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Life-Cycle Assessment of the thermal and catalytic pyrolysis over sepiolite of face masks

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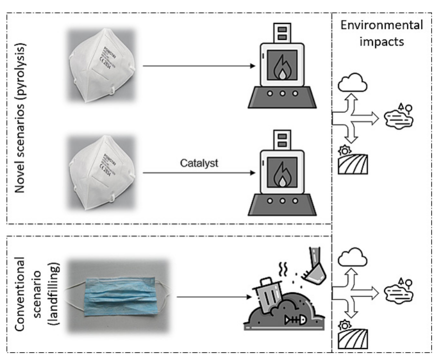
HIGHLIGHTS

- Large amounts of face masks were used and discarded during the COVID-19 pandemic.
- Current options for managing this waste are costly and have environmental impacts.
- Thermal and catalytic pyrolysis of face masks is proposed as a sustainable option.
- We analyse the environmental impact of the pyrolysis using Life-Cycle Assessment.
- Thermal pyrolysis has a better environmental performance than catalytic pyrolysis.

GRAPHICAL ABSTRACT



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ABSTRACT

Since the start of the global COVID-19 pandemic, extensive quantities of face masks have been used and discarded. Most of these masks end up in landfills, causing a high environmental impact and no benefits. However, there are alternative ways to deal with this waste in a more sustainable way. For example, valorisation of face masks through pyrolysis has received special attention because it offers efficient application to produce a liquid oil that can be used as a diesel substitute and a solid char that can be used as an activated carbon substitute after activation. In this context, this study applies the Life-Cycle Assessment methodology to quantify and analyse the environmental impacts of different treatment scenarios based on the pyrolysis of surgical masks and FFP2 masks. It also compares their environmental performance with the conventional practice of landfilling. The scenarios studied include both thermal and catalytic pyrolysis by using sepiolite, a low-cost material abundant in Spain. Data on the pyrolysis process were obtained from laboratory experiments. It was found that the use of the produced oil as a diesel substitute very significantly reduces the environmental impact in all pyrolysis scenarios. Consequently, the pyrolysis of face masks can reduce the environmental impact caused by the treatment of this waste material. Furthermore, the thermal pyrolysis performs environmentally better than the catalytic pyrolysis. In all scenarios, freshwater ecotoxicity and marine ecotoxicity are the environmental impact categories that cause the highest environmental impact overall.

1. Introduction

Large amounts of disposable plastic face masks have been produced and used for preventing the global COVID-19 pandemic (Liao et al., 2022). There are two main types of plastic masks: surgical masks, which filter the particles emitted by the wearer, and the high-efficiency masks (Filtering Face Piece, FFP/Filter Personal Protection, FPP), designed to filter particles, liquid aerosols and pathogens present in the environment, preventing them from being inhaled by the user. In both cases, the filtering material is a network of plastic fibres that retains the contaminant. Depending on its filtering efficiency, according to the European Union standard EN 149, three

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types are distinguished: FFP1 (filtration efficiency 78 %), with low efficiency; FFP2 (filtration efficiency 92 %), with medium efficiency; and FFP3 (filtration efficiency 98 %), with high efficiency. The N95 filtering masks, according to American regulations, have a particle filtering capacity of 95 %.

Plastic masks are made of single-use polymers, and therefore they are major sources of plastics and toxic pollutants in the environment, posing an emerging threat as source of microplastics via degradation (Li et al., 2022). Unfortunately, managing the enormous amount of new plastic masks waste generated by the pandemic is a challenge that currently remains unaddressed. Incineration of masks is a possible treatment, but some toxic substances like harmful dioxins can be released into the atmosphere (Wang et al., 2020). Landfilling is the most established practice of disposal of plastic mask waste. Although this option can effectively address the accumulation of plastic masks waste, it introduces other environmental problems, such as secondary pollution and greenhouse gas emissions (Yuwen et al., 2023). Therefore, an efficient and innovative waste management strategy for the discarded face masks, both surgical and FFP, is urgently needed (Kiong et al., 2022).

Pyrolysis is one of the most promising techniques to manage plastic mask waste. Pyrolysis is a thermochemical conversion process where the thermal degradation of waste takes place in the complete absence of oxygen at temperatures between 400 and 600 °C for some specified time. The products of pyrolysis are mainly a liquid oil, non-condensable gases, and solid char. The liquid oil is mainly composed of hydrocarbons with a good calorific value and similar properties to those of fossil fuels (Cui et al., 2023). The non-condensable gases are mainly composed of methane, carbon monoxide and hydrogen. The solid char is a carbon-rich solid material with inorganic compounds present in plastics. Some authors have successfully used char from pyrolysis of plastic waste as a cost-effective precursor for the preparation of activated carbon (Kadirova et al., 2006; Song et al., 2022). Recently, other researchers have investigated the use of plastic mask waste as a feedstock for producing valuable products via pyrolysis, e.g. fuel (Aragaw and Mekonnen, 2021), oil (Ramalingam et al., 2023; Yuwen et al., 2023), oil, gas and char (Dharmaraj et al., 2021), and bio-oil and biochar (Oginni, 2021). The oil produced via pyrolysis of plastic mask waste can be used as an alternative to diesel fuel due to their similar properties (Ramalingam et al., 2023). In addition, catalytic pyrolysis has been widely recognized as a promising platform for the thermochemical conversion of plastic waste to useful chemicals and fuels. Various catalyst types have been examined to optimize the resulting oil yields and properties, such as composition and stability. However, according to our knowledge, there are very few industrial plants that use catalytic pyrolysis in the treatment of plastic wastes, so it is an operation that remains mostly at laboratory or pilot plant scale (Xayachak et al., 2022).

Despite of the promising results of the pyrolysis of plastic mask waste reported in the literature, the determinations of the environmental impacts of the overall pyrolysis process must be examined. A theoretical way of defining the best plastic mask waste management option in terms of environmental sustainability is offered by the Life-Cycle Assessment (LCA) methodology, which can be used as a reliable decision-making support method for modern integrated waste management systems (Cossu et al., 2017). In this context, some interesting articles have quantified the environmental performance of waste plastics treatments by means of LCA. For example, Arena and Ardolino (2022) compared the environmental performances of current management options of plastic materials from waste of electric and electronic equipment, end-of-life vehicles and construction and demolition waste. Yousef et al. (2022) evaluated the pyrolysis treatment of surgical masks waste at 525 °C and reported an important reduction of global warming potential when compared to an incineration scenario. Nabavi-Pelesaraei et al. (2022) performed a structured investigation of the potential environmental impacts of various scenarios for the management of COVID-19 medical waste. Zhao et al. (2022) applied an LCA to study an efficient system for personal protective equipment waste that included twelve treating units. They concluded that their process reduced greenhouse gases emissions and fossil fuel use compared to the conventional incineration process. However, although there is some research on the environmental impact of pyrolysis of different types of polymers, we have not found any previous work that considers the use of natural clays, in particular sepiolite, as a catalyst.

In this context, this study quantifies and analyses the life-cycle environmental impact of different treatment scenarios based on the pyrolysis of surgical and FFP2 masks compared against the conventional practice of landfilling. These scenarios include both thermal and catalytic pyrolysis by using sepiolite as low-cost catalyst. Local clay and clay-based materials (such as sepiolite) are good candidates as catalysts for plastic waste pyrolysis due to their low cost and good supply (Fadillah et al., 2021; Ortega et al., 2023; Serra et al., 2022). Inventory data for both masks and the typology of the pyrolysis process were provided by laboratory experiments.

