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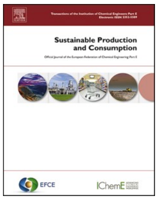

Life cycle assessment of absorbent hygiene product waste: Evaluation and comparison of different end-of-life scenarios

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ABSTRACT

In 2019 in the world, $45 \cdot 10^3$ Mt. of Absorbent Hygiene Product (AHP) wastes were produced, and their current disposal through landfills and incineration is causing greenhouse gas emissions and economic issues. This study compared the environmental impacts of four AHP-waste treatments calculated through Life Cycle Assessment. The four AHP-waste treatments included three innovative treatments: the biological process, the mechanical-thermal conversion of AHP-waste into fluff, the recycling process to recover valuable materials, and the baseline scenario including landfill and incineration with energy recovery. The functional unit was 1 t of AHP-waste, and the approach was from bin to grave. The evaluation concerned climate change and human toxicity with ReCiPe 2016 Midpoint (H) and non-renewable energy with cumulative energy demand. Among the four treatments, only the recycling of AHP-waste achieved avoided environmental impacts; -2.68 kg CO_2 eq./t AHP-waste, -0.07 kg1,4 DB eq./t AHP-waste, and -26.36 MJ/t AHP-waste, because the rate of recovered material offset the efforts required to treat AHP-waste. The biological and mechanical-thermal treatment of AHP-waste reached the same rank position, but the latter could be further improved through an energy valorisation of fluff. The sensitivity analyses confirmed the trends of the four treatments and underlined the importance of the proper product recovery rate to counterbalance the effort required by the treatment.

1. Introduction

The amount of Absorbent Hygiene Product (AHP) waste depends on the social and economic conditions of countries (Colon et al., 2013). This means that accurate quantification of the annual production of AHP-wastes is not easy to provide (Dhokhikah et al., 2015). Considering that AHP-waste represents 2–7 % of municipal solid waste (MSW) produced in the world and Europe, and 2–4 % of MSW produced in Italy (Colon et al., 2013), in 2019, based on the MSW production in the world (World Bank, 2019), Europe (Eurostat, 2023) and Italy (Ambiente Italia Srl, 2019), the annually average productions of AHP-waste were $45 \cdot 10^3$ Mt. in the world, 96.5 Mt. in Europe, and 1.2 Mt. in Italy.

AHP-waste consists of (expressed on volume base) 88.3 % diapers, 3.9 % bedding, 3.7 % dressings, 1.2 black bags, 0.8 % gloves, and 2.1 % other materials containing body fluids from non-infectious humans (Liza, 2019), with an average wet weight of 80 g per piece, and moisture content of about 75.50%*w*/w. In the last ten years, AHPs were designed to reduce their weight by - 44 % due to the introduction of super adsorbent materials (SAP) and the substitution of fossil-based materials with cellulose (Horie et al., 2004).

In Europe, AHP-wastes are identified with waste code (EER) 150203 and 180104, but the End of Waste regulation of 15/05/2019 N62 assessed the specific criteria for heterogeneous polyolefin-based plastic, SAP, and cellulose, deriving from the recovery of AHP-waste, which stops being classified as waste, allowing the development of a Circular Economy (Ambiente Italia Srl, 2019). In accordance with the global waste management, AHP-waste is not collected in a separate stream, but they are mixed with municipal solid waste (MSW) and, in accordance with the study of Arena et al. (2016), 40 % of MSW in the EU-27 is recycled or composted, 38 % is landfilled, and 22 % is incinerated. AHP-wastes contain both organic and inorganic fractions, and for this reason, the possibility of their separation and recycling is greatly complicated. Typically, in AHP-waste urine and faeces occupied about 76 % *w*/w of single-use AHP waste, hence, in the case of landfilling disposal, the decomposition of AHP-waste requires a long time, and continuous monitoring (Khoo et al., 2019) because it releases contaminants to groundwater and soil (Lam et al., 2019). Rather than general bio-waste, AHP-waste requires more stringent storage and disposal measures, but

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their non-hazardous nature makes them feedstock suitable for the valorisation process. The European Waste Framework Directive (WFD; 2008/98/EC and the updated 2018/851) and Circular Economy policy promote the waste management hierarchy consisting of prevention, preparation for re-use, recycling of material, recovery (including Waste-to-Energy) and disposal (Clift et al., 2000). Considering the valuable materials present in the AHP-waste and their environmental and health problems, it is necessary to identify new greener technological solutions to convert AHP-waste into stabilized and high-added value products. The Sustainable Development Goal 12 of Agenda 2030 promotes the sustainable practices of production and consumption, which includes the reduction of toxic substances and proper waste management, hence a specific analysis of how the environmental impacts of AHP-waste evolved could be helpful to detect which are the critical aspects of the waste and identify areas on which technical innovation should focus to decrease environmental impacts. Life Cycle Assessment (LCA) is a tool defined in the ISO 14040-44 standards, able to detect and quantify the environmental impacts associated with a product.

The present study compared the environmental impacts of four AHP-waste treatments, and among them, three innovative scenarios were selected in the regional project BIOENPRO4TO; the biological process, the mechanical-thermal conversion, the recycling technology, and the traditional treatment defined as the baseline scenario which consisted in incineration combined with landfill. The adopted approach concerned the evaluation of the environmental impact through LCA with the database Ecoinvent 3.7 and the software SimaPro 9.1.1. For all the investigated scenarios, the functional unit was 1 t of AHP-waste with the approach from cradle (bin) to grave according to the analysis performed by Bishop et al. (2021).

2. Literature review

A considerable portion of scientific studies supports and promotes a shift toward sustainable AHP-waste management to reduce environmental, social, and economic problems.

