LIFE CYCLE SUSTAINABILITY ASSESSMENT OF DECENTRALISED COMPOSTING OF BIO-WASTE: A CASE STUDY OF THE ŁÓDŹ AGGLOMERATION (POLAND)

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Abstract: The study examines the concept of decentralised composting of bio-waste as an alternative approach to current waste management practices, using the Łódź Agglomeration (Poland) as an exemplary case study. Consequently, the aim of the presented research is to compare and discuss the sustainability of the functioning bio- waste management system (status quo) against an alternative solution based on decentralised composting. Combined application of process-based life cycle assessment (LCA) and life cycle cost analysis (LCCA) was selected as the methodology to compare the sustainability framework for the waste management practices under analysis. The study has made it clear that decentralised composting of bio-waste offers broader environmental, economic and social benefits, albeit with the level of that benefit being very much correlated with the type of local government area (commune or in Polish *gmina*). Regardless of the impact category, rural and urban–rural *gminas* achieved the greatest savings, reaching >90%, and thus are seen to offer the greatest potential for decentralised composting to be put into effect, on the basis of household/backyard composting. In consequence, decentralised composting can constitute a fundamental form of bio-waste management in 20 out of the 28 *gminas* of the Łódź Agglomeration. The results obtained from the research facilitate the implementation and wider utilisation of decentralised composting, as an important element of the transition to a circular economy, where bio-waste is concerned.

Keywords: life cycle assessment, waste flow, bio-waste, circular economy, sustainability, Poland

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Introduction

Waste management is an important topic in the context of European Union policy and business but is first and foremost a quality-of-life and environmental improvement issue. The associated problem of waste generation qualifies as a problem of national or even global rank (Łuniewski 2015). In the geographical context, many publications relate to the waste generation process (Malinowski et al. 2009a; Malinowski et al. 2009b), waste transport optimisation (Badran, El-Haggar 2006; Ghose et al. 2006; Malinowski, Woźniak 2011) or waste flow analysis (Binder,

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Mosler 2007). Further publications include comparative analyses of the waste management system in Poland and other EU countries (Plewa et al. 2014), the planning of waste management (Contreras et al. 2008; Demirbas 2011) and the optimisation of waste management (Nema, Gupta 1999; Noche et al. 2010). In the 2000s, much space in the literature was devoted to decision-making models (Fiorucci et al. 2003; Hung et al. 2007; Abelioitis et al. 2009). In general, work focuses on the optimisation of the waste management systems (by reference to supply and processing), with GIS tools being used, most often in relation to a selected region. In recent years, multidisciplinary research devoted to both spatial analyses and waste management issues has become more popular (Mazurek, Czapiewski 2021). The latter authors, *inter alia*, demonstrate that strategic planning at regional level, combined with social participation at local level, can bring tangible benefits in the form of more effective planning of the waste flow in a large area managed by many independent units (e.g. municipalities).

Waste management studies were performed as early as the 1980s. Polish researchers then looked at possibilities for waste to be re-used and used the term 'circular economy'. Important works in this area were published by geographers, among others, relating in this way to the fields of protection of the human environment (Leszczycki 1974; Kamiński, Szyrmer 1981a), models of waste flows (Kamiński, Szyrmer 1981b) or waste-free management in the context of waste-free technologies – 'tbo' (Cała 1985).

Currently, the principles of the circular economy model gain common recognition and application in the development of waste management (e.g. Tundys 2015; Szyja 2016; Turoń, Golba 2016; Pieńkowski, Kośmicki 2016). Much attention has been paid to this issue in the world literature (e.g. Lacy, Rutqvist 2015; Haas et al. 2015; Singh, Ordoñez 2016; Tisserant et al. 2017; Malinauskaite et al. 2017; Winans et al. 2017 and many others). The development of research devoted to this topic is, on the one hand, a reflection of technological progress in the field of waste management and processing, resulting in new products (recycling) and, on the other hand, a consequence of the activities of pro-environmental communities, which had a significant impact on the introduction of this concept into the scientific discourse.

A key relevant change in Polish law was the Waste Act of December 14, 2012 (with subsequent amendments in the Waste Act of November 17, 2021). More broadly, the member states of the European Union should, *inter alia*, in accordance with the Directive of the European Parliament (Directive 2008/98/EC with subsequent amendments – Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste), strive to move from a linear economy system to a circular economy model. In line with these guidelines from the EU, Polish regulations introduce a list of processes aimed at reducing the amount of waste generated and ensure most effective waste management. The following objectives can be found in the legal provisions, as arranged into the waste hierarchy of (1) waste prevention; (2) preparation for re-use; (3) recycling; (4) other recovery processes, e.g. energy recovery; and (5) disposal (the Waste Act of December 14, 2012).

The authors of this article seek to examine a solution that is based on decentralised composting, and this places particular emphasis on points 2–4 of the waste hierarchy. As, in the view of the author, there is room to implement some alternative solutions to the problem of waste generation, the research work described here has explored the role of decentralised composting as an alternative to current practices in bio-waste management. The potential advantage of the decentralised composting system for bio-waste over the current solution is not so obvious. It seems that composting waste for re-use by its producers is an ecological and economic solution. The concepts of system decentralisation may, however, differ both in technology and the scale of the project. Dulac (2001) argued that the operation of large plants composting waste from urbanised areas was much less efficient and less profitable than composting biowaste in rural areas directly by its producers (a case of India). There are several reasons for this state of affairs, and some of these arguments may also apply to Poland. The costs of running large installations as well as the costs of transport turned out to be disproportionate to the effects. Moreover, the treatment of low-quality bio-waste, often in a mixed form, is impossible or of little use for potential compost recipients, e.g. farmers (Zurbrügg et al. 2004). The literature review shows that the problem of bio-waste management is very complex since it depends on administrative, socio-economic, technological as well as geographical conditions related to, *inter alia*, population density, types of buildings and logistics.

On the other hand, however, decentralised composting of bio-waste might bring numerous benefits of an environmental, economic and social nature (Pai et al. 2019). Regarding sample environmental benefits, decentralised composting drastically reduces the transport of bio-waste for treatment, and hence the associated consumption of fuel and emissions of air pollution. As for the economic benefits, decentralised composting reduces the costs of collection and treatment associated with bio-waste. Additionally, a diversion of biowaste from centralised composting extends the life cycle of existing waste treatment facilities and reduces the need for new ones to be built (Drescher et al. 2006). Finally, as regards the social profits, decentralised composting reduces noise and odour during bio-waste collection, transport and treatment, decreases costs related to the chemical fertilisers purchase by citizens and finally reduces public space consumption by composting facilities (Platt et al. 2014).

The research involves the Łódź Agglomeration (Poland) as an exemplifying case study. This area is characterised by a diversified settlement structure; it includes vast urbanised areas of the city of Łódź, smaller towns as well as vast rural areas. This will allow for a comparative analysis of individual areas which, apart from geographical factors, are characterised by different approaches in the context of decision-making process (e.g. contracts' criteria) and implementation of the system of local fees. And, thanks to it offering a scientific basis for the decision-making process, the proposed sustainability framework can be used as a planning tool by which to address, define and improve bio-waste management.

The aim of the article refers to the sustainability analysis of the functioning bio-waste management system (status quo) against an alternative solution based on decentralised composting. The study is two-dimensional: the spatial dimension covers the issues of spatial differences in potential benefits or disadvantages, while the non-spatial dimension relates to general conclusions regarding changes in the entire waste management system.

The article is organised in the following manner: Section 2 outlines the materials and methods used for the present research, with particular focus on the approach applied to calculate the sustainability framework of bio-waste management. Section 3 presents the results of the sustainability assessment of bio-waste management in the Łódź Agglomeration (Poland). Subsequently, the achieved results and their implications are discussed in Section 4, followed by the conclusions and limitations in Section 5.

