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The effects of the technological setup of plastic waste pyrolysis on its environmental performance

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Pyrolysis currently emerges as a promising technology capable of treating mixed plastic waste that is otherwise unsuitable for mechanical recycling. However, its large-scale adoption requires a comprehensive understanding of its environmental impacts based on different technology setups. This study uses life cycle assessment (LCA) to compare different pyrolysis configurations, varying in operational parameters such as maximizing or managing process gas. The results reveal a high variability of environmental impacts across configurations. Sensitivity analysis further indicates that a shift towards renewable energy sources has a potential to enhance the overall environmental performance of pyrolysis. Presented findings emphasize the need to carefully select pyrolysis process parameters when considering scale-up and integration into waste management strategies. The study thus provides insights for decision-makers evaluating pyrolysis as an environmentally sound plastic waste treatment solution.

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Environmental significance

The paper deals with the pyrolysis for the treatment of mixed plastic waste, which can be considered as promising from the perspective of circular economy and potential for reduction of environmental impacts including climate change. The paper presents how various process configurations of pyrolysis technology can have big influence on environmental impacts and highlights key operation parameters. The study results reveal a high variability of environmental impacts across configurations, ranging from −133 to 966 kg CO_2 eq. per tonne of mixed plastic waste. The most environmentally favourable configuration minimizes process gas production, along with its subsequent capture, compression and natural gas substitution. Compared to mixed plastic waste-to-energy treatment, pyrolysis results in lower environmental impacts among all studied configurations.

1 Introduction

Plastic waste represents a significant global environmental challenge due to the large amount generated by society, coupled with inadequate disposal practices and low recycling rates.[1] The production and improper disposal of plastic waste have severe negative impacts on both human health and the environment. A promising solution lies in adopting a circular economy and enhancing recycling processes. While mechanical recycling is widely used and valuable, it has limitations in effectively addressing certain technical issues associated with plastic waste. The efficiency of mechanical recycling depends on factors such as the quality of the collected plastic and the sorting methods used.[2] The process is complicated by the inability to handle mixed or contaminated plastics.[3] Another disadvantage is that recycled plastic obtained through mechanical recycling is not the same high quality as virgin plastic and may contain impurities, reduced strength, and color variations.[4]

The imperfections of existing waste management practices highlight the need for innovative approaches to plastic recycling, such as chemical recycling, which offer the potential to extract value from plastic waste and promote circularity in the plastic value chain.[5]

Additionally, the convergence of the plastic pollution crisis, resource security concerns, and advancements in technology has elevated chemical recycling to a hot topic of discussion among governments, industry stakeholders, and experts. Through chemical recycling, plastic waste can be transformed into fully marketable products, which can be used, for example, in the fuel industry.[6] The advantage of chemical recycling over mechanical recycling is its ability to handle a mixed composition of input plastics.

To date, none of the chemical recycling technologies for plastic waste, such as pyrolysis, gasification, oxidation or depolymerization, have been widely implemented. The economic viability and scalability pose challenges for the widespread implementation of chemical recycling. Establishing a balance between environmental and economic considerations is crucial for achieving the widespread adoption of this revolutionary technology.[7] Each of them has its advantages and disadvantages, highlighting the need to find an optimal

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solution for managing plastic waste recycling. The classification of chemical recycling technologies involves categorizing them based on various criteria, such as the type of chemical reactions, raw materials, process conditions, and environmental impact.[8] For example, in pyrolysis technology, where molecular decomposition occurs through a thermal process in the absence of oxygen, the methods include fast pyrolysis, slow pyrolysis, microwave pyrolysis, fluidized bed pyrolysis, and catalytic pyrolysis.[9] Pyrolysis is quite promising in terms of chemical recycling of plastic due to its ability to process various types of plastic waste, ranging from packaging waste to more complex materials.[10] Thus, pyrolysis of plastic waste is undoubtedly one of the recently discussed technological solutions to the problem of waste disposal and recovery.

The pyrolysis process depends on several factors, starting with process temperature, which ranges from 300 °C to 800 °C, depending on the chosen technology.[11] Besides temperature, the heating rate is also important.[12] Retention time, which usually depends on various factors, including reactor design, operating conditions, and feedstock composition, also plays a significant role.[13] According to the scientific literature,[14,15] the retention time can range from 20 minutes to 60 minutes, but it can also be as short as 5 seconds in the case of fast pyrolysis.[16] The thermal decomposition process can be influenced by various types of catalysts, which directly affect the reaction rate and the quality of the yielded products.[17] The distribution of the output products primarily depends on the characteristics of the feedstock.[18] For example, the smaller the size of the plastic granulate, the better the heat exchange process, which accelerates the reaction time. The aforementioned parameters, such as process temperature, heating rate, retention time, catalyst type and feedstock, influence the formation of by-products. Pyrolysis can break down plastics into valuable chemicals and fuels, such as liquid recyclate (pyrolysis oil), process gas (pyrolysis gas) and solid residue (pyrolysis char).

Pyrolysis oil can be considered the primary product of pyrolysis, and its quality greatly depends on the characteristics of the process.[9] Nevertheless, with the correct choice of catalyst, a lower operating temperature with a higher yield of pyrolysis oil can be achieved.[19] The study[20] showed that the dependance of the liquid product's yield on the temperature increase; the lower the rate, the more liquid product can be obtained.

Two other important process parameters are the higher calorific value of the oil and the fractional yield of the oil.[21] The pyrolysis oil produced from mixed plastics can substitute primary fossil feedstocks (*e.g.*, naphtha) in the manufacturing of monomers (ethylene an propylene), which are important in the polymerization of polyolefins.[22]

The gaseous products of polymer pyrolysis typically consist of mixtures of C_xH_y hydrocarbons and hydrogen.[23] Research[24] shows that the gas produced from the pyrolysis and liquefaction of polyethylene and polypropylene mainly consists of methane, ethane, propane, and butane, while in the case of polyethylene terephthalate (PET) pyrolysis, the primary gases are CO_2 and CO. High temperature and extended residence time are the best conditions for maximizing gas production in the pyrolysis process.[25] The yield of gaseous products also depends on the feedstock; for example, pyrolysis results[26] show that gas formation is higher in the case of polyethylene (PE) than polystyrene (PS). Therefore, determining the most efficient pyrolysis reaction conditions and choosing the reactor are among the key challenges for obtaining the desired product output.[27] Pyrolysis gas is either flared and cogenerated to improve the energy efficiency of technology, or flared and compressed as a product that can replace, for example, compressed natural gas (CNG).[28] Concluded in their research, that pyrolysis char mainly consists of inorganic substances, which are challenging to dispose of but have potential uses in road coverings and as building materials. The study[29] showed that high ash content limits its use in tyre production, but the product can be used in rubber compounds. Due to its high carbon content, pyrolysis char has an excellent absorptive capacity and can be used as a sorbent in various applications.[30]

Despite numerous studies on the plastic pyrolysis process, it has not yet seen practical large-scale application. M. S. Qureshi *et al.* attribute the problem of large-scale application of this technology to the quality of the feedstock as well as the stability and standardization of the product.[31] Zhilong Yuan *et al.* concluded in their work that plastic pyrolysis is accompanied by technical issues, such as contamination of pyrolysis oil and corrosion of reactor materials, which may result from the formation of hydrogen chloride (HCl) during polyvinyl chloride (PVC) pyrolysis.[32] Another technical problem could be the clogging of internal reactor pipelines with benzoic acid formed as a result of PET pyrolysis.[33] A. Buekens believes that the pyrolysis process is economically unviable, mainly due to the high costs of preliminary plastic preparation, hoping only that these costs will be offset by the value of the obtained product.[34] Kim Ragaert *et al.* reported that plastic pyrolysis technology becomes economically viable only when implemented on a large scale.[35] Analyzing the life cycle of pyrolysis, Vibhuti Chhabra *et al.* concluded that the process is economically feasible with a payback period of 6.17 years.[36] However, a major drawback of pyrolysis is its high energy demand and associated environmental impacts. As emphasized by Stijn van Ewijk *et al.* circular economy efforts must carefully consider the energy implications of recycling.[37]