In recent years, the environmental assessment of AHPs has been evaluated from cradle to grave and the outputs depicted that the highest environmental item was the production stage due to the selection of the materials, followed by the end of life for some impact categories, while the contribution of manufacturing, packaging, and transport had minor relevance (Cordella et al., 2015). Most of the LCA studies concerned the comparison between the production of disposable and reusable AHPs (Liu et al., 2014) because the first one had an impact related to resources consumption and waste management, while the second one required water and energy for the recycling treatments (Cordella et al., 2015). A second explored area of study about AHP was related to the environmental impacts due to its eco-design (Ghosh et al., 2000) and the introduction of innovative materials (Mirabella et al., 2013). A third less explored area of study was the evaluation of AHP-waste disposal. From an environmental point of view, the most important issue is not the amount of waste generated, but the impacts associated with their disposal (Erhart and Erhart, 2022) which depends on the collection system and AHP brands that influence the AHP composition (Cordella et al., 2015). One recent study about AHP-waste disposal was performed by Płotka-Wasylka et al. (2022), which analysed the environmental and health issues associated with the prevention and mitigation of single-use, re-usable, and biodegradable AHPs. Considering that many efforts were done to improve the AHP composition, but the currently employed materials are irreplaceable, the focus should be moved toward a proper AHP-waste valorisation aimed to recover the valuable compound.

Consequently, new green technological solutions are necessary to reduce the environmental and health impacts of disposable AHP-waste. Among the available technologies, the most studied to clean up AHP-waste included dimethyl ether extraction, centrifugation extraction, thermal dehydration, pyrolysis (Liuzzi et al., 2020), and biological processes like aerobic and anaerobic digestion (Płotka-Wasylka et al., 2022), mechanical and steam sterilisation as the technology promoted by Ompeco and a combination of thermal-mechanical recycling like the one designed by Knowaste, and Fater.

The current disposal for AHP-waste is either incineration or landfilling or a combination of them, but landfilling of biodegradable materials requires control due to the production of significant emissions of greenhouse gases (Rossi et al., 2015). Since AHP-waste contains organic matter, biological process like composting and anaerobic digestion has been studied in the literature, but the study of Colón et al. (2011) about the composting of diapers with the organic fraction of MSW, proved that the stability, and phytotoxicity of the compost were not efficient because an increase of zinc content was found, which limited the possibility of composting the product in large amounts. Another problem was related to the long degradation time required by SAP and its complicated separation from organic materials, which could contaminate the compost or digestate in the anaerobic process (Colón et al., 2011). AHP-waste contains valuable materials, like plastics, fibers, and cellulose pulp, which can be extracted or recovered and used as secondary raw materials to produce other products (Khoo et al., 2022).

Among the biological processes, Liza (2019) and Espinosa-Valdemar et al. (2011) tested at a pilot scale the application of AHP-waste as a substrate for the growth of the fungus Pleurotus Ostreatus and the production of animal protein feed. This biological process could guarantee the absence of health problems and the stabilisation of waste. However, in the last ten years, some experimental recycling systems have been tested by European Commission's Eco-innovation Projects, but the initial drawback of these techniques was the low quality of the recovered materials, which can end up in fertilizers and low-value plastic products. If the quality of the recovered product is not enough to cover the environmental and economic costs of recycling, the process is not considerable environmental and economically feasible (Takaya et al., 2019a). In Europe, only England, Italy, and Netherlands have technologies to recycle AHP-waste. The technology developed by Knowaste Ltd., currently adopted in the United Kingdom (UK), consists of four steps; shredding of AHP-waste, washing them with a dehydrating agent, sterilisation, and selective separation into fibre and plastic elements (Knowaste, 2021). This technology can recycle approximately 360,000 t of AHP-waste annually. In Italy, the AHP-waste recycling company Fater (processing capacity of about 100,000 t annually) can recover about 150 kg of cellulose, 75 kg of plastic, and 75 kg of SAP from 1 t of AHP- waste with technology like Knowaste (Fater, 2019). Recently, the Netherlands implemented a technology to recycle AHP-waste through multi-step technology; collecting, grinding, washing, mechanically separating plastic materials, and then granulating them, and the final waste is only 2 % of the whole AHP-waste treated (Diaper Recycling Europe, 2020). Recycled materials can be used to produce construction purposes, cat litter (Diaper Recycling Europe, 2020), stable supercapacitor electrodes, and energy (Lobato-Peralta et al., 2021). Based on the literature review and technical report, the most promising AHP-waste treatment detected at the pilot scale are biological treatment (Espinosa-Valdemar et al., 2011); mechanical- thermal processes provided by Ompeco, and recycling as the technology designed by Knowaste, and Fater and investigated by Arena et al. (2016). Since, new waste treatment strategies require significant investments, and structural modifications, the present study aimed to provide an environmental analysis able to guide the employment at the industrial scale of the AHP-waste techniques with the lowest environmental impact by identifying key environmental areas on which to focus.

In scientific literature, the available environmental studies about the impacts of AHP-waste are the review of Płotka-Wasylka et al. (2022) about the environmental considerations of AHP-waste from cradle to grave, and the LCA of Arena et al. (2016) about recycling of AHP-waste. In the literature, to the best author's knowledge, there are no available LCA studies about biological treatment using AHP-waste as a substrate or mechanic-thermal treatment of AHP-waste and their comparison with recycling and current management of AHP-waste. The novelty of the present research was the environmental comparison of innovative AHP-waste treatments to fill the missing information about these processes and coupled them with industrial and scientific developments by highlighting their pros and cons. The innovative result of this research was the identification of the technology with the lowest environmental impacts able to replace the current AHP-waste management according to Waste hierarchy principles.

3. Methods

Life Cycle Assessment (LCA) was performed according to ISO 14040-14044 (2006) with the database Ecoinvent 3.7 and the software SimaPro 9.1.1. The key information about LCA structure is summarized in Table 1 and deeper explained in paragraphs 3.2–3.6.

3.1. Goal and scope

The goal of the present LCA was the comparison of four AHP-waste treatments in Italy to detect the environmental impacts and identify which technique could be the most environmentally sustainable AHP-waste management. The four AHP-waste treatment processes concerned three innovative treatments: biological, mechanical-thermal conversion, and recycling, and one baseline scenario consisting of 35 % incineration with energy recovery and 65 % landfill with a 30 % CH_4-capture system according to Italian AHP-waste management.