2. Methodology

This study applies the LCA methodology to study the environmental impact of several waste treatments of surgical and FFP2 masks. The LCA applied complies with the following standards by the International Organization for Standardization: ISO 14040:2006 and ISO 14044:2006 (ISO, 2006a, 2006b). According to these standards, LCA should be divided into four phases: goal and scope, life-cycle inventory, life-cycle impact assessment and interpretation. The first two phases are covered in the next two subsections, while the last two, that present and discuss the LCA results, are presented in Section 3.

2.1. Goal and scope

The objective of this LCA was to quantify the environmental impact of the pyrolysis of face masks. The functional unit was set as the treatment of 1 kg of face masks. Four scenarios were considered:

1. Pyrolysis of FFP2 masks with no catalyst
2. Pyrolysis of FFP2 masks with catalyst
3. Pyrolysis of surgical masks with no catalyst
4. Pyrolysis of surgical masks with catalyst

The results from these scenarios were compared against conventional practices, which form the following two scenarios:

5. Landfilling of FFP2 masks
6. Landfilling of surgical masks

The six scenarios considered are represented in Fig. 1.

The processes modelled and included in the scope of the study are shown in Fig. 2, while the value for each flow under each scenario is listed in Table 1. Arrows represent flows of material or energy, whereas boxes represent processes. The "market" boxes represent the substitution of a marketed product by the product from the pyrolysis. Thus, the oil produced in the pyrolysis substitutes the use of commercial diesel based on their Higher Heating Value (HHV), while the char (coke) produced was assumed to substitute commercial activated carbon.

The system analysed included emissions and resource depletion of all the processes needed to undertake the pyrolysis (Fig. 2) as well as all emissions and resource depletion associated with the materials and processes within the system boundaries, e.g., use of electricity and catalyst. The main raw material in the process, i.e., face masks, was allocated no environmental impact, following a zero-burden approach along the lines of other waste management studies, for instance Garcia-Garcia and Rahimifard (2019).

2.2. Life-cycle inventory

Data to form the life-cycle inventory were collected from experimental work, described in detail in our previous article (Ortega et al., 2023) and

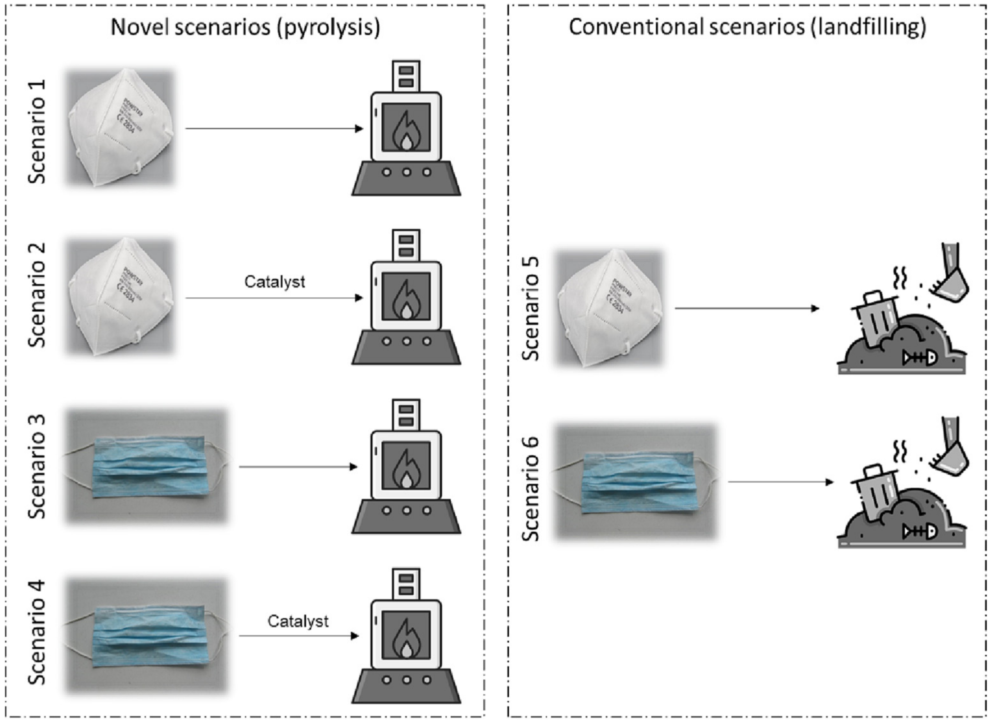

Fig. 1. Scenarios considered in the study.

summarised below, and the commercial database ecoinvent 3.7. The life-cycle inventory is shown in Table 1.

A detailed characterization of the two types of face masks is reported in our previous article (Ortega et al., 2023). The composition of the masks was determined by Fourier-transform infrared spectroscopy (FTIR), using a Perkin-Elmer Spectrum 65 spectrophotometer. The masks were separated into their individual layers. The surgical mask contained three layers, while the FFP2 mask contained five layers. In addition, both masks contain a nose bridge and ear straps, which are discarded. All layers of surgical masks were made of polypropylene (PP). However, FFP2 masks have two types of materials, three layers of PP and two layers of polyethylene (PE). Also, different ash contents were determined. In addition, in plastic materials used in most products the basic polymer is incorporated into a formulary (plastic compound) with different 'additives', which are chemical compounds added to improve the performance, functionality and ageing properties of the polymer. Each of them plays a distinct role in delivering/enhancing the (final) functional properties of a plastic product. These additives can modify the pyrolytic behaviour of the plastic materials. For

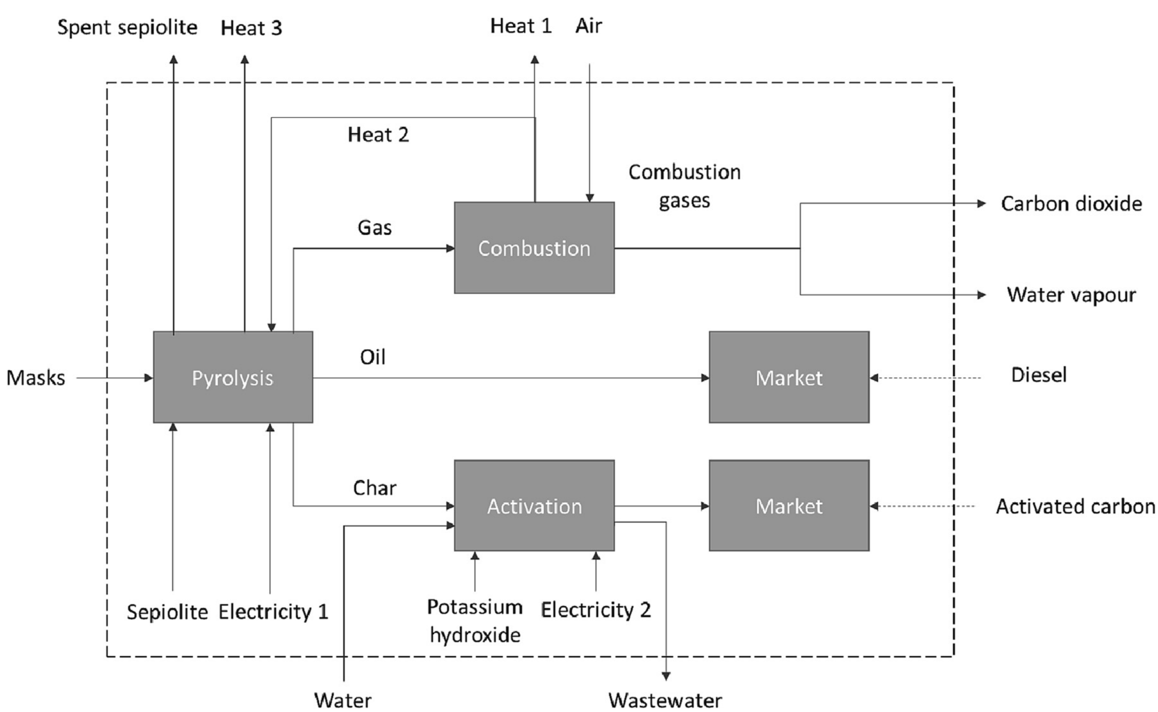

Fig. 2. Block flow diagram and system boundaries.