To understand the overall impact of pyrolysis, it should be studied from the perspective of life cycle assessment (LCA), which involves a comprehensive approach to determining environmental impact. LCA is recognized as the best tool for assessing the life cycle impact of products or process.[38] It is important to note that the LCA methodology can provide useful information even at the design stage, as it allows for identifying alternative planning options.[39] The advantage of using LCA for analyzing waste management systems is that it provides a comprehensive view of the processes and impacts involved, even taking into account its connections with other sectors.[40]

In the LCA study of the pyrolysis process,[41] it is also shown that most technological emissions are associated with electricity consumption. Nevertheless, researchers,[42] considering the direct electrification of thermal energy supply, concluded that the impact of pyrolysis on global warming would decrease by 67%. It is important to include LCA indicators that consider

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the impact of plastic on the environment beyond greenhouse gas emissions[43] because it is essential to consider emissions of air pollutants, including toxic substances. As the study[44] concludes, other categories besides climate change such as ecotoxicity, freshwater or human toxicity should be reviewed to provide a more well-rounded analysis of the environmental benefits of plastics recycling. Given the high energy intensity of pyrolysis, it is appropriate to make comparisons in terms of different impact categories to provide more reliable results,[45] because the source of electricity can influence the importance and contribution of each impact category to the overall impact of pyrolysis. When studying the life cycle of plastic pyrolysis, it is also necessary to consider geographic variability, as the environmental impact of plastic pyrolysis can vary significantly depending on regional factors such as energy balance and waste management infrastructure.[46]

The variety of LCA methods and the need for project-specific parameters mean that the results of one LCA are rarely comparable with others. Nevertheless, even such comparisons can generate new insights, such as identifying the most effective ways to combine processes to reduce adverse outcomes.[47] However, existing LCA studies require greater consistency and accuracy.[48]

Up-to-now, there are many studies comparing mechanical recycling with one of the types of chemical recycling.[49] This is an outdated approach; at the present stage of recycling technology development, it is worth focusing on chemical recycling methods, selecting the most efficient one, and working on its improvement.[50]

This study represents further progress in addressing the knowledge gap surrounding the pyrolysis of plastic waste, specifically the lack of detailed comparative LCA studies that evaluate the various technology configurations, environmental benefits and drawbacks of pyrolysis technology across different environmental impact categories. Existing studies often focus on specific aspects or stages of the pyrolysis process; however, there is a lack of detailed comparative analysis that considers various pyrolysis technology configurations across multiple environmental impact categories, such as global warming potential, resource use, eutrophication, ozone depletion and more. In this context, sensitivity analysis is crucial for understanding how variations in operational parameters affect the overall environmental performance of the technology. It also helps to identify the most efficient and environmentally safe configurations for scaling up pyrolysis processes.

Since chemical recycling is an alternative way of waste plastics treatment and also a technology producing valuable secondary products, this work deals with the assessment of the potential environmental impacts of different configurations of this technology from two perspectives, namely waste treatment and secondary products' production.

2 Experimental

2.1. Description of assessed technology

Pyrolysis of mixed waste plastics takes place without air at temperatures of 350–450 °C. The technology considers a two-stage parallel reactor where low-temperature thermal decomposition (controlled homolytic fission) occurs. It is an endothermic process that occurs in anaerobic environments, *i.e.* without access to air or other oxidants. The outputs of this technology are process gas, solid residue and liquid recyclate. The process gas can be used as a source for energy recovery (gas turbine, cogeneration unit), which subsequently covers part of the energy consumption of the actual operation of the technology, or it can be separated into individual gas components. Liquid recyclate and solid residue are secondary products that can be used as a substitute for primary raw materials, *e.g.* in the petrochemical or chemical industry. Pyrolysis, therefore, involves depolymerisation, *i.e.* the cleavage of long, complex hydrocarbon chains to form new process products with relatively low molecular weight. The volumes of the individual new products obtained in pyrolysis depend not only on the composition and properties of the feedstock but also on the actual process conditions. The proportions of the gaseous and liquid product obtained can be controlled to a limited extent by setting appropriate process parameters to suit the intent and needs of the operator. The considered technology can process a maximum of 0.2 tons per hour of mixed plastics. Waste plastics with a composition of up to 10% PET and up to 3% PVC are considered as input. Assumption of output production: solid residue 5%, process gas 5% for minimum and 30% for maximum, liquid recyclate 65% for minimum and 95% for maximum values.

Four different configurations of the pyrolysis process were assessed to analyse their influence on the process' environmental performance. For each configuration, the assumed minimum and maximum values of the individual parameters were determined based on the technical characteristics of the individual equipment and pilot-scale operation data. As individual parameters were considered % of waste production from sorting, electricity consumption for shredding and pneumatic transport of shredded material, electricity consumption for the operation of the hopper and conveyor, the electricity consumption of the depolymerization reactor, electricity consumption for cleaning of depolymerization products, electricity consumption for the liquid recyclate pump, electricity production for pyrolysis gas cogeneration, electricity consumption for pyrolysis gas capture and compression, electricity consumption for process oil bottling, % production of process gas, solid residue. The aim is to show how changing the basic operational settings affects the overall technology assessment and its environmental performance.

2.1.1. Configuration A. Pyrolysis with capture, combustion, cogeneration of process gas, and use of the generated electricity are used within the operation of the technology. Configuration with maximisation of process gas production.

2.1.2. Configuration B. Pyrolysis with capture, combustion, cogeneration of process gas and use of the generated electricity within the operation of the technology. Configuration with minimisation of process gas production.

2.1.3. Configuration C. Pyrolysis with capture and compression of process gas that is not incinerated and used in

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Table 1 Input data for all pyrolysis configurations

Pyrolysis	Capture, combustion and cogeneration of process gas				Capture and compression of process gas			
	Max. process gas production		Min. process gas production		Max. process gas production		Min. process gas production	
Configuration	A (min)	A (max)	B (min)	B (max)	C (min)	C (max)	D (min)	D (max)
Sorting, shredding, transport								
Waste production from sorting (%)	5	15	5	15	5	15	5	15
Electricity consumption for shredding and pneumatic transport of mixed plastic waste (C in kW h)	C	1.4C	C	1.4C	C	1.4C	C	1.4C
Electricity consumption for hopper, screw conveyor (C in kW h)	C	1.4C	C	1.4C	C	1.4C	C	1.4C
Pyrolysis unit								
Electricity consumption in pyrolysis unit (C in kW h)	C	1.4C	C	1.4C	C	1.4C	C	1.4C
Aerosol and gas production in pyrolysis unit (%)	95	95	95	95	95	95	95	95
Solid residue production in pyrolysis unit (%)	5	5	5	5	5	5	5	5
Purification of pyrolysis products								
Electricity consumption of purification	C	1.4C	C	1.4C	C	1.4C	C	1.4C
Liquid recyclate production (%)	68	68	95	95	68	68	95	95
Process gas production (%)	32	32	5	5	32	32	5	5
Liquid recyclate management (pumping, bottling)								
Electricity consumption (C in kW h)	C	1.4C	C	1.4C	C	1.4C	C	1.4C
Process gas management								
Electricity consumption for gas transport, capture/compression	C	1.5C	C	1.5C	23.1C	34.4C	23.1C	34.4C
Electricity production from process gas for own operation	✗	✗	✗	✗	—	—	—	—
Pyrolysis outputs								
Solid residue	✗	✗	✗	✗	✗	✗	✗	✗
Liquid recyclate	✗	✗	✗	✗	✗	✗	✗	✗
Compressed process gas	—	—	—	—	✗	✗	✗	✗

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the plant. The process gas is captured and compressed. Configuration with maximisation of process gas production.