Materials and methods

The methodology chosen for the sustainability assessment is the process-based life cycle assessment (LCA), providing quantification of the environmental aspects and potential environmental impacts related to a given product system. The LCA methodology is structured along a framework that has become the subject of worldwide consensus and forms the basis of ISO 14040: 2006 and ISO 14044: 2006 standards (Rybaczewska-Błażejowska 2019). It is divided into four phases, namely, the goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006a; ISO, 2006b). Following the common practice in LCA of waste management, consequential modelling is applied, positing that the products generated alongside the treatment of bio-waste substitute the corresponding market products (Vadenbo et al. 2017). Due to the fact that LCA has an environmental and social centric approach, it was integrated with life cycle cost analysis (LCCA). LCCA addresses the aggregated costs related to a given product or process along its life cycle. Unlike in the case of LCA, no standards are published for LCCA.

Scope and functional unit

The research focuses on the management of bio-waste, understood as the vegetable, fruit and garden fraction generated by households in the Łódź Agglomeration (Poland). The system under study includes the following processes: collection, transport, treatment and the generation of substituting materials.

The geographical scope of this study encompasses the Łódź Metropolitan Area (in Polish

'Łódzki Obszar Metropolitalny' (ŁOM), albeit with the term Łódź Agglomeration used interchangeably in the article). It is located in central Poland and comprises a main communication hub located on axes in Poland running both north–south (between Gdańsk and Upper Silesia) and east–west (Warsaw and Poznań; Fig. 1). The ŁOM is made up of 28 units of local government (communes or from Polish *gminas*) falling with 5 higher-tier units at the county level known as counties: the city of Łódź, Brzeziny, Lodz East, Pabianice and Zgierz. The total population of the agglomeration is about 1.1 million. The largest city is Łódź itself (having nearly 700,000 inhabitants), as surrounded with medium-sized cities such as Pabianice, Aleksandrów Łódzki and Zgierz, as well as urban centres of local importance such as Stryków, Brzeziny, Ozorków, Tuszyn, Koluszki, Głowno and Andrespol. The studied area consists of 16 *gminas* assigned the 'rural' status, seven of which are 'urban' and five classified as 'urban–rural'.

The functional unit of this research is the collection, transport and treatment of 1 tonne of wet weight per year ($1\ t \times a^{-1}$) of bio-waste generated by households in the Łódź Agglomeration.

Inventory data

The inventory encompasses a set of site-specific data related to the management of bio-waste in the Łódź Agglomeration, involving quantities of vegetable, fruit and garden waste, as well as the transport and treatment thereof. To retrieve environmental information for background processes, including the fuel and energy consumption as well as the provisioning of resources, use was made of relevant databases, i.e. the *Ecoinvent* and *EASETECH* databases, consequential modelling.

Values for masses of vegetable, fruit and garden waste were derived from municipal waste management reports, which are developed

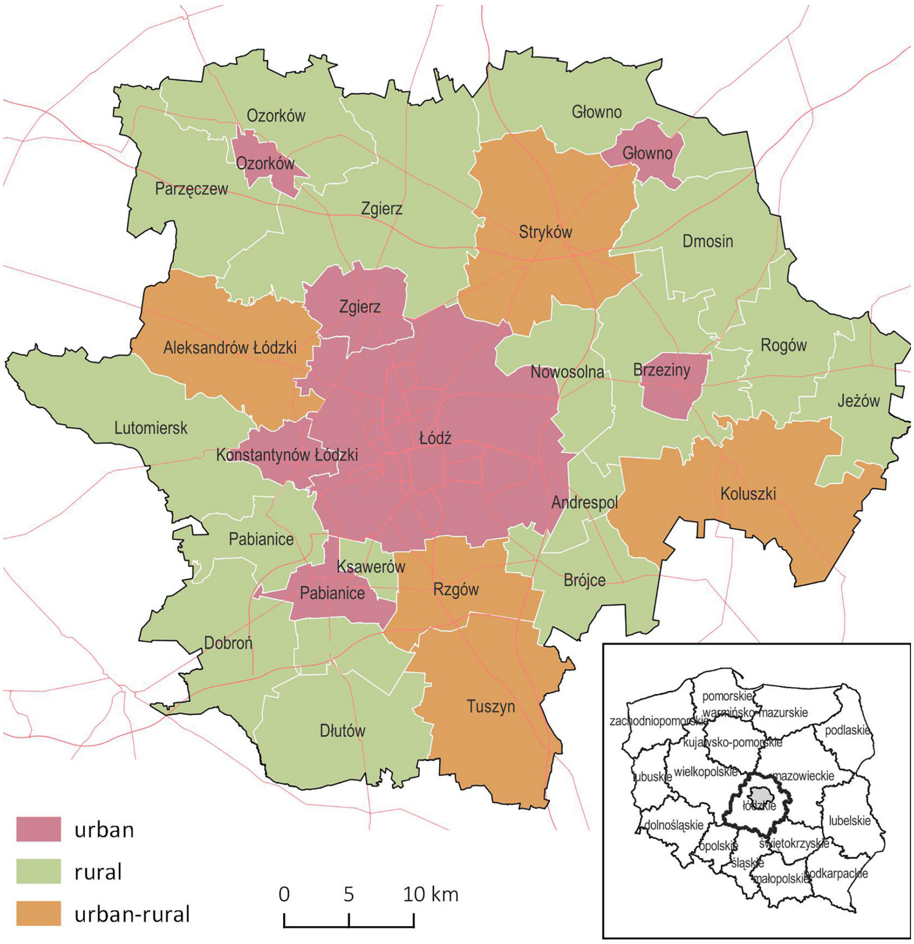

Fig. 1. The study area with its administrative division.
Source: authors' own elaboration.

annually by each *gmina* (local authority) within the Łódź Agglomeration (unpublished data). In total, there is 104,482.098 Mg of bio-waste produced in ŁOM, where 83,585.678 Mg constitutes vegetable and fruit waste and 20,896.42 Mg constitutes garden waste. In general, only 25.31% of bio-waste in ŁOM is source-separated, whereas the remaining 74.68% is collected as commingled municipal waste. In turn, datasets used as a proxy to model the chemical composition and physical properties of vegetable and fruit waste were derived from the database on food products, as described in Tonini et al. (2018). Information on the composition of garden waste was obtained from the *EASETECH* database.

Different approaches were applied for the modelling of the collection and transport of bio-waste. In any case, this depended upon a series of data being gathered concerning shares of separately collected vegetable, fruit and garden waste, distances travelled to waste treatment facilities and types of transport used in covering those distances. In essence, it was municipal waste management reports that were relied on (unpublished data), as well as spatial data prepared by reference to locations of waste management installations (address data). The locations in question were obtained via an address geocoding process, before transport paths were generated. A network analysis algorithm that determines the shortest path (point-to-point) using spatial data (road network from openstreetmap.org) was used to determine transport paths. Travel routes were calculated by reference to centroids of housing in municipalities as well as waste-management installations. The maximum travel distance was >84 km while average distance is equal to 48 km. Quantum GIS software was used in the data analysis. The other remaining missing information was retrieved from the EASETECH database.