Table 1
Life-cycle inventory.

Flow name	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Unit
Mask	1000	1000	1000	1000	g
Sepiolite	0	50	0	50	g
Spent sepiolite	0	50	0	50	g
Gas	394	505	395	439	g
Oil	589	463	591	522	g
Char	17.3	32.0	14.0	39.3	g
Air	4867	6320	4767	5360	g
Combustion gases	1513	1980	1500	1687	g
Carbon dioxide	1013	1233	973	1080	g
Water vapour	502	747	525	605	g
Diesel	647	579	667	590	g
Electricity 1	0.300	0.300	0.300	0.300	kWh
Electricity 2	0.095	0.175	0.076	0.215	kWh
Water	347	640	280	787	g
Potassium hydroxide	6	11	5	14	g
Wastewater	353	651	285	800	g
Activated carbon	17.3	32.0	14.0	39.3	g
Heat 1	6.8	8.0	6.3	6.9	MJ
Heat 2	10.0	11.9	9.2	10.3	MJ
Heat 3	1.9	1.5	1.1	1.2	MJ

example, post-industrial PP film or dirty post-consumer rigid PP can show different product yields and product composition. Therefore, because of the differences observed in characterization and pyrolysis, we have separated these two masks under two different entities for their study.

The experimental work started with the pyrolysis of 15 g of FFP2 or surgical masks, depending on the scenario. No shredding was performed since the samples were small and light enough to be fed to the pyrolysis oven and no shredding would be carried out at an industrial scale. It must be noted that the data presented in Table 1 were scaled up to 1 kg of masks, which was the reference flow of the model. The experimental data obtained for the pyrolysis of 15 g of masks are presented in Supplementary Material (Table S1).

The mask samples were introduced in the pyrolysis oven and heated at 10 °C/min until reaching the temperature target of 500 °C. This temperature was maintained for 1 h, during which 50 L/h of N_2 were passed through the system. N_2 left the system with the gases formed in the process. Nevertheless, since N_2 is not used in industrial pyrolysis, this gas flow has not been considered in this study. The gas formed was cooled at −8 °C to condensate the heaviest hydrocarbons and separate them from the lightest hydrocarbons, which remained in gas form.

The proportion of gas, oil and char obtained from the pyrolysis process was measured, while the composition of each of these mass flows were also determined experimentally. Oil composition was determined by gas chromatography (GC) coupled with mass spectrometry (Agilent 7890A/Waters Quattro MicroGC), gas composition by using a gas chromatograph Agilent 990 equipped with two channels for separation and detection and a micro-machined thermal conductivity detector, and char composition was determined by elemental analysis using an elemental analyser (TruSpec Micro CHNS). The composition of the gas, oil and char for each scenario is given in Supplementary Material (Tables S2–S4).

The gas obtained from the pyrolysis was combusted to recover its energy, which was fed back to the pyrolysis. This is a common approach followed in similar studies (e.g., Chamkalani et al., 2020; Li et al., 2022; Peters et al., 2015). The combustion did not need an input of energy. This combustion was assumed to be complete, so only CO_2 and H_2O were produced, which were released to the environment. The composition of this combustion gas was determined based on the stoichiometry of the chemical reaction. Based on this calculation, it was determined that an input of O_2 was needed for the combustion. Based on the mass ratio of oxygen in air, the input of air needed for the combustion was calculated. In scenarios 1 and 3 no catalyst was used for the gas combustion, while in scenarios 2 and 4 sepiolite, with chemical formula $Mg_4Si_6O_{15}(OH)_2{\cdot}6H_2O$, was added as catalyst. The amount of catalyst added was 5 % of the mask sample, i.e., 0.75 g. Due to low price and the large amount of energy needed to regenerate sepiolite, spent sepiolite was discarded after each batch, and new sepiolite was added for the subsequent batch.

The composition of the oil was used to determine how much commercial diesel it could substitute. Previous research has shown that oil generated by pyrolysis of Covid-19 medical waste, such as face masks, has very similar properties to those of diesel and that this oil can be used as a fuel without any modification in a diesel engine (Ramalingam et al., 2023). Arjharn et al. (2022) and Sushma (2018) also confirmed that oil from pyrolyzed plastic waste has very similar physical properties to those of conventional diesel. However, Arjharn et al. (2022) observed some differences on combustion characteristics and exhaust gas emissions produced by both fuels burned in a diesel engine. Pyrolysis oil contributes to the larger amount of nitrogen oxides than diesel fuel. Carbon-based emissions also increased when the engine operates with pyrolysis oil by retarding the ignition onset of their combustion occurrences. Therefore, the utilization of pyrolysis oil causes slightly different effects from the conventional diesel fuel.

In our work, the emissions have been calculated based on theoretical combustion reactions and elemental composition of pyrolysis oil, since there are no experimental data on emissions obtained for the combustion of pyrolysis oil from plastic masks in a diesel engine.

These reasons justify the choice of direct substitution of commercial diesel by the oil. For such a substitution, the HHV of the oil was calculated based on the work by Channiwala and Parikh (2002). Its values are given in Table 2. The HHV of commercial diesel was assumed to be 45.6 MJ/kg (Engineering Toolbox, 2001). Based on this, 1 kg of oil substituted between 1.10 and 1.15 kg of diesel, depending on the HHV under each scenario. Similarly, the calculated HHV of the gases, used to calculate Heat 1 and Heat 2, are listed in Table 2.

The char was activated so it could be used as a substitute of commercial activated carbon. The composition and Brunauer-Emmett-Teller (BET) surface area of two commercial activated carbons can be found in Table S6 of Supplementary Material. Based on such composition and that of the activated char (Table S5), like that of commercial activated carbon, a substitution ratio of 1:1 was considered realistic.

The HHV of the gas (Table 2) was used to calculate the heat that can be obtained from the combustion. A heat loss of 40.4 % was assumed (*Heat 1*), as in similar work by Zhang et al. (2020). The remaining heat (*Heat 2*) is used in the pyrolysis. The heat needed in the pyrolysis was taken from Zhang et al. (2020), who calculated a value of 20.6 MJ/kg for the pyrolysis of polyethylene at 500 °C. Therefore, an excess of heat was released (*Heat 3*), which was calculated from the difference between *Heat 2* and 20.6 MJ/kg.

The electricity needed in the pyrolysis plant was taken from Kodera et al. (2021), who estimated that 60 kW of power are needed for the pyrolysis of 200 kg/h of polypropylene and laminates of polypropylene with polyethylene terephthalate.

The waste treatment modelled in this article is a small-scale intervention, with negligible effects in existing supply chains of the products substituted due to the small quantity of the outputs produced. Consequently, average data was used to model the background system, prioritising processes, and materials from firstly Spain and secondly Europe. Therefore, an attributional LCA was applied.