The functional unit (FU) was 1 t of AHP-waste, which was chosen to quantify and compare the environmental impacts of the four different AHP-waste treatments (Velasco Perez et al., 2021; Arena et al., 2016). The study was geo-contextualized in North-West Piedmont, a region in the North-West of Italy, because the mechanical-thermal conversion and the baseline scenario took place there.

Fig. 1 depicts the system boundaries from the bin to the grave (Thushari et al., 2020), which were considered to develop the LCA. Transport of raw material, manufacturing, packaging, and distribution of AHPs were not included in LCA study because the goal of the study was the development of comparative LCA of AHP-waste treatments, and the life cycle inventory (LCI) considered only the activities which differ between the four AHP-waste treatments (Clift et al., 2000). In the four scenarios, only the direct consequences of AHP-waste management were considered, and the environmental impacts of the infrastructures and capital goods were excluded (Thushari et al., 2020), because they were less important to the overall results.

The AHP-waste system included the foreground system and background system in agreement with the study of Clift et al. (2000). The foreground system was directly involved with reference flow management and the background system linked with the foreground system included energy production, chemical supply, and avoided products (Thushari et al., 2020).

Multi-output products have been solved by expanding the boundaries of the system to include the avoided primary production by the recovery of materials and energy from AHP-waste, according to ISO 14040 series. The adopted approach was consequential because LCA aimed to describe how environmentally relevant flows will change in response to the selected AHP-waste treatment.

Table 1
key information of LCA structure which includes the type of study, aim, environmental indices, and system boundary.

Parameters	Key information
Type of study	Comparative study with consequential approach
Aim of the study	Comparison of four AHP-waste treatments in the North-West Piedmont (Italy), to: • quantify their environmental impacts, • identify the one with the lowest impact, • suggest improvements for a more environmentally friendly AHP-waste management.
System boundary	From bin (gate) to cradle
Functional unit	1 t of AHP-waste.
Type of data	Combination of primary and secondary data.
Environmental indices	Climate changes, and human toxicity with ReCiPe 2016Midpoint (H) and cumulative energy demand (CED).

3.2. Life cycle inventory (LCI)

The LCI phase describes the inputs and outputs of the proposed technologies by referring them to the chosen FU equal to 1 t of AHP-waste. The three investigated innovative technologies were the biological process, the mechanical-thermal conversion, and the recycling process, whereas the baseline scenario was the combination of 65 % landfill with CH_4 capture and 35 % incineration with energy recovery, which represents the current AHP-waste management. The four AHP-waste treatments are detailed and described in the supplementary materials (SM), and this paragraph provides the inventory of each treatment to understand the process flow diagram.

The AHP-waste composition was considered to evaluate the amount of biogenic carbon to consider in the environmental evaluation.

The AHP-waste composition was 63.8%*w*/w organic body fluids, 17.6 % w/w cellulose, 8.5 % w/w SAP, 4.6 % w/w polypropylene, 2.7 % w/w polyethylene, and 2.8 % w/w other polymers (Liza, 2019). The elemental composition of AHP-waste consisted of 19.01 % of O, 4.63 % of H, 76.22 % of C, 0.05 % of S, 0.0051 of N, and 0.08 % of Cl, with a high heating value (HHV) equal to 10.36 MJ/kg, according to (Fater, 2019).

According to the zero-burden assumption, it was assumed that AHP-waste did not have any credits related to the impacts released during the previous stages of their life cycle (Buttol et al., 2007), and considering the elemental analysis and composition, the calculated biogenic carbon of AHP-waste was 68%*w*/w. The only impact of AHP-waste was related to its transport to the treatment plant, which was assumed equal to 47 km and performed with a lorry 16–32 t Euro 5, for all four investigated treatments.

The LCA of the biological process was based on secondary specific data, which came from the studies at the pilot scale of Espinosa-Valdemar et al. (2011) and Liza (2019). The complete data to carry out the biological process are summarized in Table S1 (SM) and Table 2.

The biological process employed the sterilised AHP-waste as a substrate for the fungus *Pleurotus Ostreatus* and to produce protein animal feed.

In the biological process, 1 t of AHP-waste was sterilised and washed with H_2O and H_2O_2 (Elviliana et al., 2020) by consuming energy and producing wastewater. After that, the sterilised AHP-waste was cut homogeneously with a shredder, and then the biological treatment consisted of three phases: a) inoculation, b) first fungi growth in the darkness and c) second fungi growth with light, but in Fig. 1 and in the LCI the biological treatment was considered as one process unit since they occurred in the same reactor. To treat 1 t of AHP-wastes, 0.053 % *w*/w of *Pleurotus Ostreatus* seeds were added. The biological technique achieved weight and volume reductions respectively equal to 72 and 88 % according to the study of Liza (2019) and Espinosa-Valdemar et al. (2011). Among the 0.225 t of produced fungi, 0.191 t was used as animal feed due to its protein contents, and it was considered as avoided emission, whereas the residual 0.034 t was disposed in the landfill for biowaste.

The mechanical-thermal conversion of AHP-waste in sterilised fluff was experimentally tested in a pilot scale plant and designed according to the patented technology “Disposable Diaper Recycling Process US005292075A”, and its environmental assessment was based on primary data. The details of the mechanical-thermal conversion of AHP-waste are provided in Table S2 (SM) and the inventory data is in Table 3. This mechanical-thermal conversion of AHP-waste included mechanical shredding under continuous negative pressure, followed by the converter, which removed the humidity of AHP-waste, and then by