Municipal waste treatment, including treatment technologies, was modelled using information provided in the waste management plan for the Łódź Voivodeship (Voivodeship Fund for Environmental Protection and Water Management, 2016), municipal waste management reports issues at *gmina* level (unpublished data) and finally the websites of individual waste management installations. According to information provided by individual facility managers

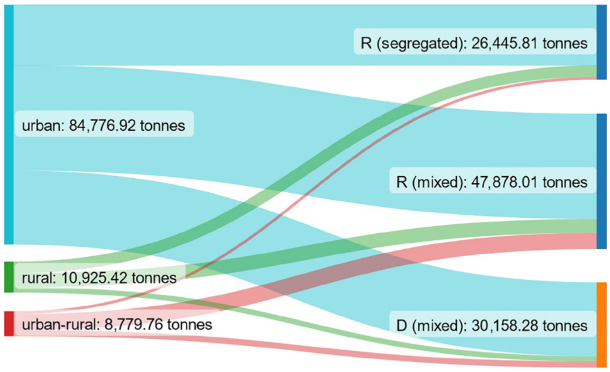

Fig. 2. ŁOM bio-waste flows by treatment and types of local government (*gminas*).
R – recycling/composting, D – disposal operations, ŁOM – *Łódzki Obszar Metropolitalny*
Source: authors' own elaboration.

and information from municipal reports, in the ŁOM area, bio- waste undergoes either recycling/reclamation of organic substances (including composting and other biological transformation processes; 20.6% of bio-waste) or disposal operations. Analysis of the processes shows that the quality of collected raw materials is low, which negatively affects the efficiency of their further processing. It can be assumed that bio-waste from households is a low-quality raw material due to problems associated with proper segregation by inhabitants. Individual waste quantities by process and origin are summarised in a Sankey diagram (Fig. 2). Despite the significant share of all bio-waste in the flow coming from cities, the amount of recycled waste is relatively small. In all types of municipalities, the majority of waste requires recycling processes; however, the share of waste subjected to 'R' processes in rural areas is relatively higher.

The map (Fig. 3) shows the sizes and directions of flows of bio-waste generated in the study area as well as maximum processing capacity (for composting) of the plants. The predominant share in the waste stream is that accounted for by installations located outside the agglomeration. As they choose a waste collector, local authorities are guided by the best price principle. This results in a large dispersion of the waste flow, no correlation between the mass of waste transported from a given *gmina* and the distance to the plant. Large biomass processing plants do not process the largest amounts of waste. There are several relatively small installations located on the outskirts of the region – Danielów, Kamieńsk and Dylów A; they collect large amounts of waste from the ŁOM, including from Łódź. However, operational expenditures (OPEXs) relating to waste transport and management are also important and vary significantly in line with the type of municipality (urban, urban–rural or rural). According to a report by *Deloitte* (2021), differences between types of municipalities may be as high as 50% when it

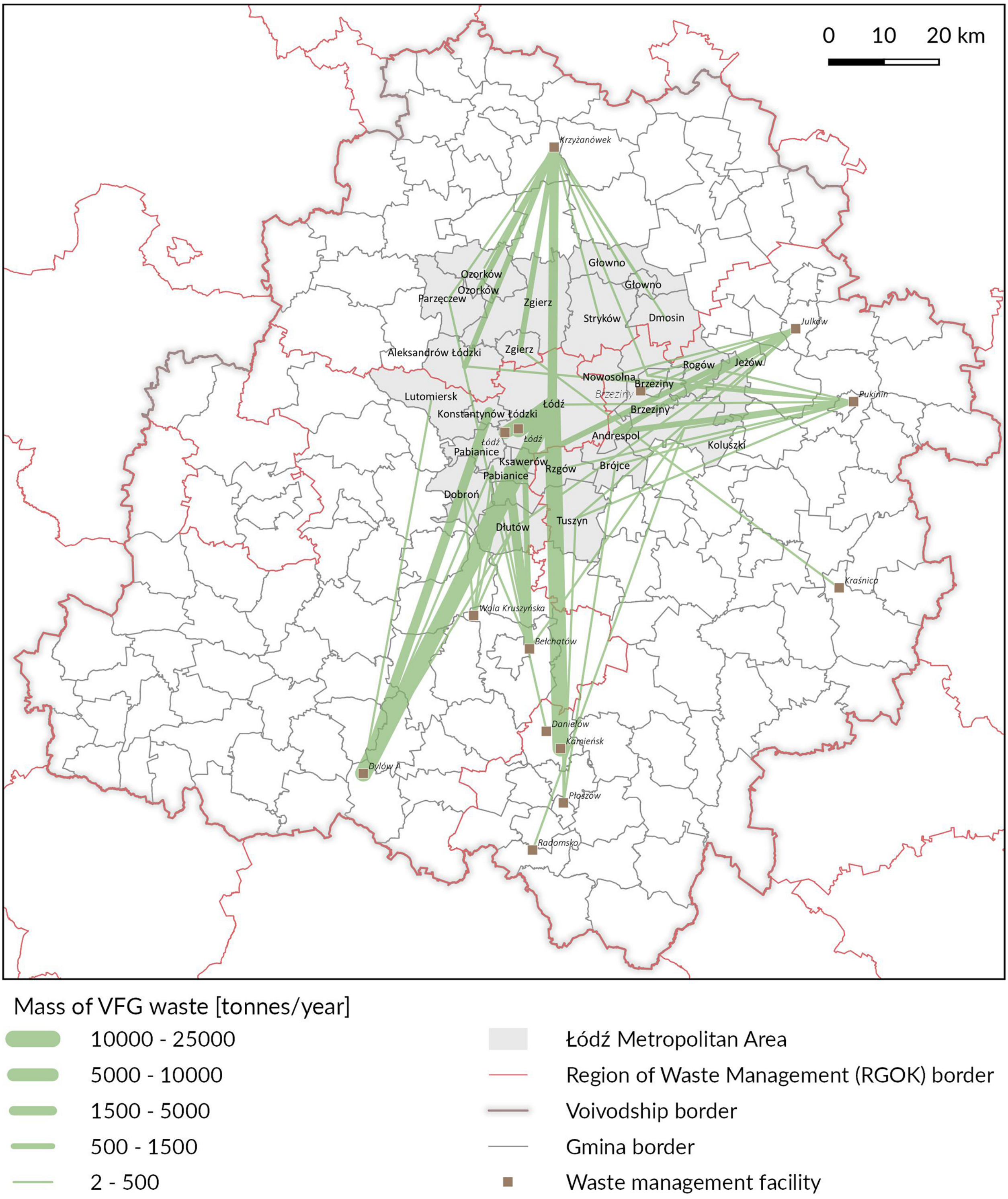

Fig. 3. Flows of bio-waste generated within ŁOM by way of road linkages.
ŁOM – *Łódzki Obszar Metropolitalny*; VFG – vegatable, fruit, and garden
Source: authors' own elaboration.

comes to the collection and management of waste of the type in question. Smallest amounts are not surprisingly characteristic of urban *gminas*, and largest amounts for those officially enjoying 'rural' status. This means that it is in particular in rural areas that it may prove possible to reduce the amount of bio-waste in the overall stream by way of on-premises composting.

Data assumptions in relation to the decentralised composting involve aerobic home composting of source-separated bio-waste for all households having private gardens. Additionally, it involves centralised anaerobic digestion of the remaining source-separated bio-waste from households without gardens. Considering the structure of the ŁOM (basically rural areas) and the types of buildings, it was estimated that the waste mass reduction (WR) indicator for bio-waste is equal to 19% (Tonini et al. 2020).

Impact assessment

The development of the sustainability framework and thus the impact assessment of bio-waste management in the Łódź Agglomeration was inspired by two research projects: *Application of life cycle assessment in integrated municipal waste management* – a DAAD-funded project (Schluchter, Rybaczewska-Błażejowska 2012), and *REPAIR* (REsource Management in Peri-urban AReas: Going Beyond Urban Metabolism) – an EU-funded project (Taelman et al. 2020). Both research projects have shown clearly that only the interrelation of environmental, economic and social sustainability makes waste management systems a truly responsible for current and future generations and thus is a global necessity.

