle assessment is a powerful method to understand the environmental impacts of recycling routes. Reaching the end of use and leaving the households, plastic waste undergoes a serial of processes until the recycling facilities. These pre-treatment steps are characterized by a high variability due to technological factors such as collection and sorting scenarios, and spatial factors such as the distance driven by the waste trucks or the electricity mix. This paper investigates (i) the possible advantages of bring point collection compared to door-to-door collection system and (ii) the influence of relevant regional issues. The overarching goal of the study is setting the boundaries to secure an environmentally meaningful chemical recycling process and to quantify the environmental impacts related to the background systems. A comparative LCA is performed to evaluate both systems and subsequently, the influence of regional varying elements is tested through sensitivity analysis. These analyses include different scenarios where the collection, transport and sorting practices are at the scope. The results reveal the advantages of source separation and the importance of regional aspects in LCA modeling.

Keywords: plastic waste; source separation; life cycle assessment (LCA); background systems

---

1. Introduction

Plastics are indispensable for packaging purposes, enabling storage of fresh food with the aid of temperature and atmosphere controlled packaging options. Besides providing health and safety in food and water packaging applications, plastics offer ease in manufacturing and installation of water control and distribution facilities [1]. In addition to the advantages that plastics provide, plastic waste streams are also the source of a massive problem to the society. Increasing production and utilization of plastics leads to an extended volume of municipal solid waste [1]. Reaching a global amount of 359 million tons, 17% of global production takes place in Europe [2]. Recycling, when reuse is not possible, is the only end-of-life option that enables waste products entering back into the supply chain [5]. In Europe, only 27,1 million tons of plastic is recovered and only 31% is efficiently recycled into new products [3]. Even though recycling is promoted among the EU waste hierarchy and the most preferred option after waste prevention and reduction, approximately 70% of European plastic waste is nowadays sent to landfill (27%) or incineration facilities (42%) [3], [4].

10.1016/j.procir.2021.01.036

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

Mechanical recycling is a state-of-art recycling technique for plastic waste, which is melting the plastic by type and reprocessing into recycled products. However, it requires pure mono-material streams, which makes it inapplicable for mixed plastic waste or multi-layer segments [6]. Besides mechanical recycling, emerging chemical treatment technologies aim to obtain fuel additives from plastic waste or to transform plastic waste into added-value chemicals [7]. No matter which recycling option is preferred, collection and sorting of waste is an inevitable step to secure proper waste stream as input for recycling processes. Like the recycling processes, sorting and collecting activities release emission as well. Systematic approach is essential to evaluate the environmental impacts of all related processes and the superiority of one option to another.

Life Cycle Assessment (LCA) is a systems analysis methodology for the assessment of environmental impacts of the product systems on a life cycle perspective [8]. LCA is a widely preferred methodology to assess waste management systems due to its comprehensiveness in terms of its life cycle perspective and including environmental aspects. This property of LCA enables to consider environmental impacts of variable production systems with numerous unit processes, including emissions taking place in different time and place [9]. LCA is adopted to assess the environmental performance of collecting and sorting activities in the scope of this paper. The primary goal of practicing this study is setting the boundaries for an environmentally meaningful chemical recycling process aiming to unfold the regional dependencies of the technical infrastructure.

This paper aims to present an understanding of the environmental burdens related to the background processes: collection, transportation, and sorting. Besides, their sensitivity to the regional differentials is investigated in more detail. Apart from these, the motivation of the paper is to enlighten how far the performance of these processes is essential for the implementation of a novel chemical treatment process for plastic waste streams and to investigate their significance on waste management decision-making schemes and the circularity of recyclable materials. Therefore, the conclusion intents to inform the decision-makers and motivate them for adopting corrective actions to promote their recycling strategies.

2. Environmental Relevance of Sorting, Collection, and Transport Systems

Sorting, collection and transport systems belong to the background systems, where the unit processes directly linked to the recycling activities are researched as the foreground systems in LCA terminology of End-of-life (EoL) studies. Sorting, collection and transport systems have a direct influence on the environmental performance of recycling / disposal activities through the emission originating from the activities involved. They also have an indirect influence by affecting the reprocessing quality, enabling an acceptable input for following treatment steps [10]. Therefore, these systems deserve focus in terms of environmental performance of EoL systems.