The products and processes chosen to model the scenarios from the ecoinvent database are listed in Supplementary Material (Table S7). It must be noted that, since both FFP2 and surgical masks are mostly made of polypropylene (Richaud et al., 2021), their landfilling process was

Table 2
HHVs of the oils produced in the four scenarios.

Scenario	HHV oil, MJ/kg	HHV gas, MJ/kg
Scenario 1	50.16	42.73
Scenario 2	52.29	39.43
Scenario 3	51.49	39.18
Scenario 4	51.54	39.23

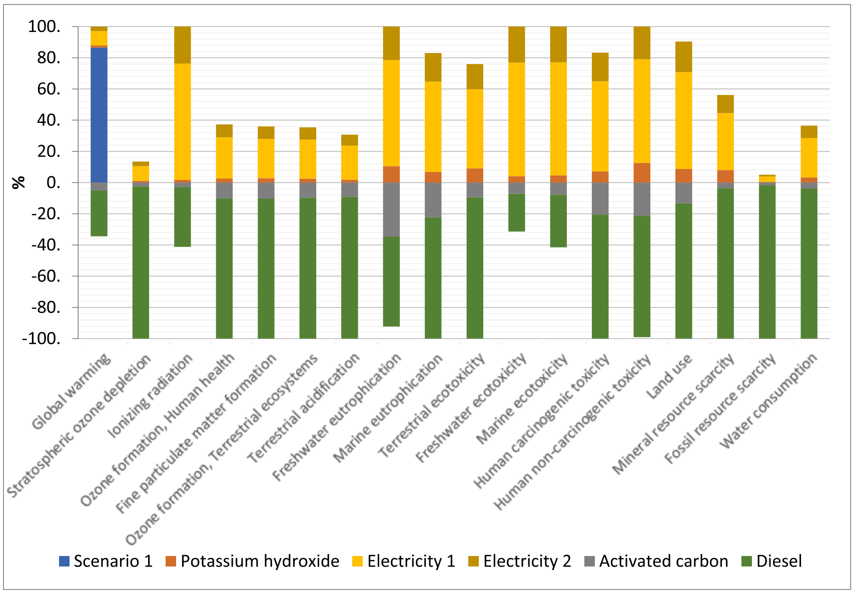

Fig. 3. Characterised results for scenario 1.

modelled using the same dataset from ecoinvent, and therefore scenarios 5 and 6 are the same.

3. Results and discussion

The LCA results are presented in Section 3.1, while the interpretation of these results is presented in Section 3.2.

3.1. Life-cycle impact assessment

LCA calculations were performed with the software SimaPro 9.4 (PRé Sustainability). The life-cycle impact assessment method used was ReCiPe 2016 Midpoint (H) V1.03, including long-term emissions and infrastructure, unless stated otherwise.

The characterised results for scenarios 1–4 are presented in Figs. 3–6, respectively. The avoided production of diesel reduces very significantly the environmental impact in all categories for all scenarios. This is due to the high environmental impact associated with the production of conventional diesel. The generation and distribution of the electricity needed in the process contributes significantly to the impact within all categories for all scenarios, particularly for ionizing radiation, freshwater ecotoxicity and marine ecotoxicity. The production of the catalyst contributes mostly to toxicity impact categories, land use and mineral resource scarcity in scenarios 2 and 4. The pyrolysis process only contributes to global warming, where it is the dominant process in all scenarios, due to the release of carbon dioxide.

The life-cycle environmental impact results for all scenarios are shown in Table 3. Scenarios 1–4 show negative values (i.e., favourable results) for all impact categories except global warming, ionizing radiation, freshwater eutrophication, freshwater ecotoxicity and marine ecotoxicity (and marine eutrophication, terrestrial ecotoxicity, human carcinogenic toxicity, land use and mineral resource scarcity in scenarios 2 and 4, and human non-carcinogenic toxicity in scenarios 1, 2 and 4). This is explained by the production of avoided products. In contrast, the conventional scenario

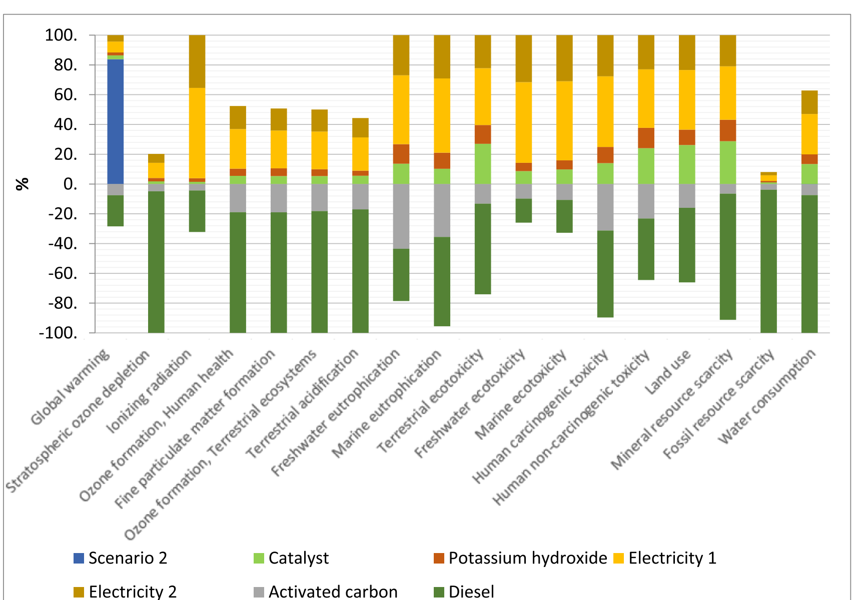

Fig. 4. Characterised results for scenario 2.

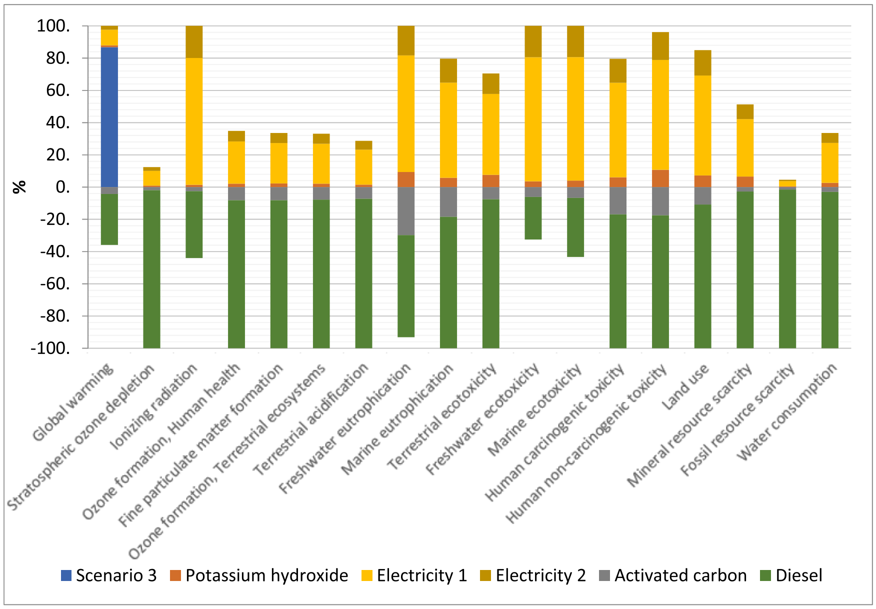

Fig. 5. Characterised results for scenario 3.