2.1.4. Configuration D. Pyrolysis with capture and compression of process gas that is not incinerated and used in the plant. The process gas is captured and compressed. Configuration with minimisation of process gas production.

Differences in operating parameters of the configurations are presented in Table 1. C is a specific constant for each of the parameters listed.

2.2. LCA

LCA was conducted according to ISO guidelines 14 040 and 14 044.[51] Two functional units were defined based on different perspectives on the benefits of pyrolysis technology: one tonne of produced secondary product (liquid recyclate, process gas, or solid residue) and one tonne of treated mixed plastic waste (at the moment of classification as waste, *i.e.*, before pre-treatment).

Fig. 1 shows the system boundaries for the production of secondary products and for the mixed plastic waste treatment, separately for configurations A, B and C, D. Both perspectives consider also sorting of input mixed plastic waste, because the composition of input is limited with regard to the optimal operation of the technology. In case of waste management perspective, substitutions of secondary products are applied to compare potential environmental impacts with alternative waste management options that produce other types of valuable outputs.

Specific data used in the study were provided by the technology supplier based on pilot-scale operation. The specific data for individual technologies included data on specific consumption of electricity, fuels, auxiliary materials in individual process blocks, specific data on waste production, emissions, secondary products, *etc.* In addition, the study used secondary background datasets, *i.e.* database processes that quantify the impacts of specific processes, such as production of input materials, transportation, waste management by type and method, *etc.* The secondary data come from the Sphera 2024.2 and ecoinvent 3.9.1 databases. Sofware LCA for Experts from Sphera was used for all life cycle analyses. All data used in the inventory and calculations are based on the EU region. European electricity grid mix is used in the study. Only global data used in the study relates to truck transportation. It was assumed that the transport distance for waste collection and

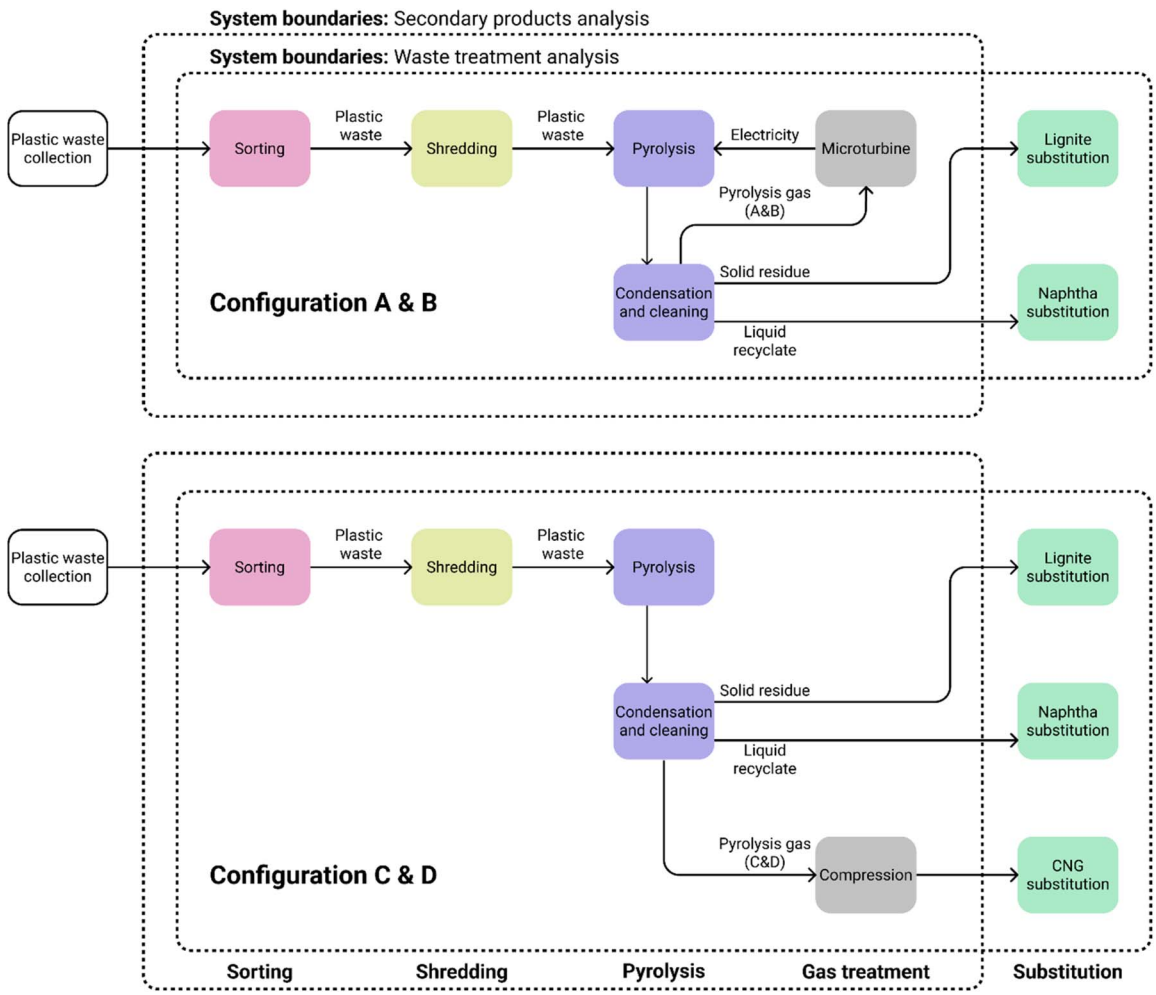

Fig. 1 System boundaries.

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disposal is 50 km. Truck transport was considered. Waste produced during the operation of the technology is transferred to a waste-to-energy facility and the polluter-pays principle is applied. Detailed description of all used secondary data is provided in the SI.

To determine the environmental impacts of outputs, mass allocation was used. The allocation of common inputs and outputs is based on a general allocation rule, which represents the share of the production of each secondary product in the total production expressed in tonnes. As the aim of the study is also to compare environmental indicators with alternative waste management technologies, the principle of substitution is applied for secondary products coming out of the technologies under consideration. In this case, the substitution of secondary products by the production of primary raw materials or products of equivalent quality is chosen, specifically for lignite (solid residue), the primary production process for compressed natural gas (CNG) and the primary production process for naphtha (liquid recyclate). This approach was chosen in accordance with the quality and characteristics of secondary products and possible applications also foreign studies to make the results comparable.[52] From the perspective of the LCA study, it is important to choose the appropriate substitutes to best match the quality of the secondary products as the chosen approach can have a significant impact on the overall impacts.

All impact categories have been assessed according to the environmental footprint (EF 3.1) methodology. EF 3.1 methodology also allows quantifying the aggregate potential environmental impacts, where the results of the potential impacts in each impact category are converted through normalisation and weighting to a single dimensionless number. The technology configurations are assessed in terms of producing 1 tonne of secondary product based on mass allocation of products. The study quantified the environmental impacts for the construction and operation phase. No relevant data were available for the demolition phase.

3 Results and discussion

Based on the assessment performed, the construction phase was found to contribute a minimal (less than 5%) amount to the total environmental impacts. The operation phase accounts for the majority of the total potential environmental impacts for all technologies assessed. For this reason, the analysis of the results in the next section of the article will focus on this phase.