Environmental sustainability is defined through two major objectives: the conservation of natural resources and a reduction in environmental pollution (Den Boer 2007). In the present context, economic sustainability is understood as such an integration of waste management options that allows them to be operated at a cost acceptable to the community. Finally, social sustainability requires such an organisation of waste management to be the most convenient for users to participate.

On the basis of the rational arguments given above, it was possible to identify a set of impact categories representing each pillar of the sustainability framework regarding the bio-waste management in the Łódź Agglomeration. The sustainability framework encompasses the following environmental, economic and social impact categories:

1. Environmental:
   1.1. Climate change (kg CO_2 eq)
   1.2. Eutrophication (freshwater) (kg P eq)
   1.3. Ecotoxicity (aggregated: terrestrial, freshwater and marine) (CTU)
   1.4. Land use (m^2 × year)
   1.5. Fossil fuel scarcity (kg oil eq)
2. Economic:
   2.1. Operational expenditure (OPEX) (PLN)
   2.2. Capital expenditure (CAPEX) (PLN)
3. Social:
   3.1. Human toxicity (aggregated: carcinogenic and non-carcinogenic) (CTU)
   3.2. Ozone depletion (kg CFC-11 eq)
   3.3. Particulate matter formation (kg PM2.5 eq)
   3.4. Tropospheric ozone formation (kg NO_x eq)
   3.5. Ionising radiation (kBq Co-60 eq)

The environmental- and social-impact categories are described with the reference to the midpoint-oriented ReCiPe method (Huijbregts et al. 2017). The only exceptions concern climate change, ecotoxicity and human toxicity, which were calculated in line with PEF recommendations, that is, as based upon IPCC and USETox models respectively (European Commission 2018). The assessment of economic impacts refers to OPEX and CAPEX. Operational costs (OPEX) are the costs associated with operating the waste collection and management system. This may include administrative expenditure, personnel maintenance, fuel, equipment and vehicle maintenance, property maintenance and other costs related to the activities of offices and companies dealing with waste collection and management. Such costs are covered by residents who are obliged to pay fees for waste collection; therefore, in order to calculate the operating costs for the bio-waste fraction, data on fees adopted in individual municipalities were used. Capital costs (CAPEX) are investment expenditures incurred in order to develop the waste management system in a given territory (in this case, in the area of *gmina*). Data on costs incurred by individual communes were obtained from the Local Data

Bank of Statistics Poland. The selection of impact categories representing each pillar of the sustainability assessment framework was limited by the availability of data at local level.

The inclusion of transdisciplinary impacts, spatial differences characterising the occurrence of impacts and finally the coupling of traditional environmental LCA with social and economic aspects ensures a comprehensive sustainability assessment where the management of bio-waste is concerned. Due to its complexity, the research was facilitated with the sophisticated *EASETECH* life cycle software (Clavreul et al. 2014).

Results

The sustainability framework for the management of bio-waste in the Łódź Agglomeration is presented in Figure 4, in relation to each of the impact categories. Positive values indicate burdens, and negative ones savings. In the analysis of results, the identified stages to waste management were collection, transport and processing, as well as products and processes avoided (in association with energy generation and compost production), and final landfilling processes.

The study estimated the environmental, economic and social savings from the decentralised composting of bio-waste in the Łódź

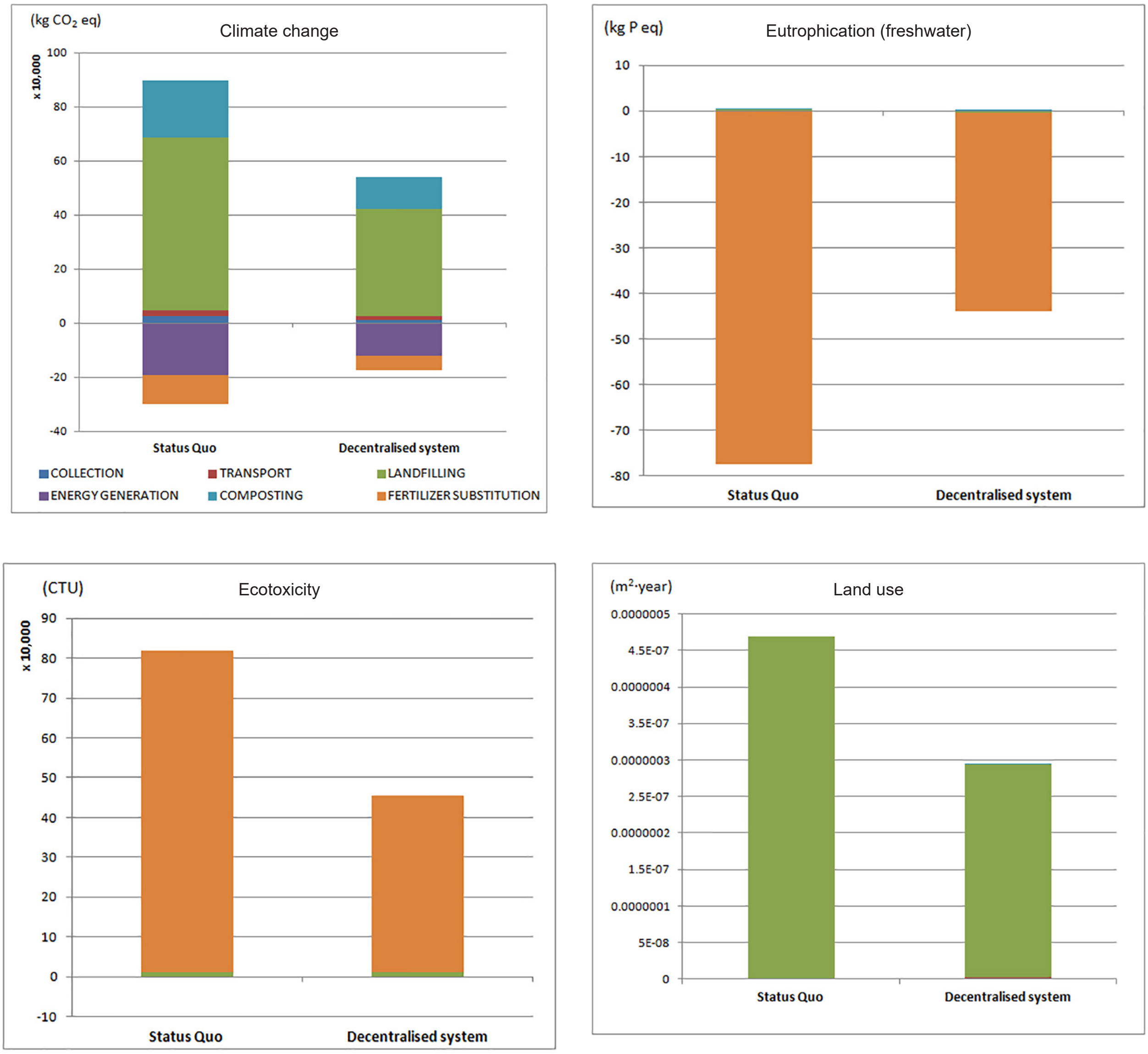

Fig. 4. *Status quo* and a decentralised system of biowaste management in ŁOM – impact categories.
Source: authors' own elaboration.