Variety of collection and sorting mechanisms exist in waste management literature. However, lack of common definitions make it complex to discuss waste systems and to compare different mechanism with one another [11]. In Table 1, definition for two systems which are at the focus of this paper, bring systems and door-to-door service types, is presented as adopted from Rodrigues and colleagues [11].

Table 1. Definitions for different type of services [11]

Service type	Definition
Door-to-door (also full service collection, curbside, alley pick-up or household containers)	Containers like bins, racks, sacks and bags are allocated to individual families, very near to the source of waste generation, where the homeowner is responsible for placing the containers to be emptied at the curb on collection day and for returning the empty containers to their storage location
Drop-off systems or bring systems	Provides containers of different sizes and shapes, and residents are required to deliver recyclables

Local authorities and municipalities mainly develop collecting and sorting strategies. Different residential units may have different collection & sorting mechanisms. Sweden, for example, separates 10 different waste streams [12]. Dahlén and colleagues give projection about the efficiency of adopted waste collection services in six municipalities of Sweden [12]. The article highlights the benefits of door-to-door collection in terms of increased recycling rates and shows even higher rates are achievable when biowaste is separately collected. It also underlines that it is hard to make conclusions due to high uncertainties and practical problems in data collection of waste compositions [12]. Larsen and colleagues display a comprehensive study about the environmental and economic analysis of the waste collection system in Denmark and underline the higher performance of curbside collection compared to drop off system. Considering the avoided incineration and the amount of recovered material due to higher recycling rates, environmental impacts, and extra investments from collecting and sorting activities pay off [13].

BiPRO with the cooperation of Copenhagen Resource Institute publishes a report on a systematic assessment of collection schemes in 28 capitals of the EU. The findings of the report indicate the collection of recyclable materials when the door-to-door collection system is introduced. This system also provides not only the highest recycling rates but also the highest quality. The higher recycling rate and the increased quality offsets the higher economic costs. The results also show that bring point collection system falls short in terms of encouraging citizens to separate and bring their waste to the defined collection points [14]. Garcés and colleagues, who studied the sociodemographic parameters of participation in waste separation, confirms the latter with their research [15].

Iriarte and colleagues study the environmental impacts of three different selective collection systems of municipal solid waste. The study evaluates urban and inner-city scenarios separately concluding that the multi-container system has the least impacts in the urban collection, while the mobile pneumatic has the highest. Furthermore, the authors find out that the door-to-door system releases higher energy demand due to the increased driving distances and time. The paper drives the conclusion that the transport distance for collection is a crucial parameter for finding out the best environmental choices. The study does not cover the possible impacts of recycling [16]. Bovea and colleagues study the alternative municipal solid waste management systems in Spain and present a comprehensive analysis of existing structure with scenario evaluation, including sorting and collecting, and material recovery [17].

3. LCA of Sorting, Collection and Transport Systems

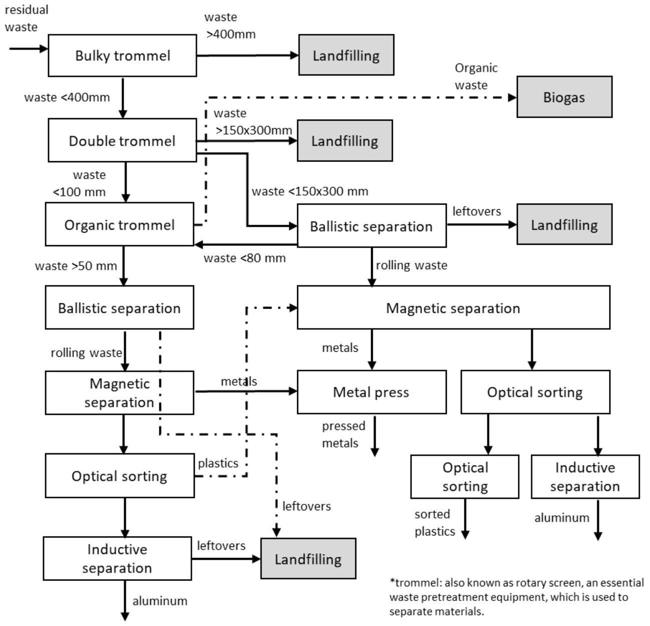
Collection and sorting systems are essential and important parts of waste management practices. A well-established collection system increases the performance of the sorting facility, which achieves a convenient waste stream for recycling activities, a waste flow in high amounts, and low contamination [14], [18]. A comparative LCA study is performed to assess the environmental impacts of two different scenarios: (1) bring point system (also known as "selective collection system" which is the service provided by Zaragoza Municipality - geographical focus of this study), (2) the door-to-door collection system and to test their sensitivity to regional changes.