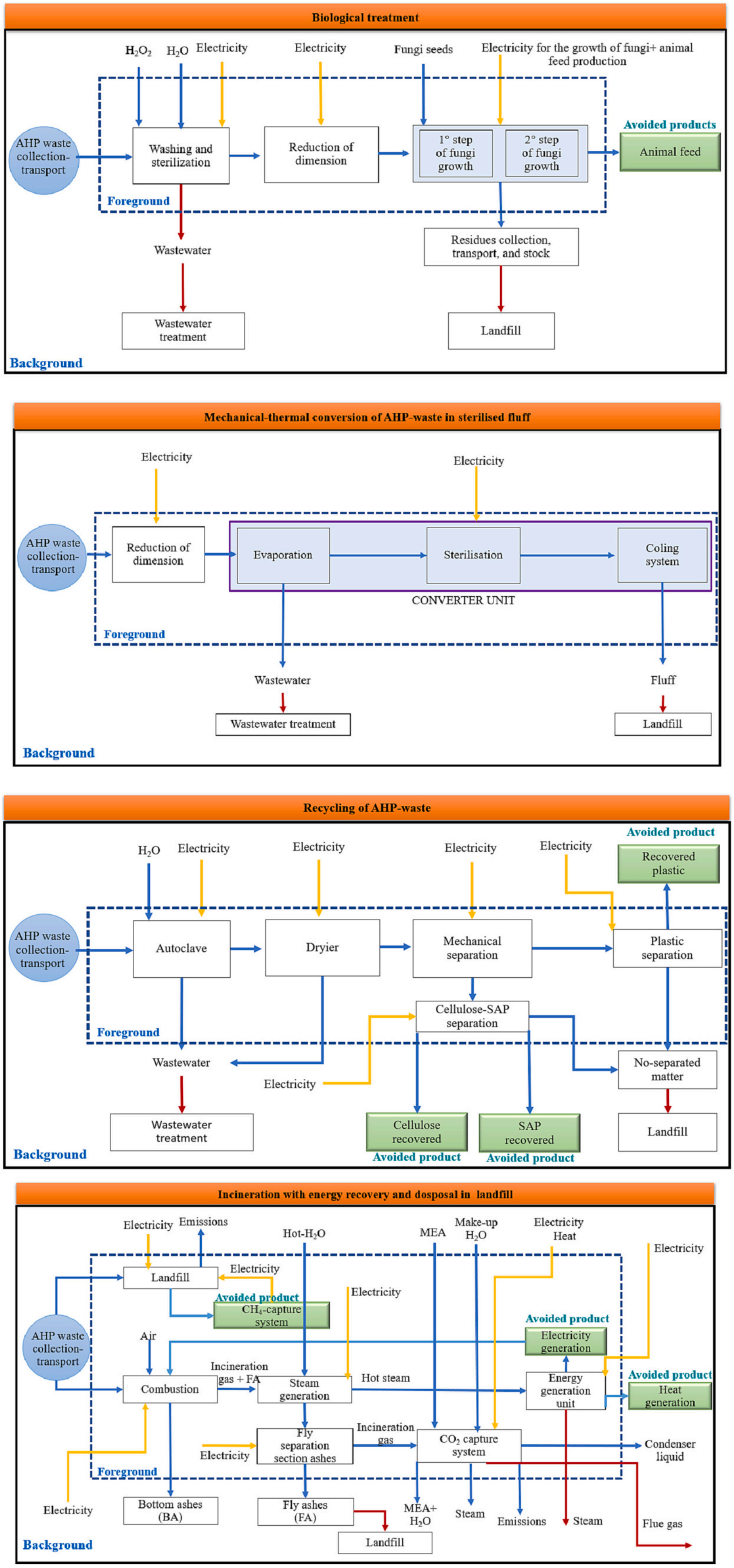

Fig. 1. Boundary conditions of the selected four AHP-waste treatments. The blue lines represent the material flows, the orange ones are the energy flows, and the red ones are the waste flows.

Table 2
Biological treatment of AHP-waste. The data are referred to the FU = 1 t of AHP-waste. The input and outputs are provided for each process unit, with the details of the type of data.

	Input/ output	Type of flow	Unit operation	Value	Reference
Collection		/	AHP waste (t)	1.0	This study
		/	Transport (km) with Euro 5	47.0	This study
Washing and sterilisation	input	Product	AHP waste transported	1.0	
		Energy	Pump (kWh)	2.5	Espinosa-Valdemar et al., 2011
		Elemental flow	H_2O (t)	0.8	Espinosa-Valdemar et al., 2011
		Chemical flow	H_2O_2 (t)	0.1	Espinosa-Valdemar et al., 2011
	output	Product target of the process unit	AHP waste clean (t)	1.0	
		Waste	Wastewater (t)	0.9	Espinosa-Valdemar et al., 2011
Reduction of dimension	input	Product target of the previous process unit	AHP waste clean (t)	1.0	
		Energy	Energy (kWh/t)	5.14	Espinosa-Valdemar et al., 2011
	output	Product target of the process unit	AHP waste clean with reduced dimensions (t)	1.0	Espinosa-Valdemar et al., 2011
I step of fungi growth-II step of fungi growth-	input	Product target of the previous process unit	AHP waste clean with reduced dimensions (t)	1.0	Espinosa-Valdemar et al., 2011
		Product flow	inoculum seed of fungi (g)	533.0	Espinosa-Valdemar et al., 2011
		Energy	electricity (kWh/t) for aspiration of 1° growth per incubation chamber	1.4	Espinosa-Valdemar et al., 2011
		Energy	electricity (kWh/t) for aspiration of 2° growth per incubation chamber	1.4	Espinosa-Valdemar et al., 2011
	output	Product target of the process unit	fungus residues (kg)	225.1	Espinosa-Valdemar et al., 2011
		Waste	waste residues (kg)	774.9	Espinosa-Valdemar et al., 2011
		Disposal scenario and transport on road	Disposal in biowaste landfill: transport (km/t) with Euro 5	15.0	Espinosa-Valdemar et al., 2011
Production for animal feed	input	Product target of the previous process unit	fungus residues (kg)	225.2	Espinosa-Valdemar et al., 2011
		Energy	energy for production (kW/t)	0.2	Espinosa-Valdemar et al., 2011
	output	**Avoided product**	Animal feed recovered and considered as 85 % of fungus residues (kg)	191.4	Espinosa-Valdemar et al., 2011
		Waste	Waste (15 % of fungus residues) (kg)	33.8	Espinosa-Valdemar et al., 2011
		Disposal scenario and transport on road	Disposal in biowaste landfill for municipal waste. Transport to landfill of waste, with lorry >32 t, Euro 6 (km)	15.0	This study

The bold is used to underline the avoided products, which means discounted environmental impact.

sterilisation at 150 °C aimed to remove the pathogenic carrier. Mechanical-thermal conversion technology transformed 1 t of AHP-waste into 630 kg of fluff, which was disposed in the landfill, and 370 L of wastewater to treat in the wastewater treatment plant (Ompeco, 2019).