3.1. Waste treatment analysis

Potential environmental impacts of pyrolysis configurations (A, B, C and D) in waste treatment system boundaries (per 1 tonne of treated mixed plastic waste) in selected impact categories are presented in Fig. 2. The results of the individual technology configurations considered are presented as the average of the values (min, max) with deviations shown in Table 2. The figure shows the contributions of each process group to the overall impact (sorting, shredding, pyrolysis, gas treatment and substitution). The figure shows the impact of the technology

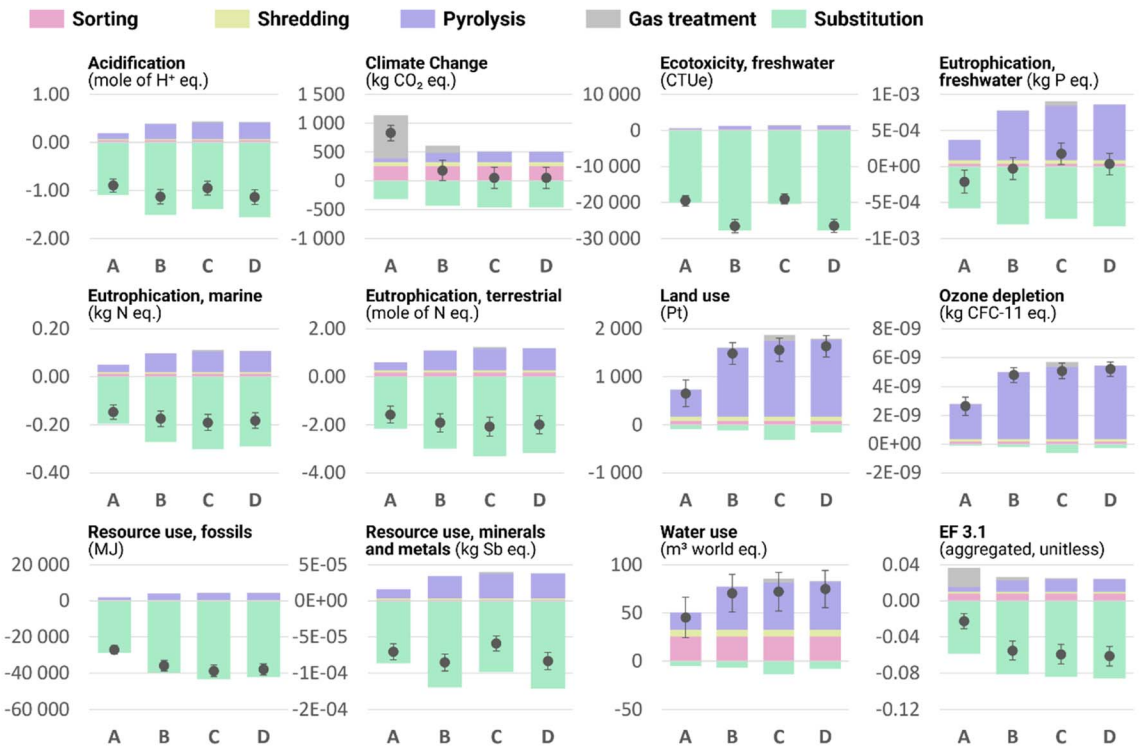

Fig. 2 Potential environmental impacts and savings of pyrolysis process phases for individual categories of the environmental footprint methodology.

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Table 2 Potential environmental impacts and savings of pyrolysis process phases for individual categories of the environmental footprint methodology

Configuration (A)	Gas treatment	Sorting	Pyrolysis	Shredding	Substitution	Total	Deviation 1	Deviation 2
EF 3.1 acidification [mole of H^+ eq.]	1.25×10^{-3}	4.19×10^{-2}	1.22×10^{-1}	2.70×10^{-2}	-1.09	-8.99×10^{-1}	1.38×10^{-1}	-1.38×10^{-1}
EF 3.1 climate change – total [kg CO_2 eq.]	7.57×10^{2}	2.55×10^{2}	6.38×10^{1}	6.69×10^{1}	-3.11×10^{2}	8.32×10^{2}	1.35×10^{2}	-1.35×10^{2}
EF 3.1 ecotoxicity, freshwater – total [CTUe]	3.94	1.06×10^{2}	3.91×10^{2}	1.04×10^{2}	-2.01×10^{4}	-1.95×10^{4}	1.43×10^{3}	-1.43×10^{3}
EF 3.1 eutrophication, freshwater [kg P eq.]	2.69×10^{-6}	3.49×10^{-5}	2.80×10^{-4}	5.26×10^{-5}	-5.82×10^{-4}	-2.12×10^{-4}	1.60×10^{-4}	-1.60×10^{-4}
EF 3.1 eutrophication, marine [kg N eq.]	3.13×10^{-4}	1.14×10^{-2}	3.05×10^{-2}	7.52×10^{-3}	-1.96×10^{-1}	-1.46×10^{-1}	3.03×10^{-2}	-3.03×10^{-2}
EF 3.1 eutrophication, terrestrial [mole of N eq.]	3.27×10^{-3}	1.73×10^{-1}	3.19×10^{-1}	9.39×10^{-2}	-2.16	-1.57	3.53×10^{-1}	-3.53×10^{-1}
EF 3.1 land use [Pt]	5.73	7.55×10^{1}	5.59×10^{2}	1.01×10^{2}	-8.62×10^{1}	6.54×10^{2}	2.74×10^{2}	-2.74×10^{2}
EF 3.1 ozone depletion [kg CFC-11 eq.]	1.47×10^{-11}	1.73×10^{-10}	2.41×10^{-9}	1.79×10^{-10}	-1.42×10^{-10}	2.63×10^{-9}	6.28×10^{-10}	-6.28×10^{-10}
EF 3.1 resource use, fossils [MJ]	1.36×10^{1}	2.20×10^{2}	1.33×10^{3}	2.38×10^{2}	-2.89×10^{4}	-2.71×10^{4}	2.41×10^{3}	-2.41×10^{3}
EF 3.1 resource use, mineral and metals [kg Sb eq.]	1.21×10^{-7}	1.54×10^{-6}	1.23×10^{-5}	1.88×10^{-6}	-8.63×10^{-5}	-7.04×10^{-5}	1.09×10^{-5}	-1.09×10^{-5}
EF 3.1 water use [m^3 world equiv.]	1.79×10^{-1}	2.52×10^{1}	1.75×10^{1}	7.35	-4.94	4.52×10^{1}	2.08×10^{1}	-2.08×10^{1}
EF 3.1	2.11×10^{-2}	7.93×10^{-3}	4.80×10^{-3}	2.47×10^{-3}	-5.89×10^{-2}	-2.26×10^{-2}	8.47×10^{-3}	-8.47×10^{-3}
Configuration (B)	Gas treatment	Sorting	Pyrolysis	Shredding	Substitution	Total	Deviation 1	Deviation 2
EF 3.1 acidification [mole of H^+ eq.]	2.10×10^{-4}	4.19×10^{-2}	3.11×10^{-1}	2.72×10^{-2}	-1.51	-1.13	1.53×10^{-1}	-1.53×10^{-1}
EF 3.1 climate change – total [kg CO_2 eq.]	1.27×10^{2}	2.55×10^{2}	1.62×10^{2}	6.70×10^{1}	-4.30×10^{2}	1.81×10^{2}	1.75×10^{2}	-1.75×10^{2}
EF 3.1 ecotoxicity, freshwater – total [CTUe]	6.61×10^{-1}	1.06×10^{2}	9.85×10^{2}	1.05×10^{2}	-2.78×10^{4}	-2.66×10^{4}	1.87×10^{3}	-1.87×10^{3}
EF 3.1 eutrophication, freshwater [kg P eq.]	4.51×10^{-7}	3.49×10^{-5}	6.86×10^{-4}	5.30×10^{-5}	-8.06×10^{-4}	-3.17×10^{-5}	1.51×10^{-4}	-1.51×10^{-4}
EF 3.1 eutrophication, marine [kg N eq.]	5.24×10^{-5}	1.14×10^{-2}	7.76×10^{-2}	7.57×10^{-3}	-2.71×10^{-1}	-1.74×10^{-1}	3.23×10^{-2}	-3.23×10^{-2}
EF 3.1 eutrophication, terrestrial [mole of N eq.]	5.49×10^{-4}	1.73×10^{-1}	8.13×10^{-1}	9.44×10^{-2}	-2.99	-1.91	3.76×10^{-1}	-3.76×10^{-1}
EF 3.1 land use [Pt]	9.61×10^{-1}	7.55×10^{1}	1.42×10^{3}	1.01×10^{2}	-1.17×10^{2}	1.48×10^{3}	2.29×10^{2}	-2.29×10^{2}
EF 3.1 ozone depletion [kg CFC-11 eq.]	2.46×10^{-12}	1.73×10^{-10}	4.62×10^{-9}	1.81×10^{-10}	-1.94×10^{-10}	4.79×10^{-9}	5.09×10^{-10}	-5.09×10^{-10}
EF 3.1 resource use, fossils [MJ]	2.28	2.20×10^{2}	3.38×10^{3}	2.40×10^{2}	-3.98×10^{4}	-3.60×10^{4}	2.96×10^{3}	-2.96×10^{3}
EF 3.1 resource use, mineral and metals [kg Sb eq.]	2.04×10^{-8}	1.54×10^{-6}	3.06×10^{-5}	1.90×10^{-6}	-1.19×10^{-4}	-8.53×10^{-5}	1.19×10^{-5}	-1.19×10^{-5}
EF 3.1 water use [m^3 world equiv.]	3.01×10^{-2}	2.52×10^{1}	4.45×10^{1}	7.37	-6.61	7.05×10^{1}	1.95×10^{1}	-1.95×10^{1}
EF 3.1	3.55×10^{-3}	7.93×10^{-3}	1.22×10^{-2}	2.48×10^{-3}	-8.13×10^{-2}	-5.52×10^{-2}	1.05×10^{-2}	-1.05×10^{-2}
Configuration (C)	Gas treatment	Sorting	Pyrolysis	Shredding	Substitution	Total	Deviation 1	Deviation 2
EF 3.1 acidification [mole of H^+ eq.]	2.88×10^{-2}	4.19×10^{-2}	3.43×10^{-1}	2.70×10^{-2}	-1.39	-9.51×10^{-1}	1.47×10^{-1}	-1.47×10^{-1}
EF 3.1 climate change – total [kg CO_2 eq.]	1.51×10^{1}	2.55×10^{2}	1.79×10^{2}	6.69×10^{1}	-4.63×10^{2}	5.33×10^{1}	1.85×10^{2}	-1.85×10^{2}
EF 3.1 ecotoxicity, freshwater – total [CTUe]	9.07×10^{1}	1.06×10^{2}	1.09×10^{3}	1.04×10^{2}	-2.04×10^{4}	-1.90×10^{4}	1.42×10^{3}	-1.42×10^{3}
EF 3.1 eutrophication, freshwater [kg P eq.]	6.19×10^{-5}	3.49×10^{-5}	7.54×10^{-4}	5.26×10^{-5}	-7.28×10^{-4}	1.75×10^{-4}	1.48×10^{-4}	-1.48×10^{-4}
EF 3.1 eutrophication, marine [kg N eq.]	7.19×10^{-3}	1.14×10^{-2}	8.56×10^{-2}	7.52×10^{-3}	-3.02×10^{-1}	-1.90×10^{-1}	3.43×10^{-2}	-3.43×10^{-2}
EF 3.1 eutrophication, terrestrial [mole of N eq.]	7.53×10^{-2}	1.73×10^{-1}	8.96×10^{-1}	9.39×10^{-2}	-3.31	-2.07	3.98×10^{-1}	-3.98×10^{-1}