3.1. Scenario Definition

Selective Collection System: Zaragoza city established a collection and sorting mechanism and name it as "selective collection system" in 2009 for the acquisition of recyclables [19]. The service system complies with the service type of bring points as described in Table 1. The waste, originating from private households and industries in the residential area, consists of every type of waste material while there are no regulations concerning insertion (called as *residual waste* in the rest of text). The consumers bring their waste to the containers at the public collection points. Next to the waste containers, the city provides separate containers for paper, light packaging, and glass waste (called as *separated waste* in the rest of text) [20]. The separately collected wastes from these containers follow a different sorting line. Both collection points are emptied by the trucks of the waste management services.

Residual waste and separated waste are delivered separate sorting lines, which consist of various equipment that works with high-energy demand, trammeling, delivering, or with the magnetic field. However, *separated waste* follows a shorter system, since less effort is required as a result of source separation [21]. A simplified flow diagram, representing the sorting line of *residual waste* is presented in Fig. 1. The materials that are suitable for recycling from both lines are sent to material recovery facilities and the rest ends up in landfills [22]. The waste streams after sorting processes follow treatment procedures. This scenario, which aims to reflect the current situations, indicates 36% landfilling, 10% incineration, 32% composting and 22% recycling [19], [22].

Door-to-door scenario: In door-to-door scenario, the waste, either separated waste or comingled, *residual* or *separated*, is picked up from households (as described in Table 1). Therefore, the trucks need to drive increased distances. Assuming the door-to-door scheme requires an increased amount of inner-city transport for the collection phase, the effort related to the collection phase is increased in the comparative scenario. On the contrary, decreased work load is assumed for sorting phase, since higher amount of recyclables are separated at source [14].



*trommel: also known as rotary screen, an essential waste pretreatment equipment, which is used to separate materials.

Fig. 1 Simplified diagram of sorting line

This scenario aims at representing an improved mechanism of collecting and sorting in terms of the amount of collected recyclables. To represent a better case, capture and recycling rates of Ljubljana are adopted for this scenario, since beyond 28 EU capitals, it has the highest capture score. Ljubljana has only 40% residual waste and 60% capture rate from the separate collection. The recycling rate for the city is 39,5% [14]. Therefore, recycling rate increases from 22% to 40%, where landfilling decreases to 18% for the modeling purposes of the door-to-door scenario. The ratio between residual waste and separated waste is also adopted as in Ljubljana case. However, the composition of sorting and treatment lines and the composition of recovered material kept as basis scenarios, since they are developed using the demographic information.

3.2. Goal and Scope Definition

The goal of this LCA study is to compare the potential environmental impacts of two different sorting and collection systems. The researched system boundary starts with the generation of waste, followed by collection and transportation, sorting of waste and ends with the treatment phase. Fig. 2 displays the system boundaries for the researched system. For both scenarios, the life cycle phases are the same; however the collection services, the distribution of waste between sorting and treatment lines differ. The temporal representation of the system is 2013-2019, since the data is available for these years. Zaragoza, Spain is the geographical representation of the study.

Functional unit is defined as the collection, sorting, transportation, and treatment of 100 tons of municipal solid waste for the simplicity in calculations and for providing a better understanding of the results.

The selected environmental indicators for this study are Global warming potential (GWP), Acidification potential (AP),

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

and Eutrophication potential (EP), using CML methodology. In addition, an endpoint indicator from methodology ReCiPe is included to evaluate the fossil depletion. The related impact categories display the highest relevance with the researched systems and comply with the existing literature. Besides, GWP is mainly dominated by electricity usage and relevant for the sorting phase where fossil depletion reflects the influence of fossil fuels usage and mainly relevant for the collection and transport phases. Display of these two categories aims at underlining the problem shifting between two life cycle phases.