The LCA of the recycling process was based on secondary specific data, which came from the studies at the pilot scale of Fater (2019), and the patented technology “Equipment and Process for Recycling Absorbent Sanitary Products ITTO20111092A1”. The complete data to carry out the recycling process are summarized in Table S3 (SM) and Table 4.

The recycling technology aimed to recycle cellulosic and plastic fractions from the sterilised AHP-wastes. The first step included the sterilisation in a horizontal cylindrical autoclave able to treat in 4 h 1 t of AHP-waste then the sterilised AHP-waste was sent to a sorting machine, and 83 kg of SAP, 170 kg of cellulose, and 65 kg of plastics was recovered. The recovered materials could be used in different applications: cellulose is used in paper mills to produce cardboard as a substitute for virgin cellulose pulp and starch and plastic can be further employed as filler for 3D printing.

The LCA of the current AHP-waste management was based on primary data coming from the landfill and the incineration plant (located in the North-West of Piedmont, Italy), and the latter was recently investigated in the study of Barracco et al. (2023) for the management of municipal solid waste (MSW). The data about the current AHP-waste management is reported in Table 5. The baseline AHP-waste treatment scenario consisted of 35 % in incineration with energy recovery and 65 % in landfill with 30 % of CH_4-capture capacity and conversion in energy to run the landfill. The incineration with energy recovery consisted of a combustion unit at 800 °C, followed by a steam generation unit, an energy generation unit to produce energy to sell. The wastes of incineration were treated as followed: bottom ashes were sold as clinker filler, the fly ashes were recovered in the fly ashes removal section and sent to a German mine, and the CO_2 was captured in the CO_2 capture-unit.

According to AHP-waste management in the Nord-West part of Piedmont, the distances of landfill and incineration with energy recovery from the collection centre were 15 km. For the incinerator, the energy recovered was 1973 MJ/t of AHP-waste burned since the high heating value of AHP waste is 10.36 MJ/kg.

3.3. *Life cycle impact assessment (LCIA)*

Life cycle impact assessment was performed with ReCiPe 2016 Midpoint (H) method and cumulative energy demand (CED). With ReCiPe 2016 Midpoint (H) the following impact categories were

Table 3
Mechanical-thermal conversion of AHP-waste into sterilised fluff. The data are referred to the FU = 1 t of AHP-waste. The input and outputs are provided for each process unit, with the details of type of data.

	Input/ output	Type of flows	Unit operation	Value	References
AHP waste collection	Input	/	AHP waste (t)	1.0	This study
		/	Transport (km) with Euro 5	47.0	This study
	Output	Product	AHP waste (t)	1	
Comminution	input	product	AHP waste (t)	1	This study
		Energy	Energy (MJ/ t)	1.69	This study based on technical sheet of the equipment (MOCO ES 04, Germany)
	output	Product target of the process unit	AHP waste reduced dimensions (t)	1.0	This study and (Ompeco, 2019)
CONVERTER: Evaporation, sterilisation and cooling down	input	Product target of the previous process unit	AHP waste reduced dimensions (t)	1	
		Energy	Energy (MJ/ t)	9	This study
	output	Product target of the process unit	Fluff production (kg) Production factor = 63.0 % based on AHP-waste treated	630	This study and (Ompeco, 2019)
		Waste	Wastewater (L)	370	This study and (Ompeco, 2019)
		Disposal scenario and transport on road	Transport with lorry >32 t, Euro 6 to dispose the fluff. in inert waste landfill (km)	15	Primary data from this study

Table 4
Recycling of AHP-waste. The data are referred to the FU = 1 t of AHP-waste. The input and outputs are provided for each process unit, with the details of the type of data.

	Input/ outputs	Type of flows	Unit	Value	Reference
AHP waste collection			AHP waste (t)	1.00	This study
			Transport (km) with Euro 5	47.00	This study
Sterilisation	input	Product flow	AHP waste transported (t)	1.00	(Fater, 2019)
		Elemental flow	Water (m3)	0.50	(Fater, 2019)
		Energy flow	Autoclave (kWh/t)	2.50	(Fater, 2019)
	output	Waste flow	Wastewater for treatment municipal plant (m3)	0.50	(Fater, 2019)
		Product target of the process unit	AHP waste sterilised (t)	1.00	(Fater, 2019)
Dryer	input	Product target of the previous process unit	AHP waste sterilised (t)	1.00	(Fater, 2019)
		Energy flow	Energy to dry (kWh/t)	1.44	(Fater, 2019)
	output	Waste flow	Wastewater (m3)	0.36	(Fater, 2019)
		Product target of the process unit	AHP waste dry (t)	0.64	(Fater, 2019)
Mechanical separation	input	Product target of the previous process unit	AHP waste dry (t)	0.64	(Fater, 2019)
		Energy	Energy to separate (kWh/t)	3.58	(Fater, 2019)
	Output	**Avoided product**	Recovered SAP (t)	0.083	(Fater, 2019)
		Avoided product	Recovered plastic, (t)	0.065	(Fater, 2019)
		Avoided product	Recovered cellulose, (t)	0.17	(Fater, 2019)
		Waste	SAP waste (t)	0.047	(Fater, 2019)
		Waste	Plastic waste (t)	0.024	(Fater, 2019)
		Waste	Cellulose waste (t)	0.05	(Fater, 2019)
		Waste	No separated waste (t)	0.178	(Fater, 2019)
		Disposal scenario and transport on road	Transport with lorry >32 t, Euro 6 to dispose the fluff. in inert waste landfill. (km)	15.00	This study

The bold is used to underline the avoided products, which means discounted environmental impact.

considered: global warming potential (kg CO_2 eq.) and human toxicity (kg 1,4-DBeq) because the attention was focused both on the environmental quality (Somers et al., 2021) and human health (Rajesh, 2021), and because studies were available in the scientific literature for comparison. Whereas the CED method was employed to evaluate the energy impact of the proposed AHP-waste treatments considering the total energy required and saved in the whole process (Somers et al., 2021), especially for the evaluation of mechanical-thermal processes, which were energy expensive.