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Table 2 (*Contd.*)

Configuration (C)	Gas treatment	Sorting	Pyrolysis	Shredding	Substitution	Total	Deviation 1	Deviation 2
EF 3.1 land use [Pt]	1.32×10^{2}	7.55×10^{1}	1.57×10^{3}	1.01×10^{2}	-3.15×10^{2}	1.56×10^{3}	2.44×10^{2}	-2.44×10^{2}
EF 3.1 ozone depletion [kg CFC-11 eq.]	3.38×10^{-10}	1.73×10^{-10}	5.00×10^{-9}	1.79×10^{-10}	-6.17×10^{-10}	5.07×10^{-9}	5.44×10^{-10}	-5.44×10^{-10}
EF 3.1 resource use, fossils [MJ]	3.13×10^{2}	2.20×10^{2}	3.72×10^{3}	2.38×10^{2}	-4.33×10^{4}	-3.88×10^{4}	3.18×10^{3}	-3.18×10^{3}
EF 3.1 resource use, mineral and metals [kg Sb eq.]	2.79×10^{-6}	1.54×10^{-6}	3.37×10^{-5}	1.88×10^{-6}	-9.88×10^{-5}	-5.90×10^{-5}	1.07×10^{-5}	-1.07×10^{-5}
EF 3.1 water use [m^3 world equiv.]	4.12	2.52×10^{1}	4.90×10^{1}	7.35	-1.37×10^{1}	7.20×10^{1}	2.00×10^{1}	-2.00×10^{1}
EF 3.1	1.13×10^{-3}	7.93×10^{-3}	1.35×10^{-2}	2.47×10^{-3}	-8.42×10^{-2}	-5.92×10^{-2}	1.09×10^{-2}	-1.09×10^{-2}
Configuration (D)	**Gas treatment**	**Pre-sorting**	**Pyrolysis**	**Shredding**	**Substitution**	**Total**	**Deviation 1**	**Deviation 2**
EF 3.1 acidification [mole of H^+ eq.]	4.83×10^{-3}	4.19×10^{-2}	3.48×10^{-1}	2.72×10^{-2}	-1.56	-1.14	1.55×10^{-1}	-1.55×10^{-1}
EF 3.1 climate change – total [kg CO_2 eq.]	2.53	2.55×10^{2}	1.82×10^{2}	6.70×10^{1}	-4.56×10^{2}	5.06×10^{1}	1.83×10^{2}	-1.83×10^{2}
EF 3.1 ecotoxicity, freshwater – total [CTUe]	1.52×10^{1}	1.06×10^{2}	1.10×10^{3}	1.05×10^{2}	-2.78×10^{4}	-2.65×10^{4}	1.86×10^{3}	-1.86×10^{3}
EF 3.1 eutrophication, freshwater [kg P eq.]	1.04×10^{-5}	3.49×10^{-5}	7.65×10^{-4}	5.30×10^{-5}	-8.30×10^{-4}	3.33×10^{-5}	1.49×10^{-4}	-1.49×10^{-4}
EF 3.1 eutrophication, marine [kg N eq.]	1.21×10^{-3}	1.14×10^{-2}	8.69×10^{-2}	7.57×10^{-3}	-2.89×10^{-1}	-1.82×10^{-1}	3.30×10^{-2}	-3.30×10^{-2}
EF 3.1 eutrophication, terrestrial [mole of N eq.]	1.26×10^{-2}	1.73×10^{-1}	9.09×10^{-1}	9.44×10^{-2}	-3.18	-1.99	3.84×10^{-1}	-3.84×10^{-1}
EF 3.1 land use [Pt]	2.21×10^{1}	7.55×10^{1}	1.59×10^{3}	1.01×10^{2}	-1.56×10^{2}	1.63×10^{3}	2.24×10^{2}	-2.24×10^{2}
EF 3.1 ozone depletion [kg CFC-11 eq.]	5.67×10^{-11}	1.73×10^{-10}	5.06×10^{-9}	1.81×10^{-10}	-2.73×10^{-10}	5.19×10^{-9}	4.95×10^{-10}	-4.95×10^{-10}
EF 3.1 resource use, fossils [MJ]	5.25×10^{1}	2.20×10^{2}	3.78×10^{3}	2.40×10^{2}	-4.22×10^{4}	-3.79×10^{4}	3.09×10^{3}	-3.09×10^{3}
EF 3.1 resource use, mineral and metals [kg Sb eq.]	4.68×10^{-7}	1.54×10^{-6}	3.42×10^{-5}	1.90×10^{-6}	-1.22×10^{-4}	-8.34×10^{-5}	1.18×10^{-5}	-1.18×10^{-5}
EF 3.1 water use [m^3 world equiv.]	6.92×10^{-1}	2.52×10^{1}	4.98×10^{1}	7.37	-8.07	7.49×10^{1}	1.93×10^{1}	-1.93×10^{1}
EF 3.1	1.90×10^{-4}	7.93×10^{-3}	1.37×10^{-2}	2.48×10^{-3}	-8.56×10^{-2}	-6.13×10^{-2}	1.09×10^{-2}	-1.09×10^{-2}

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operation itself, the benefits of substitution of secondary products and the overall impact of technology configurations. In the case of sorting, the treatment of waste that has been sorted as unsuitable for the technology is also considered. In gas treatment, the cogeneration of process gas in configurations A and B is taken into account.