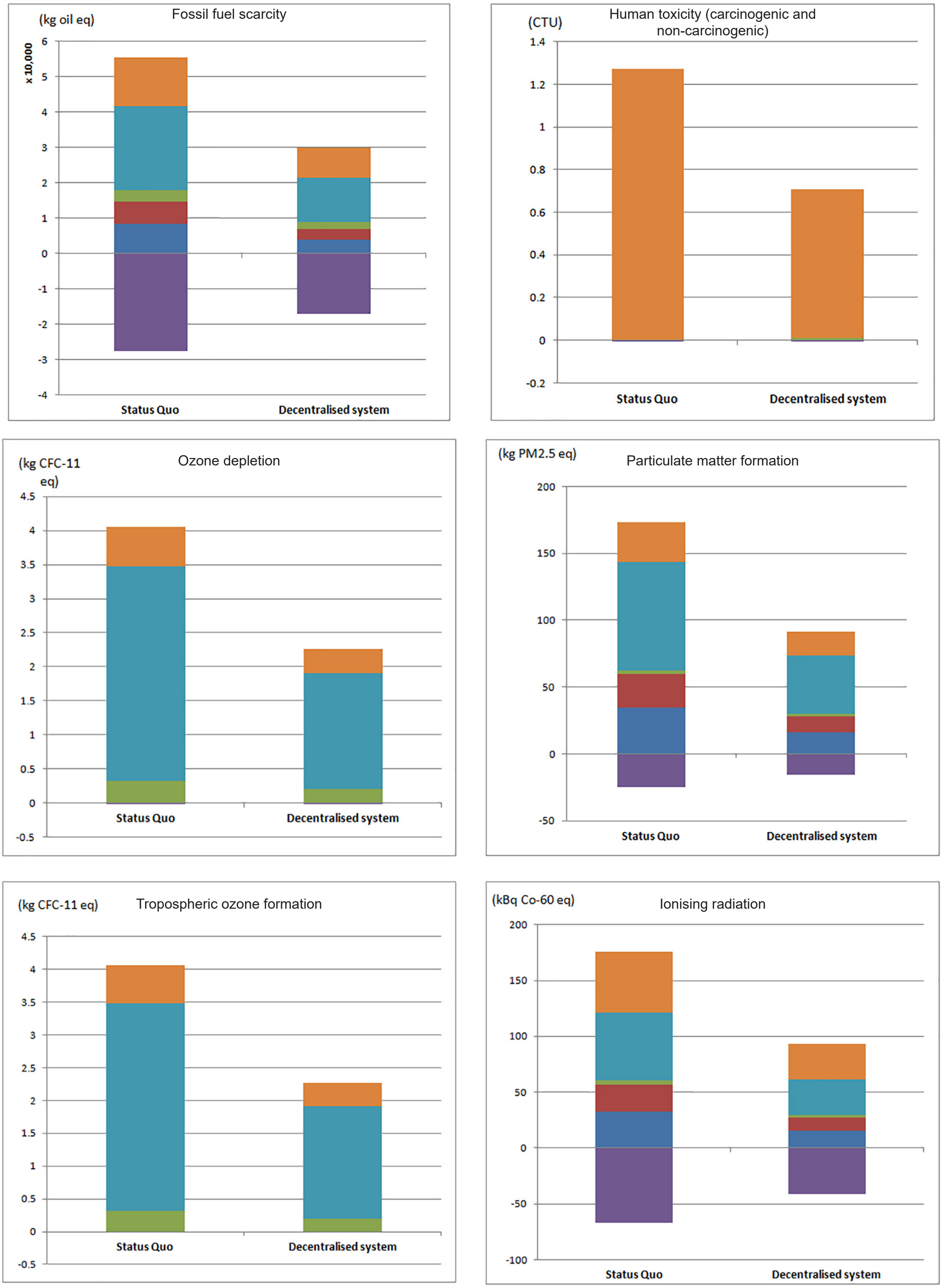

Fig. 4. *Status quo* and a decentralised system of biowaste management in ŁOM – impact categories.
Source: authors' own elaboration.

Agglomeration (Tables 1–3). However, the level of benefit correlates strongly with the type of *gmina*. Thus, regardless of the impact category, the greatest savings, reaching >90%, can be achieved in the rural or urban–rural *gminas* of Andrespol, Brójce, Brzeziny (rural), Dłutów, Dmosin, Dobroń, Głowno (rural), Jeżów, Ksawerów, Lutomiersk, Nowosolna, Ozorków (rural), Pabianice (rural), Rogów, Rzgów, Stryków, Tuszyn and Zgierz (rural). The urban *gminas*, with their dense high-rise buildings, are at the opposite end, ensuring that the benefits accruing from the implementation of decentralised composting in Łódź and Pabianice will be at the levels of 25% and 39% respectively.

Operational costs are also partly correlated with the type of *gmina*, but here there are many independent determinants relating to management, transport costs, contract conditions, etc. On the other hand, capital costs depend on the financial situation and the state of development of waste management. To achieve an adequate level of waste management for recycling purposes, less developed *gminas*—mostly assigned rural status—must incur higher capital costs. The benefits of introducing a decentralised system are tangible. Total OPEX and CAPEX may be reduced by as much as some 18m PLN per year. In municipalities for which the costs of the operation of the waste management system are high per tonne of waste, the nominal benefits from the implementation of the new system are large, especially where the amount of generated waste is high. The results (Table 2) show the CAPEX and OPEX amounts for the operation of the waste management system for the biodegradable fraction that cannot be composted on property. Part of the bio-waste volume remains in the current system, but the total cost of management is lower than that for status quo, thanks

Table 1. Impact of decentralised composting on environmental sustainability per functional unit.

Name of gmina	Climate change (kg CO_2 eq)	Freshwater eutrophication (kg P eq)	Ecotoxicity (CTU)	Land use (m^2 × year)	Fossilfuel scarcity (kg oil eq)
Aleksandrów Łódzki	2.28E+01	−3.79E−03	4.24E+01	1.72E−11	1.84E+00
Andrespol	2.80E+00	−7.74E−04	7.80E+00	9.96E−13	5.28E−01
Brójce	2.89E+00	−1.79E−04	2.55E+00	2.19E−12	4.90E−02
Brzeziny (urban)	2.80E+01	−1.14E−02	4.92E+01	4.70E−11	5.00E+00
Brzeziny (rural)	2.06E+00	−3.26E−04	3.58E+00	1.20E−12	1.91E−01
Dłutów	2.30E+00	−6.23E−04	6.27E+00	7.94E−13	4.45E−01
Dmosin	2.39E+00	−3.69E−04	3.58E+00	1.68E−12	2.12E−01
Dobroń	5.32E−01	−1.44E−04	1.46E+00	1.90E−13	1.00E−01
Głowno (urban)	3.39E+01	−5.77E−03	5.60E+01	2.62E−11	2.26E+00
Głowno (rural)	8.75E−01	−1.36E−04	1.31E+00	6.27E−13	7.33E−02
Jeżów	4.26E+00	−1.04E−03	1.00E+01	2.29E−12	6.37E−01
Koluszki	1.73E+01	−1.73E−03	1.31E+01	1.79E−11	6.58E−01
Konstantynów Łódzki	2.30E+01	−7.91E−03	7.84E+01	6.93E−12	4.94E+00
Ksawerów	4.28E+00	−1.38E−03	1.37E+01	8.58E−13	1.06E+00
Lutomiersk	1.92E+00	−3.57E−04	3.46E+00	1.13E−12	2.49E−01
Łódź	1.29E+02	−1.40E−02	1.56E+02	1.08E−10	3.48E+00
Nowosolna	8.02E−01	−1.68E−04	1.72E+00	3.91E−13	1.06E−01
Ozorków (urban)	6.04E+01	−1.10E−02	1.19E+02	3.87E−11	4.58E+00
Ozorków (rural)	7.13E+00	−1.17E−03	1.25E+01	4.30E−12	6.68E−01
Pabianice (urban)	1.17E+02	−1.57E−02	1.80E+02	7.74E−11	6.78E+00
Pabianice (rural)	6.39E−02	−7.52E−06	7.19E−02	5.00E−14	3.76E−03
Parzęczew	1.79E+01	−3.84E−03	3.38E+01	1.45E−11	2.48E+00
Rogów	1.27E+01	−8.94E−04	8.89E+00	1.15E−11	2.26E−01
Rzgów	1.54E+00	−1.99E−04	3.93E+00	9.11E−13	1.27E−01
Stryków	2.94E+00	−4.26E−04	4.15E+00	1.96E−12	2.94E−01
Tuszyn	9.99E+00	−1.12E−03	1.25E+01	7.90E−12	4.81E−01
Zgierz (urban)	6.38E+01	−1.14E−02	1.14E+02	4.61E−11	4.82E+00
Zgierz (rural)	1.34E+00	−2.25E−04	2.35E+00	8.18E−13	1.29E−01

Source: authors' own elaboration based on calculations in EASETECH.