3.4. *Interpretation data and sensitivity analysis*

The last step of LCA was the interpretation of the results to evaluate the achievement of the goal. Two sensitivity analyses were performed to prove the consistency of the results. The first one concerned the variation of process efficiency in the range of ±5 % because, in the present LCA, the efficiency of the AHP-waste treatment played a key role in the evaluation of the environmental impact.

The second sensitivity analysis considered the variation of AHP-waste transport in the range of ±10 %, because the study of (Golecha and Gan, 2016), proved the mutual influence and dependency between biomass yield density (t/ ha•y), supply distance (km) and environmental impacts. Whereas the variation of AHP-waste composition was not considered because the study of Arena et al. (2016) proved, through the sensitivity analysis of the LCA, that the variation of AHP-waste-composition did not influence the results of LCA.

Table 5
Baseline treatment of AHP-waste. The data are referred to the FU = 1 t of AHP-waste. The input and outputs are provided for each process unit, with the details of the type of data.

	Input/ output	Type of flow	Unit	Value	References
Collection	output	/	AHP waste (kg)	1000.0	This study
		/	Transport (km) with Euro 5	47.0	This study
Combustion unit	Input	/	Rate of AHP waste destinated to incineration (%)	35	This study and Eurostat (2019)
		/	Waste for incineration (kg)	350.00	This study and Eurostat (2019)
		Elemental flow	Air for combustion (kg)	2205.00	Incineration plant
		Energy flow	Consumed energy (MJ)	94.50	Incineration plant
	Output	Avoided burdens	Bottom ashes (BA) (kg)	73.50	Incineration plant
	Output	Product target of the process unit	Incineration gases + fly ashes (FA)(kg) Made up of • Fly ashes (FA) = 7.00 • Flue gas (kg) = 2477.30	2484.30	Incineration plant
Steam generation	Input	Product target of the previous process unit	Incineration gases + fly ashes (FA)(kg)	2484.30	Incineration plant
		Elemental flow	Water (kg)	752.50	Incineration plant
		Heat/energy flow	Heat from incineration gases (MJ)	2495.50	Incineration plant
	Output	Co-product (mass allocation)	Incineration gases + fly ashes (FA) (kg)	2484.30	Incineration plant
		Product target (mass allocation)	Steam (kg)	752.50	Incineration plant
Energy generation	Input	Product target of the previous process unit	Steam (kg)	752.50	Incineration plant
		Energy flow	Energy consumed (MJ)	619.50	Incineration plant
	Output	Product target of the unit	Energy produced (MJ)	690.55	Incineration plant
		Avoided burdens	Electricity, avoided product (MJ) Conversion factor = 40 %	276.22	Incineration plant
		Avoided burdens	Heat, avoided product (MJ) Conversion factor = 55 %	379.80	Incineration plant
		Waste	Low-pressure steam (kg)	752.50	Incineration plant
FA removal unit	Input	Co-product of steam generation unit	Incineration gases + fly ashes (FA) (kg)	2484.30	Incineration plant
		Energy flow	Energy consumed (MJ)	94.50	Incineration plant
	Output	Products target of the unit	Incineration gases (kg)	2477.30	Incineration plant
		Hazardous waste	Fly ashes (FA) (kg)	7.00	Incineration plant
		Transport to German mine	Transport of waste, with lorry >32 t, Euro6 (km)	260	Landfill plant
CO_2 capture system	Input	Products target of the previous unit	Incineration gases, (kg)	2477.30	Incineration plant
		Product (chemical) flow	MEA, (kg)	0.75	Incineration plant
		Elemental flow	Aqueous solution water, (kg)	0.06	Incineration plant
		Energy flow	Electricity, high tension, (MJ)	0.17	Incineration plant
		Heat/energy flow	Heat, from steam, in chemical industry {RER}, (MJ)	7.08	Incineration plant
	Output	Product waste	Flue gases, kg + MEA lost (kg)	2476.94	Incineration plant
		Waste	Biogenic CO_2, (kg)	0.12	Incineration plant
		Waste	Fossil CO_2, (kg)	0.08	Incineration plant
		Waste	Steam (kg)	0.16	Incineration plant
		Waste	condenser liquid (kg)	0.96	Incineration plant
Landfill	Input	/	Rate of AHP waste destinated to landfill (%)	65.0	This study
		/	AHP waste in landfill (kg)	650.0	This study
		Energy flow	Electricity demand for gas collecting to capture GHGS (kWh/ m^3landfill gas)	5.2	Landfill plant
		/	Efficiency of the landfilling system with gas recovery (%)	30.0	Landfill plant
		Transport on road	Transport of waste, with lorry >32 t, Euro6 (km)	16.2	Landfill plant
		/	CH_4 emitted (m^3)	3.0	Landfill plant
		Energy flow	Energy produced from captured CH_4 (kWh) Conversion factor = 40 % CH_4 captured (m^3) = 1.3	5.16	Landfill plant

4. Results

The proposed LCA evaluated the life cycle of AHP-waste treatment by comparing the environmental impacts of four AHP-waste treatments.

Table 6 reports the main results achieved from the four AHP-waste treatments in the three impact categories considered; climate change and human toxicity with ReCiPe 2016 Midpoint (H) and cumulative energy demand (CED). The discussion of the treatment was done one by one in the following paragraphs and then the obtained results of LCA were critically compared with those of the scientific literature to detect consistency with the methodological choices and if different methodological choices can lead to convergence or divergence of main findings.

Table 6
LCA results of biological process, mechanical-thermal conversion, recycling processes, and baseline scenario, considering the functional unit (FU) = 1 t of AHP-waste.