Of the 4 configurations assessed, configuration A has the lowest potential impacts in categories: acidification, eutrophication, freshwater, land use, ozone depletion, resource use, fossils and water use. Configuration B shows the lowest values in categories ecotoxicity, freshwater and resource use, minerals and metals, configuration C in categories eutrophication, marine and terrestrial and configuration D shows the lowest values in climate change and the aggregated environmental eootprint. Configuration D achieves the lowest environmental impact in these indicators mainly because it does not produce direct emissions from the combustion of process gas in the plant.

In the case of several impact categories and the aggregated environmental footprint, the benefits from the savings in primary raw material production by substitutions are higher than the technology operation itself.

In the case of the impact category climate change and water use, the sorting phase also contributes significantly to the overall impact. This is entirely consistent with the findings of the study of G. Yadav *et al.*, who concluded that the high level of emissions is related to the requirements for pre-treatment of raw materials, including the use of electricity.[53]

In the case of the aggregated indicator, this is mainly attributed to the savings in fossil resource consumption. The normalized and weighted results of the impact categories for all pyrolysis configurations (per 1 tonne) are presented in Fig. 3. The results show that the largest contribution to the environmental footprint is in the category of climate change, resource use, fossils and ecotoxicity, freshwater.

From the presented results, it can be seen how the chosen pyrolysis configuration has a significant influence on potential environmental impacts. Within each impact category, the results vary significantly for the total minimum and maximum. Specifically, in the case of the climate change category, the results reveal a high variability across configurations, ranging from −133 to 966 kg CO_2 eq. per tonne of mixed plastic waste. In the case of the environmental footprint, the results ranging from −0.014 to −0.072.

The study also aimed to compare environmental indicators with alternative waste management technologies, specifically waste-to-energy and mechanical recycling. Energy recovery and mechanical recycling are focused here since landfilling is planned to be reduced in the near future in accordance with legislative requirements. The following Fig. 4 presents the results of the climate change indicator per 1 tonne of mixed plastic waste that subsequently enters the technology, distinguishing the contribution of substitutions themselves. The result in the category climate change of the pyrolysis is presented as an average value of all assessed pyrolysis configurations. The results in the category climate change of the waste-to-energy of plastic waste are presented as an average value of the generic data from LCA professional databases. In the case of mechanical recycling, the result is related to a specific recycling technology that processes mixed plastic waste together with inert waste to produce composite tiles that can be used as a replacement for concrete tiles. It would not be appropriate to compare the results with the mechanical recycling of single plastic waste. Therefore, this specific mechanical recycling technology was chosen, which processes mixed waste plastics as does pyrolysis.

Fig. 4 shows the impact of technology operation, the savings associated with primary production substitutions, and the overall value represented by a dot for each technology. For substitution modelling, the benefits from electricity and heat

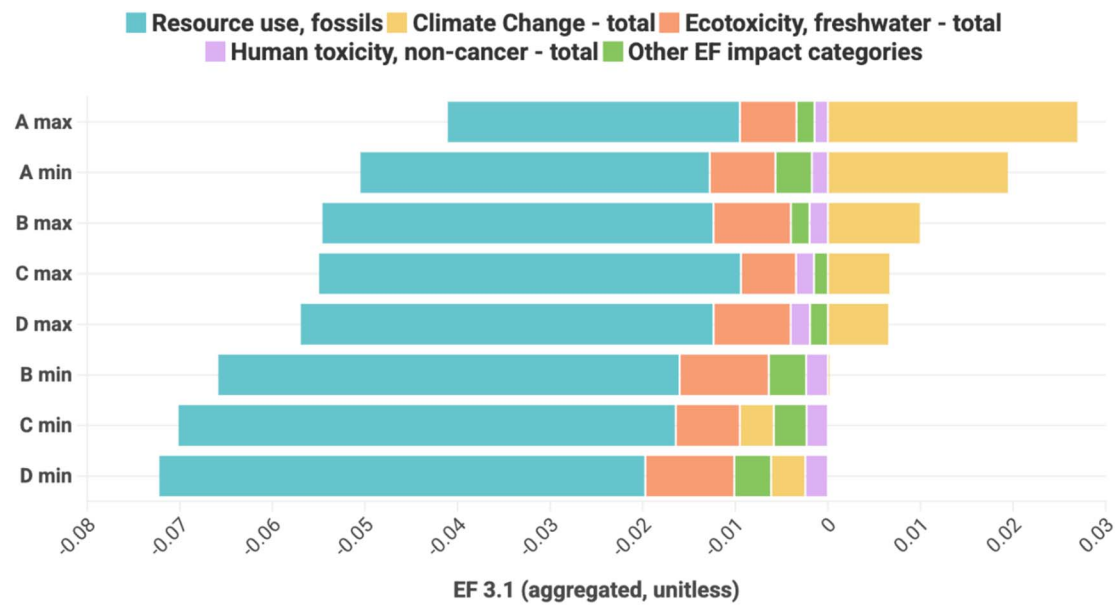

Fig. 3 The normalized and weighted results of the impact categories for all configurations.

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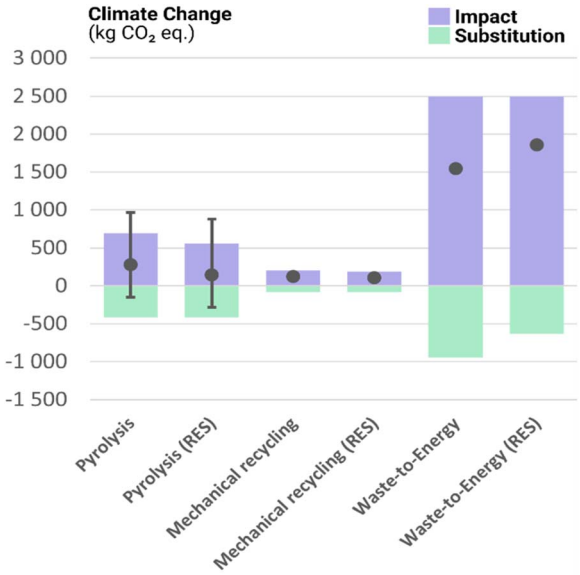

Fig. 4 Comparison of pyrolysis of waste plastics with other waste treatment technologies.

production in waste-to-energy are considered. The benefits from the secondary product (composite tiles) in mechanical recycling are considered.

The results show that the substitutions themselves, *i.e.* the contributions associated with the production of secondary products and the substitution of primary material production have a significant impact on the overall carbon and environmental footprint when assessing technologies from a waste management perspective.