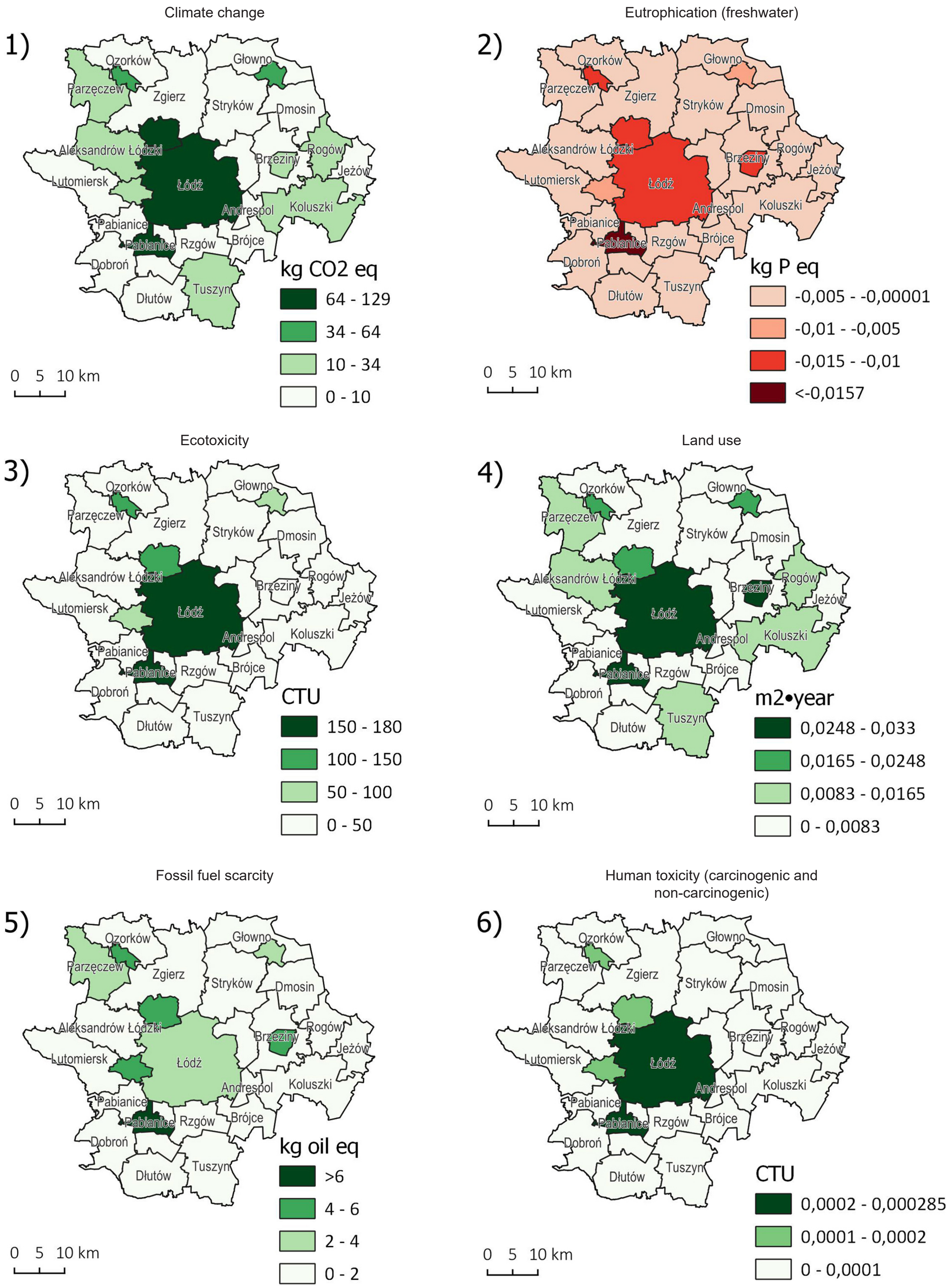

Fig. 5. Environmental analysis – spatial distribution of environmental impact categories within ŁOM.
ŁOM – *Łódzki Obszar Metropolitalny*
Source: authors' own elaboration.