(landfilling) creates a positive environmental impact (i.e., unfavourable results) for all impact categories. This means that the conventional scenario does not provide any environmental benefit.

Fig. 7 compares the life-cycle impact results for scenarios with FFP2 masks. The environmental impact in scenarios 1 and 2 is significantly higher than in the conventional scenario only for global warming, ionizing radiation, and freshwater eutrophication impact categories. It is also significantly higher in scenario 2 for terrestrial ecotoxicity, and slightly higher for human carcinogenic toxicity and mineral resource scarcity. The higher impact for global warming is caused by the release of carbon dioxide from the combustion process, while the higher impact for ionizing radiation and freshwater eutrophication is due to the impact associated with the generation and distribution of electricity used in the process. For all other impact categories, the conventional scenario creates a much higher environmental impact. Similar results are obtained for scenarios with surgical masks (Fig. 8). Normalised results showed that freshwater ecotoxicity and marine ecotoxicity are the environmental impact categories with the highest environmental impact overall for the conventional scenario. This is due to the leaching of toxic materials that reach water bodies. Although these two categories also contribute the most to the overall environmental impact of scenarios 1–4, their much lower values compared to those of the conventional scenario prove their superior environmental performance.

Next, the LCA results were normalised and aggregated into a single score for each scenario by using the method ReCiPe 2016 Endpoint (H) V1.03 (Fig. 9). Overall, the most environmentally-damaging scenario is the conventional scenario based on landfilling, due to its impact on human health, mostly due to its long-term human non-carcinogenic toxicity. For both FFP2 and surgical masks scenarios, the scenarios without

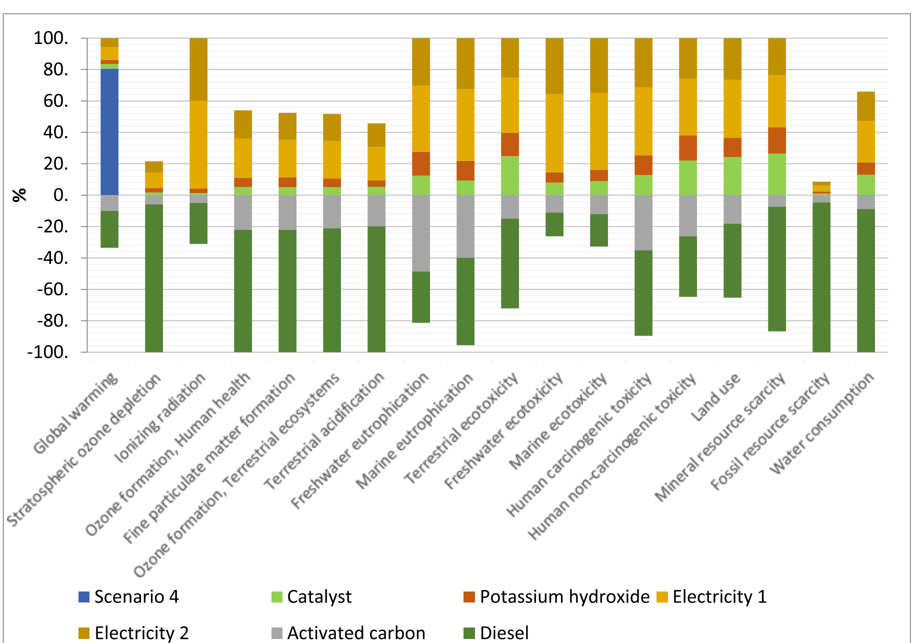

Fig. 6. Characterised results for scenario 4.

Table 3
Life-cycle environmental impact results.

Impact category	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Conventional scenario
Global warming	kg CO_2 eq	7.67E−01	1.05E+00	7.19E−01	8.91E−01	1.25E−01
Stratospheric ozone depletion	kg CFC11 eq	−5.17E−07	−4.37E−07	−5.36E−07	−4.42E−07	7.40E−09
Ionizing radiation	kBq Co-60 eq	4.65E−02	6.60E−02	4.21E−02	7.31E−02	4.30E−04
Ozone formation, Human health	kg NOx eq	−8.60E−04	−6.48E−04	−9.00E−04	−6.61E−04	8.10E−05
Fine particulate matter formation	kg PM2.5 eq	−7.04E−04	−5.38E−04	−7.36E−04	−5.50E−04	2.71E−05
Ozone formation, Terrestrial ecosystems	kg NOx eq	−9.38E−04	−7.16E−04	−9.81E−04	−7.32E−04	8.27E−05
Terrestrial acidification	kg SO_2 eq	−2.24E−03	−1.76E−03	−2.33E−03	−1.81E−03	5.67E−05
Freshwater eutrophication	kg P eq	5.72E−06	2.33E−05	4.80E−06	2.23E−05	1.86E−06
Marine eutrophication	kg N eq	−1.22E−06	3.76E−07	−1.43E−06	4.05E−07	1.10E−04
Terrestrial ecotoxicity	kg 1,4-DCB	−1.24E−01	1.77E−01	−1.53E−01	2.07E−01	2.54E−02
Freshwater ecotoxicity	kg 1,4-DCB	9.18E−03	1.33E−02	8.55E−03	1.44E−02	1.54E−01
Marine ecotoxicity	kg 1,4-DCB	9.89E−03	1.55E−02	9.07E−03	1.69E−02	2.16E−01
Human carcinogenic toxicity	kg 1,4-DCB	−1.54E−03	1.16E−03	−1.85E−03	1.28E−03	8.23E−04
Human non-carcinogenic toxicity	kg 1,4-DCB	1.16E−03	7.68E−02	−4.84E−03	8.31E−02	2.38E+00
Land use	m^2a crop eq	−4.80E−04	2.63E−03	−7.55E−04	2.91E−03	2.89E−03
Mineral resource scarcity	kg Cu eq	−2.77E−04	5.63E−05	−3.15E−04	9.25E−05	3.62E−05
Fossil resource scarcity	kg oil eq	−7.73E−01	−6.83E−01	−7.98E−01	−6.98E−01	6.14E−03
Water consumption	m^3	−2.59E−03	−1.41E−03	−2.77E−03	−1.34E−03	2.79E−04

catalyst (scenarios 1 and 3) created a lower environmental impact than scenarios with catalyst (scenarios 2 and 4), due to the production of avoided products. Even when scenarios 2 and 4 produce a larger amount of an activated carbon substitute, which reduced the impact in all categories, they also produced a smaller amount of a diesel substitute, which contributed more to an impact reduction in all categories. Furthermore, the production of the catalyst also created an environmental impact, that is avoided in scenarios 1 and 3. Nevertheless, the waste scenario for the catalyst (landfilling) does not increase the environmental impact. This is because the spent sepiolite can be considered an inert material and does not create an environmental impact when landfilled. The small amount of spent sepiolite produced does not significantly affect results on land use.