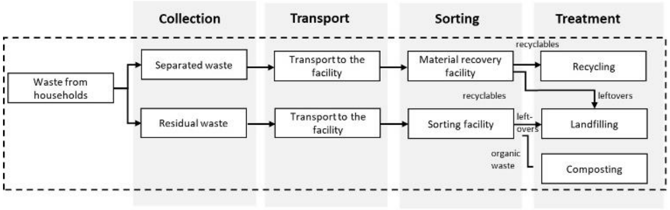


Fig. 2 System boundaries

3.3. Life Cycle Inventory

Demographic and geographical data are gathered from the documents provided by the municipality, a cluster approach is developed to estimate the performance needed to collect the dropped waste and to transport the collected waste. Clusters represent different regions of the municipal city of Zaragoza and have different values of population, the number of bins and containers, waste amount, and proximity to the waste treatment facility. This approach eases estimating total distances driven and effort for carrying waste for collection and transport phases and maximizes the proximity to the real situation. An assumption is made to estimate the waste composition of Zaragoza, based on the given data for Spain, Aragona and, Zaragoza in previous years [20], [23]. Municipal solid waste collection service by Ecoinvent database is adopted for LCA modeling of collection and transport systems. The dataset is established for a 21 metric ton lorry, with an assumption of a vehicle lifetime of 540.000 vehicle-kilometers. Based on the geographical data, two separate collection and transport lines are modeled; one for separate collection system *(selective collection system)* and one for *the residual waste*. Collection model represents emptying process of containers and bins, where transport model represents the transport of collected waste to the waste management site. Table 2 displays the data used in modeling.

Table 2 Geographical and demographical data for LCA modelling

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Population	209.991	107.439	145.291	138.946	100.759
Area of region [m2]	7	260	123	232	346
Number of containers	1.455	745	1.007	963	698
Number of bins	1.532	784	1.060	1.014	735
Distance to the plant [km]	15	13	16	27	23

Sorting line modeled using the declared information of waste management website of municipality [22]. The manufacturers' declaration for technical information such as; power, capacity is taken as a basis for the calculation of energy consumption of sorting equipment [24]. Ecoinvent dataset for Spanish electricity mix is adopted to model the energy consumption of the equipment. The reports published by city council is taken as basis for the treatment phase; the ratio of recycling, landfilling or composting and Ecoinvent database is used for modeling EoL treatment; composting, landfilling and incineration.

3.4. Results of Comparative LCA

This section displays the comparative results of two collection schemes: selective collection system and door-to-door collection system. Fig. 3 shows the results in selected impact categories. The selective collection system has lower environmental impacts in the collection phase, in all categories due to the decreased distances driven by trucks. However, the door-to-door collection system displays lower impacts at sorting phase in all categories except GWP because of the decreased workload in sorting phase. The door-to-door collection system is also advantageous in terms of decreased landfills, which lowers the impacts in treatment phase in all the selected categories.

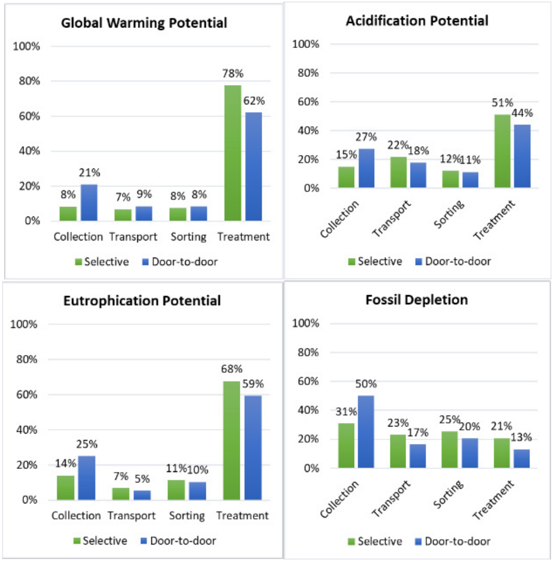


Fig. 3 Results in selected impact categories

In cumulative evaluation, a decrease in the treatment phase pays off the increase in the sorting phase for GWP and the door-to-door collection system displays a 21% decrease compared to the basis scenario. However, this does not apply to the other impact categories and the door-to-door scenario presents 9%, 12%, 23% increase in AP, EP, and fossil depletion categories.