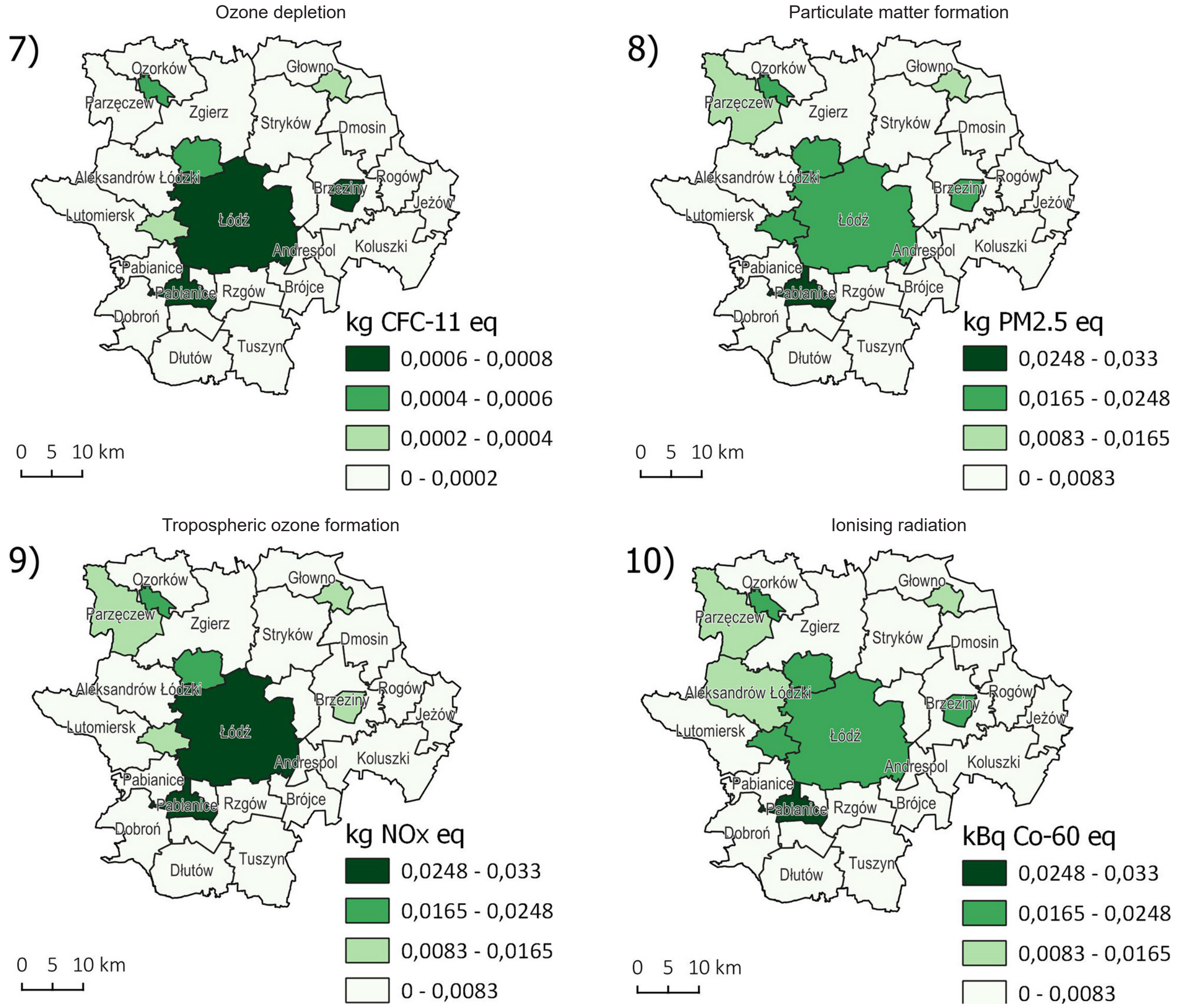

Fig. 5. Environmental analysis – spatial distribution of environmental impact categories within ŁOM.
ŁOM – *Łódzki Obszar Metropolitalny*
Source: authors' own elaboration.

Table 2. Impact of decentralised composting on economic sustainability per functional unit and total.

Name of gmina	Unit costs		Status quo		Decentralised composting	
	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX
	PLN/Mg	PLN/Mg	Total cost in PLN	Total cost in PLN	Total cost in PLN	Total cost in PLN
Aleksandrów Łódzki	921.90	494.10	1,848,200.60	990,562.29	1,497,042.48	802,355.46
Andrespol	340.04	977.00	578,202.42	1,661,297.64	468,343.96	1,345,651.09
Brójce	797.26	866.71	227,705.87	247,542.27	184,441.76	200,509.24
Brzeziny (urban)	1,248.83	130.00	671,510.47	69,902.30	543,923.48	56,620.86
Brzeziny (rural)	940.91	788.93	237,664.32	199,276.67	192,508.10	161,414.10
Dłutów	386.15	1,222.00	139,502.32	441,468.27	112,996.88	357,589.30
Dmosin	2,328.79	415.80	180,539.34	32,234.90	146,236.87	26,110.26
Dobroń	368.21	1,222.00	223,418.19	741,463.16	180,968.74	600,585.16
Głowno (urban)	1,479.61	415.80	673,623.23	189,301.27	545,634.82	153,334.03
Głowno (rural)	3,191.76	415.80	155,741.97	20,288.96	126,151.00	16,434.06
Jeżów	3,182.60	975.50	136,352.33	41,793.35	110,445.39	33,852.61
Koluszki	1,660.46	937.14	815,208.21	460,093.10	660,318.65	372,675.41
Konstantynów Łódzki	576.38	1,222.00	898,101.39	1,904,089.85	727,462.13	1,542,312.78
Ksawerów	395.68	1,222.00	394,951.98	1,219,751.52	319,911.10	987,998.73

Name of gmina	Unit costs		Status quo		Decentralised composting	
	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX
	PLN/Mg	PLN/Mg	Total cost in PLN	Total cost in PLN	Total cost in PLN	Total cost in PLN
Lutomiersk	1,474.02	1,222.00	271,074.74	224,728.24	219,570.54	182,029.88
Łódź	532.53	501.62	30,315,305.33	28,555,726.09	24,555,397.32	23,130,138.13
Nowosolna	532.70	893.33	217,384.91	364,554.15	176,081.77	295,288.86
Ozorków (urban)	797.71	415.80	822,404.06	428,669.84	666,147.29	347,222.57
Ozorków (rural)	1,009.96	415.80	324,478.62	133,588.22	262,827.68	108,206.46
Pabianice (urban)	467.45	1,222.00	2,457,327.46	6,423,961.13	1,990,435.25	5,203,408.51
Pabianice (rural)	921.94	1,222.00	271,691.56	360,119.73	220,070.17	291,696.98
Parzęczew	1,666.09	363.27	214,442.66	46,756.05	173,698.56	37,872.40
Rogów	4,943.43	729.00	175,956.55	25,948.03	142,524.80	21,017.90
Rzgów	969.29	820.00	337,733.38	285,715.88	273,564.04	231,429.86
Stryków	2,224.16	415.80	746,287.89	139,516.28	604,493.19	113,008.19
Tuszyn	1,436.88	973.00	363,001.24	245,809.96	294,031.00	199,106.07
Zgierz (urban)	1,289.84	396.10	1,847,825.31	567,452.86	1,496,738.50	459,636.82
Zgierz (rural)	1,881.41	415.80	489,699.73	108,225.67	396,656.78	87,662.79

CAPEX – capital expenditure, OPEX – operational expenditure, WR – waste mass reduction.
Source: authors' own elaboration based on local-authority reports (OPEX) and Statistics Poland (CAPEX) and WR indicator (Tonini et al. 2020).

Table 3. Impact of decentralised composting on social sustainability per functional unit.

Name of gmina	Human toxicity (CTU)	Ozone depletion (kg CFC-11 eq)	Particulatematter formation (kg PM2.5 eq)	Tropospheric ozone formation (kg NO_x eq)	Ionising radiation (kBq Co-60 eq)
Aleksandrów Łódzki	6.67E−05	1.92E−04	7.98E−03	5.26E−02	6.66E−03
Andrespol	1.22E−05	3.84E−05	1.92E−03	1.08E−02	1.82E−03
Brójce	4.09E−06	9.66E−06	4.91E−04	4.64E−03	2.81E−04
Brzeziny (urban)	5.69E−05	6.40E−04	1.79E−02	8.77E−02	1.57E−02
Brzeziny (rural)	5.62E−06	1.64E−05	8.18E−04	5.35E−03	7.02E−04
Dłutów	9.77E−06	3.09E−05	1.63E−03	9.25E−03	1.54E−03
Dmosin	5.48E−06	1.92E−05	9.31E−04	6.14E−03	7.82E−04
Dobroń	2.28E−06	7.15E−06	3.66E−04	2.07E−03	3.46E−04
Głowno (urban)	8.59E−05	3.00E−04	1.02E−02	6.72E−02	8.10E−03
Głowno (rural)	2.01E−06	7.12E−06	3.25E−04	2.15E−03	2.70E−04
Jeżów	1.54E−05	5.24E−05	2.41E−03	1.40E−02	2.21E−03
Koluszki	1.85E−05	1.00E−04	4.15E−03	3.28E−02	2.78E−03
Konstantynów Łódzki	1.22E−04	3.91E−04	1.72E−02	9.15E−02	1.66E−02
Ksawerów	2.13E−05	6.82E−05	3.74E−03	2.06E−02	3.63E−03
Lutomiersk	5.32E−06	1.83E−05	1.00E−03	6.22E−03	8.97E−04
Łódź	2.44E−04	7.44E−04	2.40E−02	1.98E−01	1.50E−02
Nowosolna	2.71E−06	8.44E−06	4.13E−04	2.49E−03	3.74E−04
Ozorków (urban)	1.86E−04	5.58E−04	1.96E−02	1.25E−01	1.62E−02
Ozorków (rural)	1.95E−05	5.96E−05	2.84E−03	1.84E−02	2.44E−03
Pabianice (urban)	2.85E−04	8.03E−04	3.30E−02	2.34E−01	2.58E−02
Pabianice (rural)	1.09E−07	4.04E−07	1.92E−05	1.39E−04	1.48E−05
Parzęczew	5.16E−05	2.00E−04	1.01E−02	6.26E−02	8.90E−03
Rogów	1.34E−05	5.15E−05	2.23E−03	2.05E−02	1.24E−03
Rzgów	6.62E−06	8.56E−06	5.45E−04	3.87E−03	4.79E−04
Stryków	6.35E−06	2.23E−05	1.28E−03	8.45E−03	1.10E−03
Tuszyn	1.95E−05	5.91E−05	2.60E−03	1.96E−02	1.93E−03
Zgierz (urban)	1.76E−04	5.89E−04	2.09E−02	1.34E−01	1.71E−02
Zgierz (rural)	3.67E−06	1.14E−05	5.44E−04	3.50E−03	4.68E−04

Source: authors' own elaboration based on calculations in EASETECH.

to reduction of the volume of biowaste due to home composting.