3.2. Interpretation

Results from the previous section show that the scenarios with pyrolysis and no catalyst (scenarios 1 and 3) perform the best environmentally thanks to the production of avoided products. The conventional scenario was the most environmentally damaging, mainly due to its high impact on freshwater ecotoxicity and marine ecotoxicity, with significant impacts on the human health area of protection. Using the ILCD 2011 Midpoint+ V1.10/EC – JRC equal weighting, the conventional scenario showed the highest environmental impact too, with scenario 3 having a negative single score. The high impact for the conventional scenario was mostly due to freshwater ecotoxicity, also very high with the ReCiPe 2016 Midpoint (H) V1.03 method. Similarly, scenarios 1–4 also created a higher impact on climate change than the conventional scenario. On the other hand, the impact of water resource depletion was higher for scenarios 1–4 than for the conventional scenario, the impact of ionizing radiation was lower for scenarios 1–4 than for the conventional scenario, and the impact of human toxicity was higher for the conventional scenario than for any other scenario. The impact of land use was negative for scenarios 1–4, while the impact of mineral, fossil and renewable resources was higher for scenarios 2 and 4 than for the conventional scenario. Using other methods such as EPD (2018) V1.00 and CML-IA baseline V3.05/EU25, scenarios 1–4 also had a greater impact on climate change and abiotic depletion (non-fossil fuels) than the conventional scenario. With EPD (2018) V1.00, the impact of water scarcity was also higher for scenarios 2 and 4 than for the conventional scenario, while with CML-IA baseline V3.05/EU25, the impact of terrestrial ecotoxicity was higher for scenarios 1–4

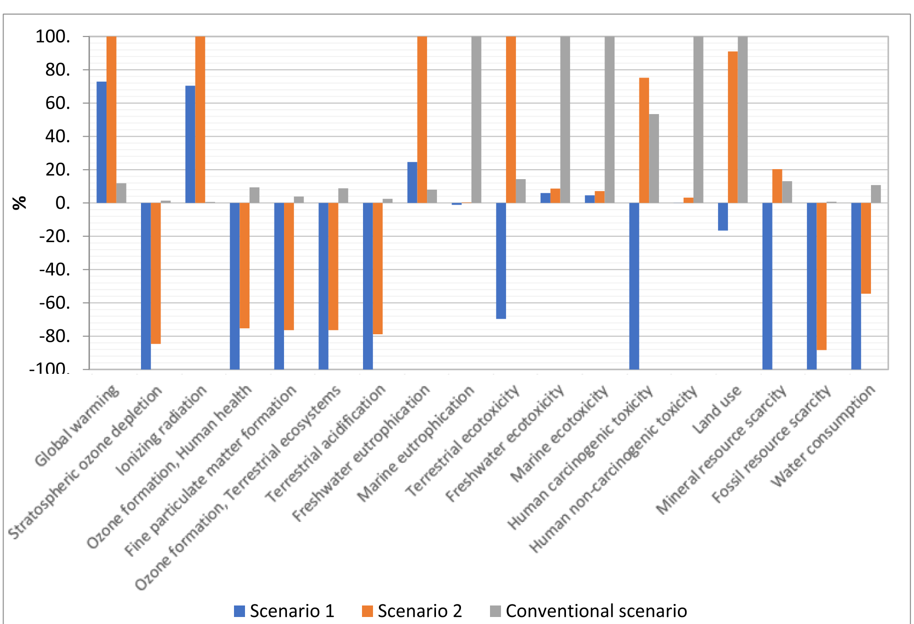

Fig. 7. Comparison among scenarios with FFP2 masks.

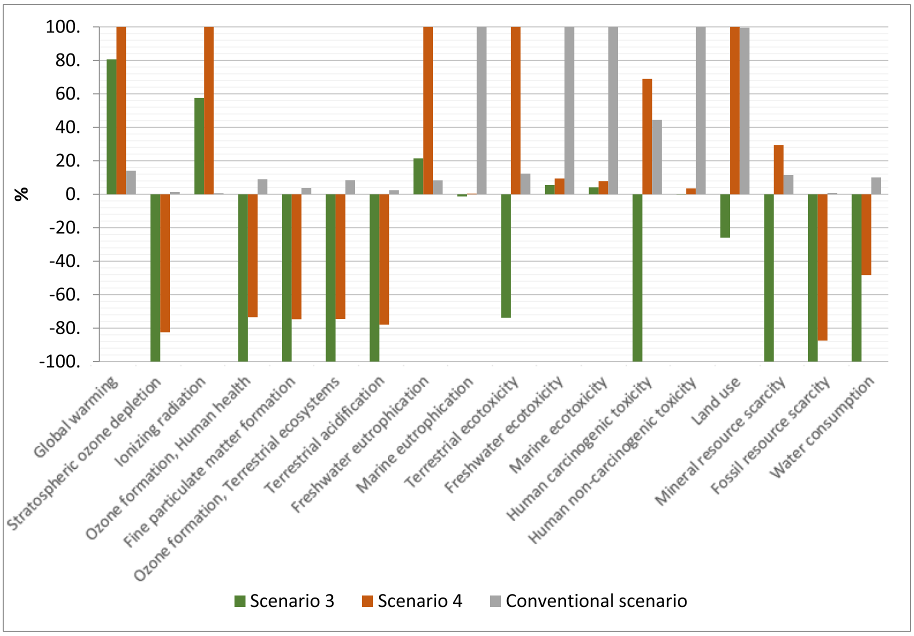

Fig. 8. Comparison among scenarios with surgical masks.

than for the conventional scenario. Results from the CML-IA baseline V3.05/EU25 method indicate, as with ReCiPe 2016 Midpoint (H) V1.03, that the high environmental impact of the conventional scenario was due to marine aquatic ecotoxicity and freshwater aquatic ecotoxicity, which can be explained by the release of toxic substances that leach and reach water bodies. Despite small differences between the results obtained by using different methods, the overall conclusions of the LCA highlighted in the beginning of this paragraph remain true regardless of the method chosen for analysis, proving the reliability of the results obtained.

Due to the high environmental impact generated by the electricity, an alternative source of electricity was considered to study how this modelling choice affects the environmental results for scenarios 1–4. Photovoltaic (PV) electricity was selected due to the steady increase in the generation of PV electricity in Spain in the last years, with a five-fold increase in the installed power in the period 2018–2022 (Red Eléctrica, 2023). Single-score results for the four scenarios with PV energy and the conventional scenario are shown in Fig. 10. As expected, the overall environmental impact was reduced in scenarios 1–4, reaching negative values in scenarios 1, 3 and 4. The impact reductions are mostly in the impact categories ionizing radiation, freshwater eutrophication, marine ecotoxicity, human carcinogenic toxicity and freshwater ecotoxicity, and in the area of protection human health. Land use was however increased, due to the large area needed for PV plants, as well as terrestrial ecotoxicity. Scenarios 1 and 3 remain the most environmentally friendly scenarios, followed by scenarios 4 and 2, and finally the conventional scenario. Despite the sensitivity of the environmental impact results for all scenarios caused by the source of electricity, this does not affect the overall conclusions of the study, proving again the reliability of the results obtained.

To further evaluate the reliability of the results, the absolute uncertainty of the model developed was assessed by using the Monte Carlo method.