3.5. Sensitivity Analysis through the Variation of Geographical Characteristics

3.5.1. Collection Phase – Influence of Inner-city Transfer

The inner-city distance driven defines the environmental burden for collection phase. Since the distances are defined

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

based on the demographical/geographical assumptions, it makes sense to test the model sensitivity by changing these values. The distances are reduced by 75%, 50% and, doubled in both scenarios to see how the model reacts to these variations. An overview of results is shown in Fig. 4.

As expected, increased inner-city traffic leads to increased environmental impacts in every selected impact category. The door-to-door scenario has a higher impact in all categories, except GWP, compared to the selective collection scenario when no change in inner-city distances are considered. Contrary, scenarios with decreased distances in the door-to-door system perform better in all impact categories. Based on these results, it can be argued, for the small residential areas, the door-to-door system can be a good replacement as a collection service. For doubled distance in the door-to-door system, no improvement in environmental impact categories is observed. However, this version still displays lower GWP values, when compared to the other scenarios.

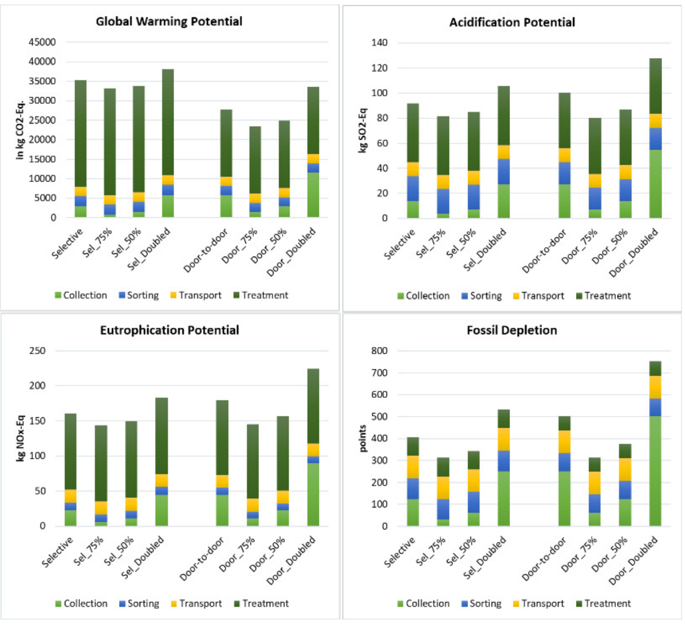


Fig. 4 Sensitivity analysis – influence of inner-city distances

3.5.2. Sorting Phase - Influence of Electricity Mix

Fig. 5 displays the result of sensitivity analysis with varying electricity mix for sorting line. Selective collection scenario is modeled with using electricity mix for Spain since the studied chemical recycling process is planned to be in Spain. As a sensitivity analysis, Norwegian and Polish mixes are replaced to see how the environmental burdens change with varying electricity mixes. Ecoinvent electricity mix datasets are used for scenario modeling. To see if fewer burdens related to the electricity mix can pay off the rising environmental impacts in the sorting phase.

A cleaner electricity mix can lower the impacts related to the sorting phase. For GWP, the advantages in the door-to-door scenario are almost lost with Polish electricity when compared to basis scenario. This means the environmental advantages in the sorting phase do not pay off when the burdens related to electricity rises. A cleaner electricity mix reverses the ranking in AP and EP. However higher truck traffic still dominates the high burdens in fossil depletion in each scenario of door-to-door, whether lower or higher the emissions from electricity are.