The maps in Figure 5 show the spatial distribution for the environmental analysis. The implementation of on-site composting resulting in a reduction in the bio-waste stream throughout the agglomeration results in tangible benefits for urban areas. As mentioned above, the financial benefits are mainly noted in rural areas. For the climate change and land-use categories, the benefits for several rural and urban–rural *gminas* are also quite high. It is worth underlining that it is in particular those urban areas and rural *gminas* that are the most major emitters of biowaste that gain most from the decentralisation of treatment.

Discussion

The research has revealed that the existing model of bio-waste management in the Łódź Agglomeration is very ineffective and thus needs adjustment to the EU legal waste provisions and the specificity of the region. In large measure, this can be achieved through the implementation of decentralised solutions based upon household/backyard composting.

The research pertaining to the sustainability assessment of bio-waste management for the Łódź Agglomeration was able to identify *gminas* showing the greatest potential for decentralised composting. These are all rural *gminas* in which >90% of the population lives in a single-family or farm building. In consequence, decentralised composting can constitute a fundamental form of bio-waste management in 15 out of the 28 *gminas* of the Łódź Agglomeration. Adding the number of urban–rural *gminas*, a total of 20 can manage their food and garden waste using decentralised composting.

Solutions based on decentralised composting are very often undervalued in bio-waste management strategies, but unnecessarily. Our research has shown, though, that in rural and urban–rural *gminas* with underdeveloped infrastructure for the bio-waste treatment, numerous environmental, economic and social benefits can be gained. This proved the sustainability assumptions associated with decentralised composting presented and discussed in the Introduction. In *gminas* assigned urban status, decentralised composting can represent a complementary solution.

Although decentralised composting (based upon the activity being engaged in at the level of the household/backyard) is a relatively simple solution, it requires a strong public commitment. This can, *inter alia,* be triggered when financial profit is offered to citizens who compost their bio-waste by themselves. This is a highly effective motivational tool and one that proves rather readily applicable. The effect of introducing greater incentives for residents will not be even everywhere due to social and geographical conditions, such as population density, diversification of built-up areas and the availability of land for composting.

In our case study involving the Łódź Agglomeration, decentralised composting is seen to reduce negative impact on the local environment as it is realised how most waste need no longer be transported. This is a real advantage of the proposed management system, especially in those directions in which the flow is very great. As maps make clear, the southern and eastern directions prevail when it comes to the distribution of biowaste within an organised system, and so it is these territories that are affected most by transport. The utilisation or preparation for re-use of these kinds of waste also affects areas in the vicinity of waste treatment plants. The most effective solution to reduce bio-waste impact involves reduced amounts of transported and treated waste, which strongly fits into the objectives of the waste hierarchy discussed in the Introduction.

The decentralisation of the system by which bio-waste is managed has the potential to concentrate the waste flow by reducing recipients and allowing for the takeover of smaller amounts of waste from other *gminas*, via installations whose operation will be necessary. A reduction in the supply of waste may affect progressing regionalisation of the flow of streams of waste that remains on the market as a raw material. The smaller amount of potential raw material will force recipients to optimise transport. The system of links between producers and recipients is currently chaotic, reflecting agreements reached between local authorities and the companies receiving waste.

The results achieved in the sustainability of the system study presented here have the potential to be used in strategic planning. Changes in the spatial directions taken by streams of waste can be planned, e.g. through the use of tools already described in the literature, such as GDSE (Mazurek, Czapiewski 2021). Analyses were developed for a settlement-diverse area which present the variation in the effects of implementing the analysed solution depending on the nature of the area. Further consideration of the impact of the changes on the environment would allow for the elaboration of scenarios to achieve the strategically planned development of a circular economy in a given area. Sustainability indicators were achieved for each spatial unit of the analysed area, which provides opportunities for waste flow planning depending on the adopted scenario for individual units separately or for the entire region.

The spatial distribution characterising the phenomena presented allowed for the determination of the potential for decentralisation of the system in rural and urban areas to take place, where these are associated with an urban agglomeration of >700,000 inhabitants. Indeed, the greatest environmental benefits are generated by cities, due to the large volume of waste generated, although the relative financial benefits are much greater in those *gminas* in which system operating costs per tonne of waste proved to be high. In turn, this is mainly the case for rural areas. The authors would like to point out that further potential for research in the field of LCA and LCCA analyses lies primarily in more detailed research. In this context, an important factor in the simulations carried out is the determination of threshold values for the composting potential of bio-waste on properties. This potential is available mainly in rural areas, in which the exact volume of bio-waste is in fact unknown (it is not known how much bio-waste is already composted for agricultural crops). Moreover, cities with a major share of single-family housing may have limited composting space due to the high density of buildings and a smaller plot area.

Conclusions

Despite the fact that the municipal waste management sector in Poland has undergone radical transformation over the last decade, there are still many challenges that authorities need to face with respect to fulfilling the objectives of the waste hierarchy. One of them is the environmental and socio-economic beneficial management of bio-waste. A comprehensive life cycle sustainability assessment in regard to the Łódź Agglomeration has indicated that decentralised composting of bio-waste is a very promising option, whenever there is no relevant infrastructure for waste treatment, and it is geographically possible. In addition, for the decentralised composting, limited transport and employment are required.

The utilisation of the results of this research, as the projected baseline impact, facilitates the practical implication of decentralised composting as a core aspect to the bio-waste management. Authorities largely lack access to information at *gmina* level in regard to possible alternative scenarios for the bio-waste management (Ai, Leigh 2017). While implementing the decentralised composting (taken down to the household/backyard level) appears to be a win–win option, it may be challenging because it requires behavioural change.

Although the research was able to provide a comprehensive life cycle sustainability assessment of the bio-waste management in the Łódź Agglomeration, it is not free from limitations. The main limitation lies in the limited access to the foreground data at local level. The issue of waste management is so complex that the conditions affecting its collection or treatment vary with the type of built-up area (multi-family/single-family housing) and the amount of waste generated by individual households. It is also difficult to determine the degree of differences in social and demographic conditions that could affect the level of waste segregation. Disaggregation of the data to a lower level would require estimation of data available to *gminas*, and that would often give rise to misleading conclusions. This is largely the case for local data related to economic impact categories, *inter alia* CAPEX, revenues or employment. In consequence, it proved difficult to apply certain impact categories for the economic sustainability assessment of waste management available in the literature.

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Author's contribution

Conceptualisation (MRB, DM, MM), writing – original draft (MRB, DM), data curation (MRB, DM), investigation (MRB, DM, MM), formal analysis (MRB, DM, MM), visualisation (DM), writing – review and editing (MRB, DM).

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