In the case of the carbon footprint, the emissions associated with the operation of the technologies considered are higher than the benefits from the savings (substitutions) in the production of primary materials. The environmental impacts of pyrolysis technology can range widely due to the variable setup. However, the results show that pyrolysis of mixed plastic waste has a lower carbon footprint compared to the waste-to-energy. This finding is consistent with the findings of other studies.[52,54,55]

The figure also presents technologies using the renewable energy sources (RES) mix for their operation to estimate potential future development. It can be seen that the shift towards renewable energy sources will have a positive effect on the carbon footprint of pyrolysis in particular.

3.2. Secondary products analysis

The Fig. 5 presents the results for pyrolysis in secondary product production boundaries in each impact category. The detailed results for pyrolysis products are presented in Table 3. The results for secondary products from pyrolysis technology are presented as the average of the values (all configurations) with the deviations shown. The results for primary products are presented as the average value of the generic data from LCA background datasets. The results are presented per 1 tonne of produced secondary product or per 1 tonne of produced primary product (naphtha, lignite and CNG).

According to the results, the carbon footprint of 1 tonne of pyrolysis product ranges from 377 to 2181 kg CO_2 eq. depending on the technology configuration. The carbon footprint of the production of naphtha and CNG is approximately at the same level as the configuration C or D. When comparing the

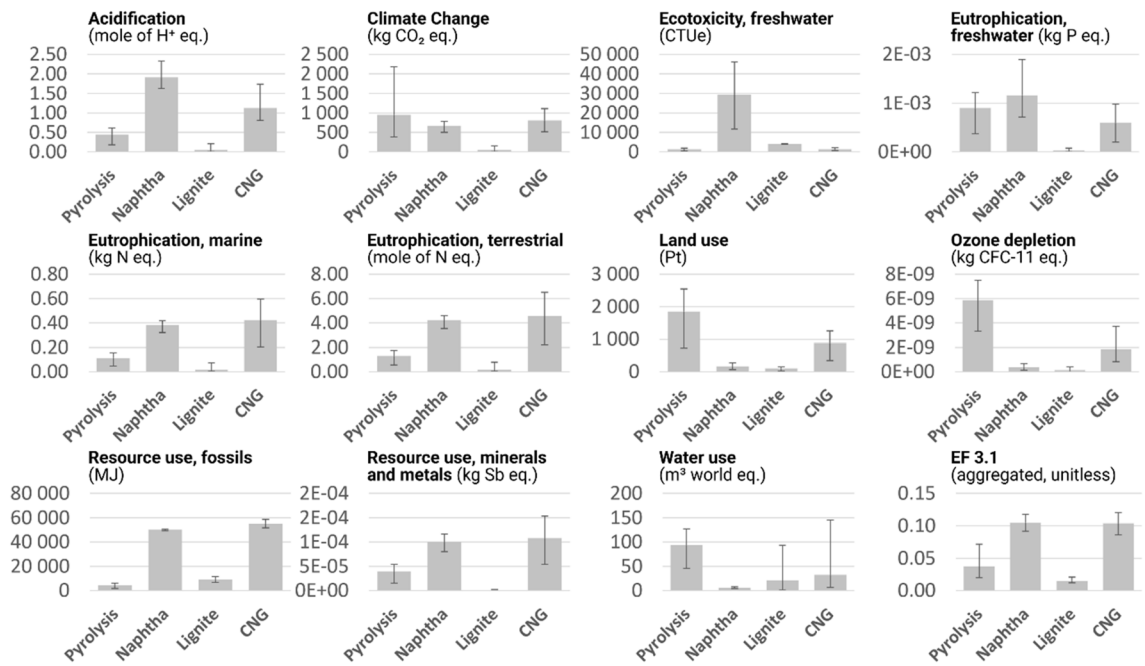

Fig. 5 Potential environmental impacts of pyrolysis secondary products compared with primary materials for individual categories of the environmental footprint methodology.

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Table 3 Potential environmental impacts of pyrolysis secondary products for individual categories of the environmental footprint methodology

Pyrolysis products	A (max)	A (min)	B (max)	B (min)	C (max)	C (min)	D (max)	D (min)
EF 3.1 acidification [mole of H^+ eq.]	4.58×10^{-1}	1.84×10^{-1}	5.65×10^{-1}	3.60×10^{-1}	6.10×10^{-1}	4.06×10^{-1}	5.85×10^{-1}	3.89×10^{-1}
EF 3.1 climate change – total [kg CO_2 eq.]	2.18×10^{3}	1.58×10^{3}	9.71×10^{2}	5.24×10^{2}	8.16×10^{2}	3.86×10^{2}	8.03×10^{2}	3.77×10^{2}
EF 3.1 climate change, biogenic [kg CO_2 eq.]	1.82	7.36×10^{-1}	2.43	1.62	2.66	1.85	2.54	1.76
EF 3.1 climate change, fossil [kg CO_2 eq.]	2.18×10^{3}	1.58×10^{3}	9.68×10^{2}	5.22×10^{2}	8.13×10^{2}	3.84×10^{2}	8.00×10^{2}	3.75×10^{2}
EF 3.1 climate change, land use and land use change [kg CO_2 eq.]	1.96×10^{-1}	1.39×10^{-1}	1.62×10^{-1}	1.20×10^{-1}	1.60×10^{-1}	1.19×10^{-1}	1.58×10^{-1}	1.18×10^{-1}
EF 3.1 ecotoxicity, freshwater – total [CTUe]	1.42×10^{3}	6.01×10^{2}	1.76×10^{3}	1.15×10^{3}	1.90×10^{3}	1.29×10^{3}	1.82×10^{3}	1.24×10^{3}
EF 3.1 ecotoxicity, freshwater inorganics [CTUe]	1.32×10^{3}	5.65×10^{2}	1.68×10^{3}	1.12×10^{3}	1.83×10^{3}	1.26×10^{3}	1.75×10^{3}	1.21×10^{3}
EF 3.1 ecotoxicity, freshwater organics [CTUe]	1.02×10^{2}	3.60×10^{1}	7.76×10^{1}	2.91×10^{1}	7.46×10^{1}	2.84×10^{1}	7.43×10^{1}	2.82×10^{1}
EF 3.1 eutrophication, freshwater [kg P eq.]	8.58×10^{-4}	3.77×10^{-4}	1.12×10^{-3}	7.59×10^{-4}	1.22×10^{-3}	8.58×10^{-4}	1.17×10^{-3}	8.21×10^{-4}
EF 3.1 eutrophication, marine [kg N eq.]	1.18×10^{-1}	4.79×10^{-2}	1.44×10^{-1}	9.13×10^{-2}	1.55×10^{-1}	1.03×10^{-1}	1.48×10^{-1}	9.83×10^{-2}
EF 3.1 eutrophication, terrestrial [mole of N eq.]	1.41	5.64×10^{-1}	1.63	1.00	1.74	1.12	1.67	1.07
EF 3.1 human toxicity, cancer – total [CTUh]	7.48×10^{-8}	3.02×10^{-8}	9.51×10^{-8}	6.19×10^{-8}	1.03×10^{-7}	7.01×10^{-8}	9.89×10^{-8}	6.70×10^{-8}
EF 3.1 human toxicity, cancer inorganics [CTUh]	1.70×10^{-8}	7.24×10^{-9}	1.87×10^{-8}	1.15×10^{-8}	1.98×10^{-8}	1.26×10^{-8}	1.91×10^{-8}	1.22×10^{-8}
EF 3.1 human toxicity, cancer organics [CTUh]	5.77×10^{-8}	2.30×10^{-8}	7.64×10^{-8}	5.05×10^{-8}	8.36×10^{-8}	5.75×10^{-8}	7.98×10^{-8}	5.49×10^{-8}
EF 3.1 human toxicity, non-cancer – total [CTUh]	1.90×10^{-6}	7.49×10^{-7}	2.01×10^{-6}	1.16×10^{-6}	2.11×10^{-6}	1.27×10^{-6}	2.04×10^{-6}	1.23×10^{-6}
EF 3.1 human toxicity, non-cancer inorganics [CTUh]	1.86×10^{-6}	7.32×10^{-7}	1.97×10^{-6}	1.13×10^{-6}	2.07×10^{-6}	1.25×10^{-6}	2.00×10^{-6}	1.20×10^{-6}
EF 3.1 human toxicity, non-cancer organics [CTUh]	4.38×10^{-8}	1.71×10^{-8}	4.63×10^{-8}	2.64×10^{-8}	4.85×10^{-8}	2.91×10^{-8}	4.69×10^{-8}	2.80×10^{-8}
EF 3.1 ionising radiation, human health [kBq U235 eq.]	1.02×10^{2}	4.11×10^{1}	1.40×10^{2}	9.44×10^{1}	1.54×10^{2}	1.08×10^{2}	1.47×10^{2}	1.03×10^{2}
EF 3.1 land use [Pt]	1.75×10^{3}	7.23×10^{2}	2.33×10^{3}	1.56×10^{3}	2.55×10^{3}	1.77×10^{3}	2.43×10^{3}	1.69×10^{3}
EF 3.1 ozone depletion [kg CFC-11 eq.]	5.88×10^{-9}	3.31×10^{-9}	6.99×10^{-9}	5.07×10^{-9}	7.51×10^{-9}	5.56×10^{-9}	7.21×10^{-9}	5.36×10^{-9}
EF 3.1 Particulate matter [disease incidences]	4.22×10^{-6}	1.69×10^{-6}	5.01×10^{-6}	3.12×10^{-6}	5.37×10^{-6}	3.50×10^{-6}	5.16×10^{-6}	3.35×10^{-6}
EF 3.1 Photochemical ozone formation, human health [kg NMVOC eq.]	3.19×10^{-1}	1.29×10^{-1}	3.85×10^{-1}	2.43×10^{-1}	4.14×10^{-1}	2.73×10^{-1}	3.97×10^{-1}	2.62×10^{-1}
EF 3.1 resource use, fossils [MJ]	4.26×10^{3}	1.75×10^{3}	5.60×10^{3}	3.72×10^{3}	6.12×10^{3}	4.23×10^{3}	5.85×10^{3}	4.04×10^{3}
EF 3.1 resource use, mineral and metals [kg Sb eq.]	3.72×10^{-5}	1.57×10^{-5}	4.94×10^{-5}	3.33×10^{-5}	5.41×10^{-5}	3.78×10^{-5}	5.16×10^{-5}	3.61×10^{-5}
EF 3.1 water use [m^3 world equiv.]	1.23×10^{2}	4.55×10^{1}	1.23×10^{2}	6.56×10^{1}	1.27×10^{2}	7.14×10^{1}	1.23×10^{2}	6.89×10^{1}
EF 3.1	7.15×10^{-2}	4.83×10^{-2}	4.05×10^{-2}	2.33×10^{-2}	3.73×10^{-2}	2.06×10^{-2}	3.63×10^{-2}	1.99×10^{-2}