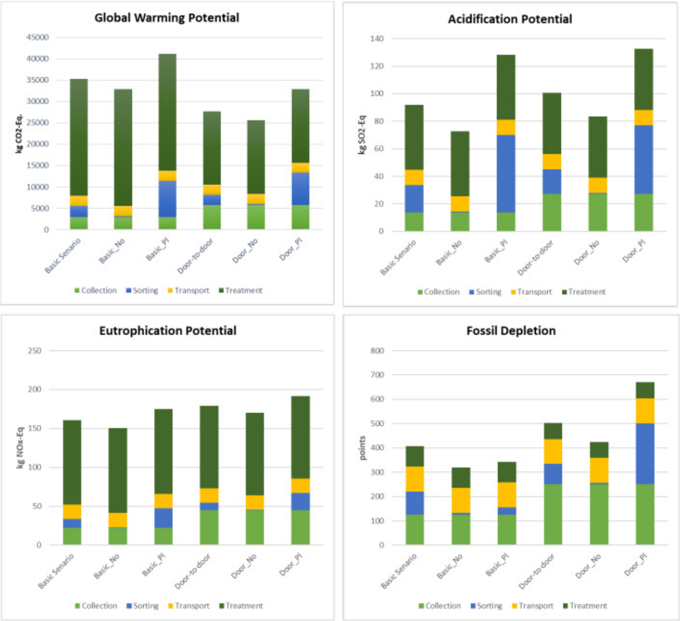


Fig. 5 Sensitivity analysis – influence of electricity mixes

4. Critical Discussion and Outlook

The results display the environmental performance of two different collections and sorting mechanisms in selected impact categories and show off the regional dependencies through the sensitivity analysis. Selective collection scenario performs better in AP, EP and, fossil depletion. This is due to the increased inner-city traffic, emissions from the trucks driven. The decreased energy consumption in the door-to-door scenario does not pay off in the categories rather than GWP.

Reduced inner-city distances carry door-to-door scenario to an advantageous state since it presents fewer burdens in the sorting phase, which is related to the electric usage. The selective collection system may present a more sustainable choice for the cities with larger geographical areas and lose its advantages to the alternatives when city borders get smaller.

Similarly, different electricity mixes influence overall results. A mix with lower environmental impacts reimburses the additional burdens related to the truck traffic and change the ranking of scenarios. A residential unit, which uses fossil fuel dominant electricity, may revise the decision of the collection system. Since the high amount of commingled waste leads to increased effort in the sorting phase, therefore higher energy demand. In this case, additional emissions from the collection phase are not tolerated and they become critical for the overall environmental performance of the system.

A trade-off between collecting and sorting phase exists in each sensitivity test. This expresses, the optimum strategy is always case dependent and each variable should be included for a sustainable management of waste. All findings related to this study are specific to the selected case, selected residential

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

area and selected system boundaries. Under different circumstances, such as different electricity mix, technology readiness level, recycling rates, waste amount and composition, different geography or demography, results can be in favor of completely different scenario. Besides the system conditions, lack of data also influence and create volatility in results. The statistics from institutions' declaration or the data from the literature may not match with each other. Assumptions have to be made in this case, which creates other uncertainties.

There are other influencers, which may dramatically change the scoring in scenarios. Sort of trucks that are used in the collection and transport system, the type of fuel that they use, or the load factor, the geography of transport roads, the distance of waste management site, the technical properties of charging and, emptying of trucks are the elements which should be considered. Testing the influence of these variables may be another research topic for the future.

Collecting and sorting influence the environmental performance of waste management systems not only achieving the introduction of waste material into recycling systems but also through the emissions caused by its own activities. For the future studies, an additional scenario can be modeled to integrate the environmental credits from material recovery activities.

Waste management systems are complex systems. LCA studies display complex results though. It is crucial to create versatile modeling methodologies, which adopts an integrating approach. To generate results from LCA that can serve in decision-making processes, a holistic view should be costumed, not focusing on just the treatment phase but starting from the very beginning where waste is generated and consolidating every dependency at the background system which may influence the output.

Acknowledgements

This project received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820770. The authors would also like to thank to the collaboration partners within the project.

References

[1] A. L. Andrady and M. A. Neal, "Applications and societal benefits of plastics," pp. 1977–1984, 2009.

[2] Plastics Europe, "Plastics – the Facts 2019," 2019.