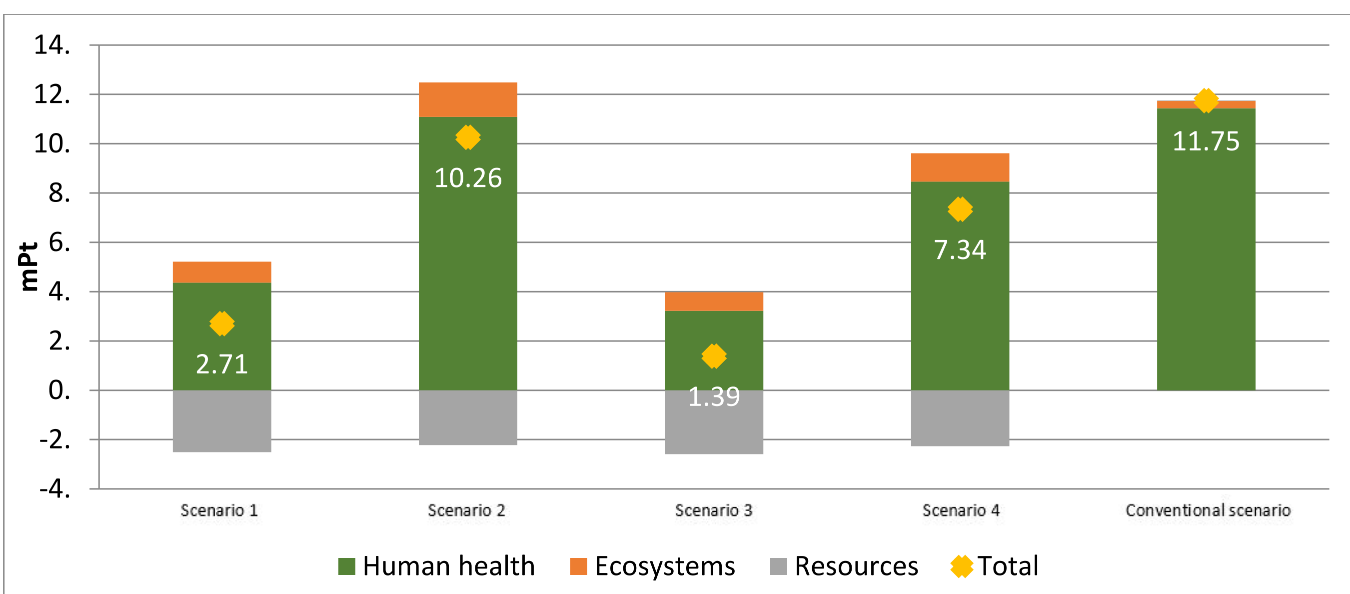

Fig. 9. Single-score results for the five scenarios.

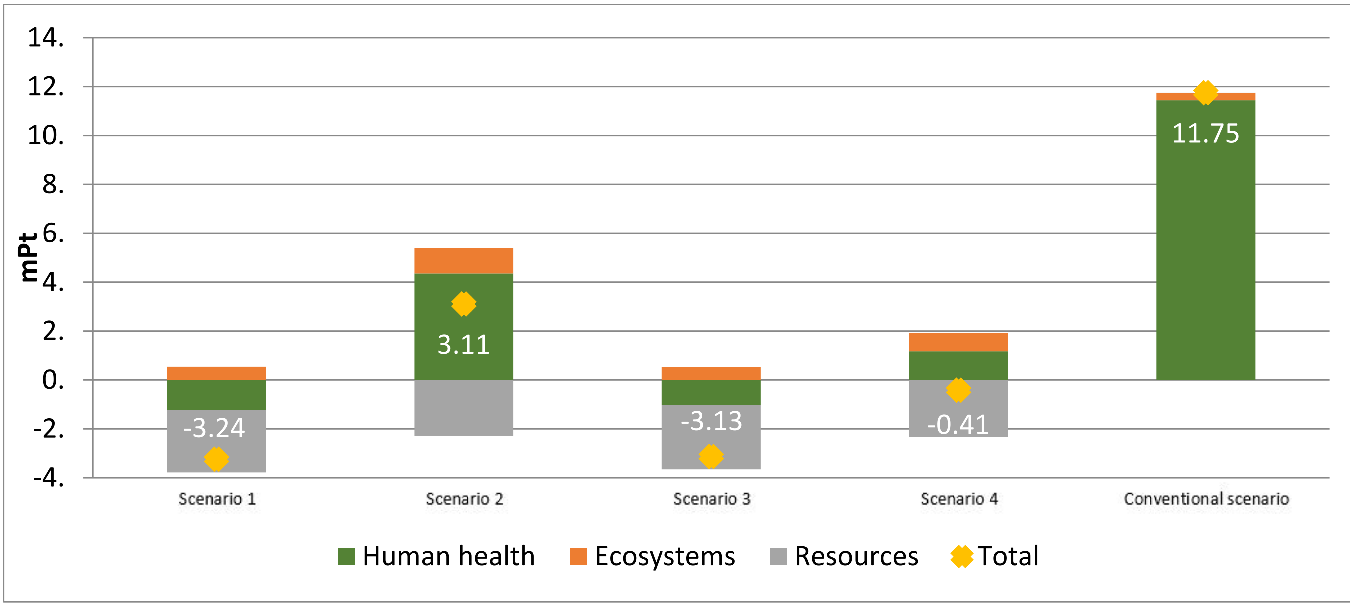

Fig. 10. Single-score results with PV energy for scenarios 1–4.

Lognormal distributions were assigned to the model variables, as they are the most important distributions in LCA and are used by ecoinvent by default (Goedkoop et al., 2016). The square geometric standard deviation of the lognormal distributions were assumed to correspond to an uncertainty of 10 % for technology (input) parameters and 20 % for emission values, as suggested by Bisinella et al. (2016). Scenario 2 was chosen as an example to evaluate its uncertainty, since it is the scenario with the highest environmental impact, which could more easily reach the value obtained for the conventional scenario, and because it has more model variables than the scenarios without catalyst. Monte Carlo was applied with 1000 runs, obtaining the distribution shown in Fig. 11.

A total of 374,488 materials and processes were used in the model, of which 63.5 % were assigned a lognormal distribution, 36.4 % were undefined, 0.051 % were assigned a triangle distribution and 0.003 % a normal distribution. The single score was between −0.0252 and 0.0363 Pt at a confidence interval of 95 %. The mean value obtained for scenario 2 was 0.0098 Pt (very close to the 10.26 mPt shown in Fig. 9), while the median was 0.0111 Pt. The fact that the mean was close to zero and the values obtained were both negative and positive explain the large coefficient of variation obtained. Furthermore, electricity generation and distribution, which contributes the most to the overall environmental impact for this scenario, has a significantly high coefficient of variation in ecoinvent. The environmental impact categories that contribute more significantly to the overall model uncertainty, with the highest coefficient of variation, are those associated with water consumption, particularly the one relevant to human health. The standard deviation and the standard error of mean were 0.0155 and 0.000491, respectively. Standard error of means below 0.01 are considered acceptable for most models (Goedkoop et al., 2016). Therefore, the LCA results obtained can be considered reliable and consistent.

The results of this article have been compared with those of similar studies. Fig. 12 shows the results from scenario 3 of this article and the results obtained by Yousef et al. (2022). Scenario 3 was selected because the experiments by Yousef et al. (2022) were also undertaken with surgical masks and no catalyst. These authors quantified the environmental impacts of pyrolyzing 1 kg of surgical masks at 500 °C to obtain gas, oil, and char, similarly to our study. They also used the ReCiPe midpoint method to quantify environmental impacts and selected Europe as the geographical region. Fig. 12 shows that results significantly differ for all the environmental impact categories except for freshwater eutrophication. The major differences can be found for the environmental impact categories with negative values for scenario 3. The production of avoided products causes these negative results, as explained in Section 3.1. In contrast, all results obtained by Yousef et al. (2022) are positive due to not considering avoided products in their analysis scope. This is a key modelling difference between the two studies. In addition, Yousef et al. (2022) included an additional process in their system boundaries, i.e., milling, which creates an additional environmental impact, albeit small compared to that of the whole modelled system. We did not undertake and model this process because the samples were small and light enough to be fed to the pyrolysis oven and this process would not be carried out at an industrial scale, as explained in Section 2.2. Yet, values obtained in scenario 3 were higher for the environmental impact categories with a positive result: global warming, ionizing radiation, freshwater ecotoxicity, and marine ecotoxicity.