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production of secondary products with primary products, a more appropriate indicator is the environmental footprint, which includes all potential environmental impacts, including the consumption of fossil resources, which is relevant in the case of the production of secondary products from waste. The environmental footprint of the production of primary materials (naphtha and CNG) is higher than that of pyrolysis products. This supports the fact that attention should be paid to integrating these technologies into waste management systems in order to promote material recovery of waste.

3.3. Sensitivity analysis

Sensitivity analysis to the range of input data is also performed by determining the pyrolysis configurations and further by determining the range of values of technological parameters in the range of min and max for all considered configurations. As the main contributor to the carbon footprint and the aggregated environmental footprint is the electricity consumption to support the technology operation, the energy mix of the electricity supplier will play an important role. This fact is also in line with the conclusion of the LCA study of the pyrolysis process,[41] which shows that most technological emissions are associated with electricity consumption.

In the case of the A and B configurations, a significant part of the energy consumption can be covered by the actual production of process gas and its combustion in a microturbine. In the case of the climate change impact category, there is a potential reduction of up to 50% for an average of all assessed pyrolysis configurations when using electricity from renewable energy sources as presented in Fig. 4. The results of sensitivity analysis of changes in the electricity mix are presented in Fig. 6. The results of this work are in line with the researchers Laura Pires Costa *et al.*, who, after analyzing existing LCA studies, believe that pyrolysis experiments should focus on improving carbon conversion efficiency and using renewable energy sources in combination with a chemical recycling approach.[56]

In addition, the sensitivity analysis considered the change in the distance of collection of incoming waste. Despite a 300% increase in the distances for transporting both collected and produced waste during technology operation, it was determined that this change had a minimal impact on the overall results, with a maximum effect of 8%.

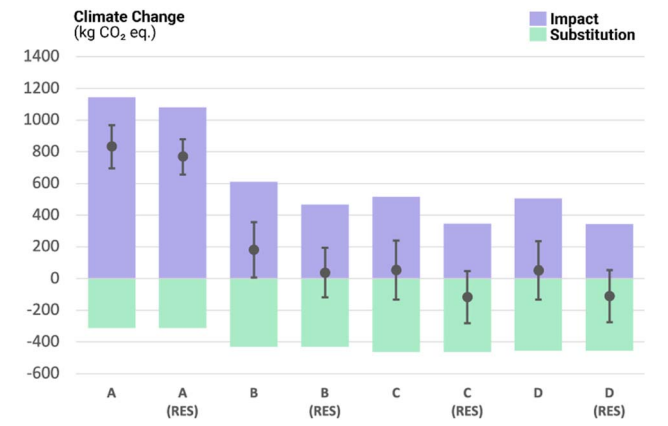

Fig. 6 Sensitivity analysis of change in the energy mix for all pyrolysis configurations.

4 Conclusions

The analysis of the results shows that the construction phase is a minor contributor to the overall impacts of the technologies considered. It can be concluded that the key impact categories for the assessed pyrolysis technology are climate change and fossil resource consumption. Although there are significant trade-offs among impact categories between the individual process configurations, the aggregated environmental footprint allows us to conclude that the lowest overall environmental impacts are associated with configuration D.

The environmental impacts of pyrolysis can vary widely due to the variable configurations. The results of sensitivity analysis show that a shift towards renewable energy sources can significantly reduce the overall environmental impacts of pyrolysis. It is very important to focus on assessing the potential environmental impacts of a particular pyrolysis technology configuration in conjunction with the consumption of a particular energy mix.

Furthermore, it is important to note that when comparing technologies in terms of waste treatment boundaries, the contributions related to the production of secondary products and the substitution of the production of primary materials have a significant impact on the overall environmental burden.

The results of this study show that the pyrolysis technology of mixed waste plastics has a lower impact in the category of climate change compared to the treatment of waste-to-energy.

For further research it is important to focus on concrete data from the real operation of pyrolysis technologies and also on the assessment of the quality of the produced secondary products with regard to their practical applications. There is also a lack of data regarding the treatment of produced secondary products to achieve quality for usable applications.

Despite this missing information, the study shows that pyrolysis of mixed plastic waste can reduce the impacts of climate change in waste management and promote material recovery of waste. These are also objectives of the European Union waste policy, *i.e.*, to reduce landfilling, promote material and energy recovery of waste, and ensure overall environmental acceptability to the maximum extent possible.

Author contributions

Tatiana Trecáková: writing – original draft, writing – review & editing, validation, methodology, investigation, formal analysis, data curation, conceptualization. Aleš Paulu: writing – review & editing, methodology, validation, visualization. Ivanna Harasymchuk: writing – review & editing, formal analysis. Hana Brunhoferová: writing – review & editing, formal analysis. Vladimír Kočí: writing – review & editing, supervision, validation.

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Conflicts of 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

All the data are available within the article.

Supplementary information: Table S1 providing list of all secondary data. See DOI: https://doi.org/10.1039/d5va00182j.

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