[3] E. MacArthur, D. Waughray, and M. Stuchtey, "Rethinking Plastics, starting with packaging," *World Econ. Forum*, pp. 1–206, 2016.

[4] European Commission - Joint Research Centre - Institute for Environment and Sustainability, *Supporting Environmentally Sound Decisions for Waste Management*. 2011.

[5] M. F. Ashby, "End of first life," in *Materials and the Environment*, 2013, pp. 79–97.

[6] K. Ragaert, L. Delva, and K. Van Geem, "Mechanical and chemical recycling of solid plastic waste," *Waste Manag.*, vol. 69, pp. 24–58, 2017.

[7] S. M. Al-Salem, A. Antelava, A. Constantinou, G. Manos, and A. Dutta, "A review on thermal and catalytic pyrolysis of plastic solid waste (PSW)," *J. Environ. Manage.*, vol. 197, no. 1408, pp. 177–198, 2017.

[8] International Organization for Standardization, "ISO 14044: Environmental management - Life cycle assessment - Requirements and Guidelines," Genova, Switzerland, 2006.

[9] M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, *Life Cycle Assessment - Theory and Practice*. Springer, 2018.

[10] J. N. Hahladakis and E. Iacovidou, "An overview of the challenges and trade-offs in closing the loop of post-consumer plastic waste (PCPW): Focus on recycling," *J. Hazard. Mater.*, vol. 380, no. February, p. 120887, 2019.

[11] S. Rodrigues, G. Martinho, and A. Pires, "Waste collection systems. Part A: a taxonomy," *J. Clean. Prod.*, 2016.

[12] L. Dahlén, V. Sanita, M. Jan-Arik, and L. Anders, "Comparison of different collection systems for sorted household waste in Sweden," *Waste Manag.*, vol. 27, pp. 1298–1305, 2007.

[13] A. W. Larsen, H. Merrild, J. Møller, and T. H. Christensen, "Waste collection systems for recyclables : An environmental and economic assessment for the municipality of Aarhus (Denmark)," *Waste Manag.*, vol. 30, no. 5, pp. 744–754, 2010.

[14] BiPRO/CRI 2015, "Assessment of separate collection schemes in the 28 capitals of the EU, Final Report," 2015.

[15] C. Garcés, A. Lafuente, M. Pedraja, and P. Rivera, "Urban waste recycling behavior: Antecedents of participation in a selective collection program," *Environ. Manage.*, vol. 30, no. 3, pp. 378–390, 2002.

[16] A. Iriarte, X. Gabarrell, and J. Rieradevall, "LCA of selective waste collection systems in dense urban areas," *Waste Manag.*, vol. 29, no. 2, pp. 903–914, 2009.

[17] M. D. Bovea, V. Ibáñez-Forés, A. Gallardo, and F. J. Colomer-Mendoza, "Environmental assessment of alternative municipal solid waste management strategies. A Spanish case study," *Waste Manag.*, vol. 30, no. 11, pp. 2383–2395, 2010.

[18] A. Frane *et al.*, "Collection & recycling of plastic waste - Improvements in existing collection and recycling systems in the Nordic countries," 2014.

[19] S. Zaragoza Ayuntamiento, "Waste Production and Management," 2016.

[20] City council of Zaragoza, "Observatorio Municipal de Estadística," 2019. [Online]. Available: http://demografia.zaragoza.es/. [Accessed: 19-Jun-2019].

[21] City Council of Zaragoza, "Zaragoza Limpia," 2019. [Online]. Available: https://www.zaragoza.es/sede/portal/medioambiente/residuos/recogida/recogida. [Accessed: 19-Jun-2019].

[22] Zaragoza Urban Waste Treatment Complex, "Urban Waste Treatment Complex, Facilities and Processes," *Zaragoza City Council*. [Online]. Available: https://www.zaragozarecicla.org/el-ctruz/instalaciones-y-proceso/. [Accessed: 26-Jul-2020].

[23] City council of Zaragoza, "Cifras de Zaragoza: Datos demograficos del padron municipal," Zaragoza, 2016.

[24] Groundsailer Media, "Recycling Inside," 2020. [Online]. Available: https://recyclinginside.com/about-recyclinginside/.

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.