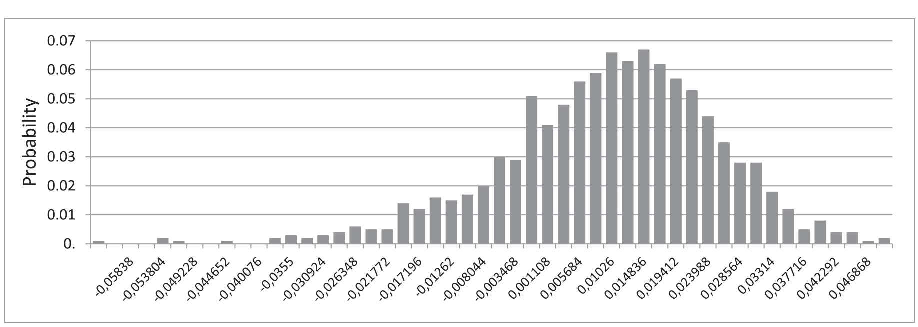

Fig. 11. Absolute uncertainty analysis of the single score of scenario 2.

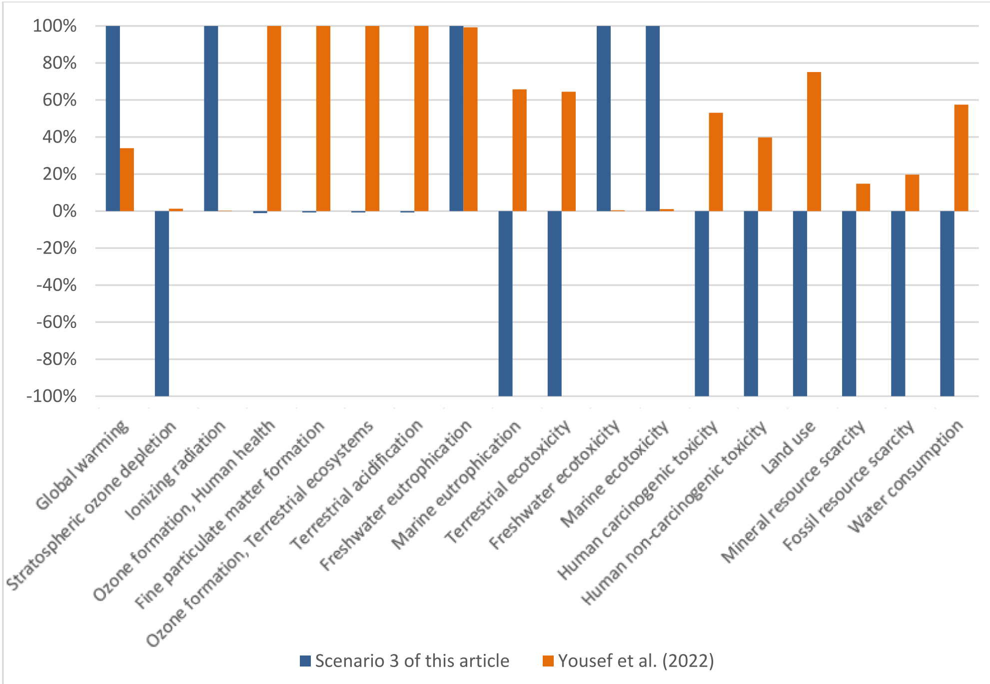

Fig. 12. Comparison of results obtained in scenario 3 of this article and results by Yousef et al. (2022).

Other authors that undertook a similar analysis include Li et al. (2022) and Zhao et al. (2022). Both studies confirm the superior environmental performance of the pyrolysis over the conventional landfilling and incineration, matching the conclusions of our study. Nevertheless, the direct comparison between their results and the results reported in our study is impossible due to key modelling differences. For instance, Li et al. (2022) included in their scope the use of oil to produce electricity and therefore the avoided production of electricity from coal and from natural gas. Our avoided products were oil, that substituted the use of commercial diesel, and char, that substituted activated carbon. These authors also recycled the char and gas obtained from the pyrolysis process to preheat the feedstock, whereas we only recycled the gas for preheating. Furthermore, the geographical background of their study was China, as opposed to Europe as in our study. Zhao et al. (2022) used a different feedstock in their study, i.e., personal protective equipment, which included face shields, surgical gowns, surgical masks, respirators, and surgical gloves. These authors also included in their system boundaries several processes that we did not model, e.g., light hydrocarbon separation, sulphur recovery, ammonia scrubbing, hydrogen production, carbon dioxide separation, hydrogen cyanide scrubbing, heavy hydrocarbon separation, aromatic extraction, and hydrogenation. They considered the generation of electricity from the combustion heat as well as the following avoided products: light naphtha, aromatic mixture, gasoline, diesel, and sulphur. In another study, Nabavi-Pelesaraei et al. (2022) also performed an LCA to study different incineration processes to treat medical waste, but they did not compare their results with the conventional practice of landfilling. Yet, their results also show that the area of protection with the highest environmental impact is human health, similarly to our study.

The goal of the LCA study, defined in Section 2.1, has been met. Contribution, sensitivity, and uncertainty analyses presented in this section confirmed the reliability and consistency of the results obtained.

4. Conclusions

The large numbers of face masks discarded since the start of the global COVID-19 pandemic have created a significant environmental problem. Therefore, environmentally friendly alternatives for their waste management are needed. This article has investigated the thermal and catalytic pyrolysis of surgical and FFP2 masks and quantified their environmental impacts using the LCA methodology. It was found that the pyrolysis without catalyst performs environmentally better than pyrolysis with catalyst. Regardless of the thermal and catalytic process, the pyrolysis of face masks provides products that can replace commercial products such as diesel and activated carbon. Considering the reduction of the environmental impact of the production of these avoided products, the environmental impact of the proposed pyrolysis process is lower than that of the conventional waste management method, i.e., landfilling. Therefore, national governments and local authorities should encourage the adoption of these alternative sustainable strategies for the management of face masks. However, a key challenge for their large-scale implementation is separation at source, as the process proposed in this article was applied to face masks alone. Separate collection of face masks has been offered in some cities, for example in the UK, but it is doubtful that this will be offered in the long term. Furthermore, as the requirement to wear face masks in certain circumstances has been relaxed in most countries, it is expected that the amount of face masks disposed of will be significantly reduced and that they will simply be disposed of with municipal solid waste. In this case, separate collection of face masks could be implemented in some specific situations, e.g., medical waste collection from hospitals and medical centres. Finally, an important aspect to consider before implementing the waste management option described in this article is the economic performance of the process. Therefore, a thorough analysis of the economic investment and economic costs associated with the proposed process is suggested as future work.

CRediT authorship contribution statement

G. Garcia-Garcia: Software, Formal Analysis, Validation, Data Curation, Writing - Original Draft, Writing - Review & Editing.

M.A. Martín-Lara: Conceptualization, Resources, Supervision, Project administration, Funding acquisition, Writing - Review & Editing.

M. Calero: Conceptualization, Resources, Supervision, Project administration, Funding acquisition, Writing - Review & Editing.

F. Ortega: Methodology, Laboratory investigation, Data Curation.

G. Blázquez: Methodology, Laboratory investigation, Laboratory Supervision, Validation, Data Curation.

Data availability

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

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.165063.

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