	Climate change kg CO_2 eq./t AHP-waste	Human toxicity kg 1,4 DB eq./t AHP-waste	Cumulative energy demand MJ/t AHP-waste
Biological	43.95	4.60	54,49
Mechanical-thermal conversion	29.54	6.39	99,18
Recycling processes	−2.68	−0.07	−26,36
Baseline scenario	136.17	25.07	208.43

4.1. Environmental evaluations of biological treatments

The biological treatment consisted of sterilisation of AHP-waste, and reduction of their dimensions to obtain a homogeneous substrate on which fungi can grow. At the end of the process, 85 % of the residual fungi can be converted into animal feeds, whereas the waste of the process which was equal to 407.8 kg (374 kg of AHP-waste substrate and 33.8 kg of fungi waste) can be disposed in the landfill for bio-waste. Based on the author's knowledge, there are no available LCA studies in the literature about fungi treatment using AHP-waste as substrate, hence the comparison of the achieved results has been done with LCA studies about other biological treatments of AHP-waste (anaerobic digestion and composting) and with biological treatment of others type of waste (like bioplastics).

In the biological process, the climate change, human toxicity, and CED were respectively 49.3 kg CO_2 eq./ t AHP-waste, 4.6 kg 1,4 DB eq./ t AHP-waste, and 54.5 MJ/ t AHP-waste. In the climate change category, the process items with the highest impact were the wastewater treatments (900 L) and the landfill for bio-waste, (407.8 kg of residues), which contributed 51.55 and 29.7 %, respectively to the total climate change impact. The bottleneck of the biological process was the amount of waste produced as wastewater and biowaste, because in accordance with the study of Donzella et al. (2022), in the biological processes, the amount of produced waste is usually higher than the amount of product.

It is of interest to evidence that the biological process for the growth of fungi required a small quantity of energy, indeed the energy contribution in the process represented 3.84 kg CO_2 eq./ t AHP-waste, in accordance with the study of Khoo et al. (2022), whereas the energy required to treat the wastewater and bio-waste represented the highest energy requirement according to the study of Kothari et al. (2010).

The pro of the biological process was the production of animal feed, which was considered an avoided product, hence it represented an environmental impact discount equal to −16.97 kg CO_2 eq./ t AHP-waste.

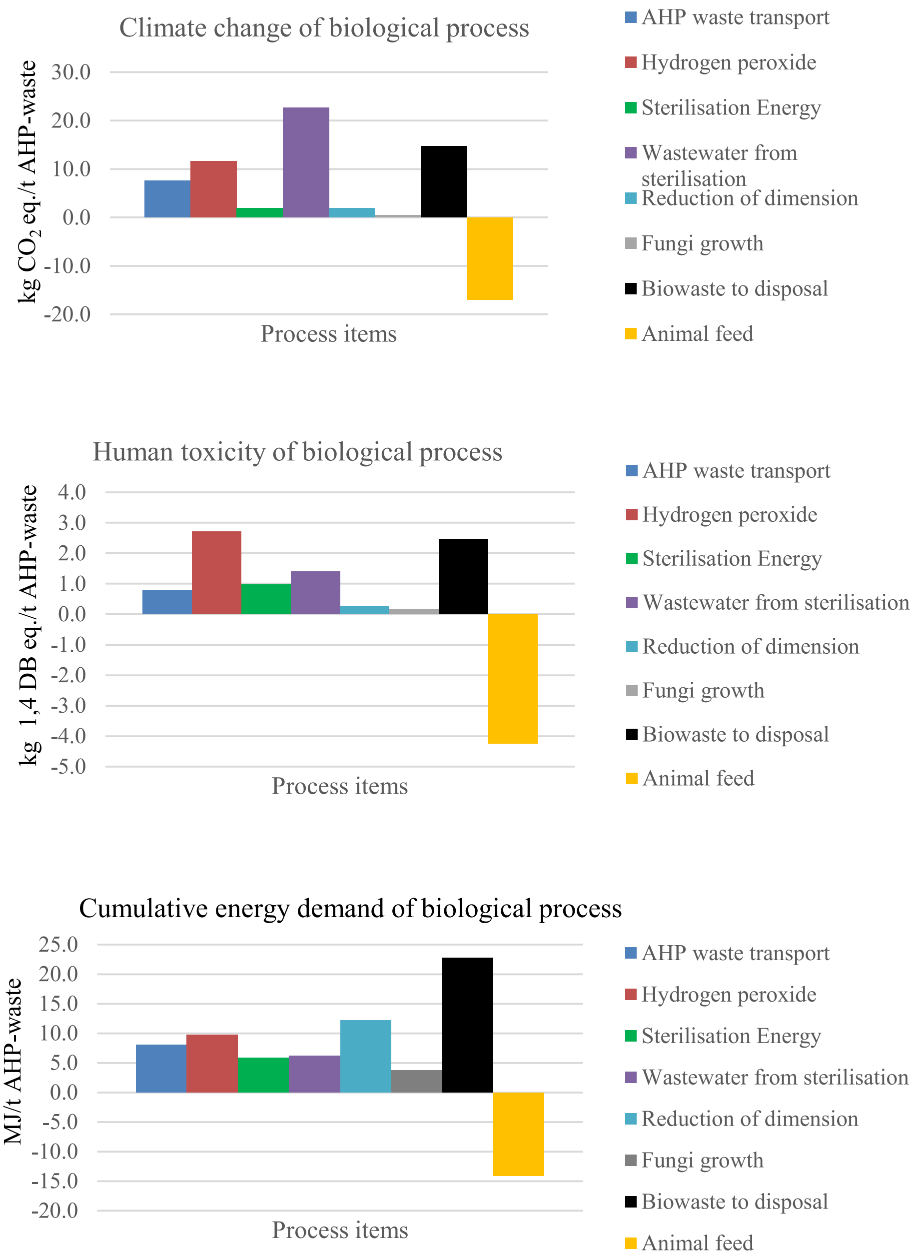

Fig. 2. Contribution of each process item to the environmental impacts in the biological process considering the impact categories climate change, human toxicity, and cumulative energy demand.

In the human toxicity category the impact was in line with others biological process like bioplastic degradation (Bishop et al., 2021) and the result ensured that the biodegradation of AHP-waste can be carried out safely for human health, as reported in the study of Espinosa-Valdemar et al. (2011). In human toxicity, the process item with the highest impact was the hydrogen peroxide used for the sterilisation of the AHP-waste, according to the study of Bishop et al. (2021).

Currently, the available biotechnologies to treat AHP-waste at technological readiness level (TRL) 4 are anaerobic co-digestion of food waste and nappy for biogas production (Zagklis et al., 2021) and composting (Mirabella et al., 2013). In all the considered impact categories, the co-digestion of food waste and nappy for biogas production carried out by Zagklis et al. (2021) achieved an impact of 45 % lower rather than the investigated biological process (in the present study). The reason was that the study of (Zagklis et al., 2021) recovered energy from the produced biogas and used it to cover the energy effort of the process and the digestate was composted and not landfilled. According to Waste Framework Directive, composting is preferable to landfill because composting can valorise waste through the production of compost (valuable product for soil application), whereas landfill is only waste disposal which leads to impact (Fig. 2).

4.2. *Environmental evaluations of mechanical-thermal stabilisation of AHP-waste*

The mechanical-thermal conversion of AHP-waste into sterilised fluff, which was then landfilled, reached the following impacts in climate change, human toxicity, and CED: 29.54 kg CO_2 eq./ t AHP-waste, 6.38 kg 1,4 DB eq./ t AHP-waste, and 99.18 MJ/ t AHP-waste, respectively.

In this process, no-avoided impacts were detected, because the mechanical-thermal conversion of AHP-waste aimed to sterilise and reduce the volume of AHP-waste to dispose of without recovering materials and/or energy.

The produced fluff represented 63.0 %w/w of the initial AHP-waste, and it should be further valorised for energy recovery, but in the present study, the energy production was not considered, because it was not still implemented in the tested pilot plant. The fluff could be employed as feedstock to produce hydrogen through dark fermentation and thermochemical process (Malsegna et al., 2021). The studies of Liberato et al. (2019) and Zagrodnik and Seifert (2020), proved that dark fermentation could be performed on the fluff with *Clostridium* sp., which is an anaerobic bacterium able to metabolize several substrates, including cellulose, and convert them into valuable products.

In the scientific literature, there is no available environmental study about the mechanic-thermal process like the present mechanical-thermal conversion of AHP-waste. To sterilise and reduce the volume of AHP- waste, previous studies investigated hydro-thermal-carbonization (HTC) to convert AHP-waste with high humidity in hydrochar (Budyk and Fullana, 2019) and pyrolysis to produce an energy vector (Lam et al., 2019). HTC and pyrolysis like sterilisation can prevent microbial growth and sanitary problems (Hoffmann et al., 2020). According to the study of Lam et al. (2019), pyrolysis of the fluff derived from AHP-waste reached higher performance than the one performed with AHP-waste as well, because the AHP-wastes have higher moisture content than fluff derived from AHP-waste.

These results proved that mechanical-thermal conversion of AHP-waste in fluff could be an intermedia process for the further valorisation of fluff for energy production.

Gerina-Ancane and Eiduka (2016) used AHP-waste as feedstock for pyrolysis to produce syngas with a high calorific value equal to 34. 40 MJ/kg, oil with valuable compound, and char with high calorific value in a range of 15.95–18.08 MJ/kg. The study of Lam et al. (2019) stated that products of fast pyrolysis can be further valorised; in detail, the oil could be employed as chemical additives, cosmetic products, and fuel due to the high contents of alkanes and esters, meanwhile, the biochar could be a soil amendment because it has high carbon content without sulphur compounds.

The mechanical-thermal conversion did not use chemical reagents or combustion principles; hence air pollution and harmful vapours were not released into the environment and consequently, the impacts on human health and toxicity were not relevant according to the study performed by Ompeco (2019). The health risk of disposable AHP-waste concerns the potential sanitary and health issues relating to exposure to different kinds of pathogens and other contaminants since currently AHP-waste are treated with MSW. The human toxicity impact of the mechanical-thermal technology was due to the treatment of wastewater, which counted for 32 % of the total impacts.

Both in terms of climate change and human toxicity categories, the landfill disposal contributed to the total impact of 31 and 32 %, respectively. The considered landfill was a landfill for inert material, since fluff was a sterilised and stabilized material, hence the emissions mainly derive from gases emission rather than leachate (Mirabella et al., 2013). However, these results proved the necessity to valorise the waste for material and energy production. Considering the energy consumption, through the CED evaluation, the process reached a high energy impact since it was a high energy-consuming process, and in its process flow design, there is no processing unit aimed to energy recovery, which can represent avoided burdens. The energy impact of the mechanical-thermal process was 40.28 MJ/ t AHP-waste and the only converter unit represented 80 % of this consumption.

The CED results highlighted the necessity of including energy recovery (which means avoided burdens) in AHP-waste treatment and recycling. Indeed, according to the analysis of Somers et al. (2021), the CED increases when the recovery of energy and materials in the process is not enough to counterbalance the primary production of the material itself (Fig. 3).

4.3. *Environmental evaluations of recycling treatment of AHP-waste*

The recycling technology consisted of the recovery of valuable material through the stabilisation and elimination of the organic matter and possible pathogenic compounds of AHP-waste. The main process phases were autoclave, dryer, and mechanical separation to recover 8.3 % of SAP, 16.75 % of cellulose, and 6.52 % of plastics based on the amount of AHP-waste treated. In the recycling process, the efficiency of material separation, and their emissions agreed with the study of Takaya et al. (2019a), which adopted similar technology.

In the recycling process, the climate change, the HT and CED were respectively −2.68 kg CO_2 eq./t AHP-waste, −0.07 kg 1,4 DB eq./t AHP-waste and −26.36 MJ/t AHP-waste.

The above-mentioned results prove that the recycling process avoided impacts in all the considered impact categories due to its capability to recover the proper quantity of valuable materials and counterbalance the energy effort and utilities required to run the process, according to the recycling principle of the Waste Hierarchy Framework (Willskytt and Tillman, 2019; Zagklis et al., 2021).

In all the three considered impact categories, the recovery of cellulose was the item with the highest contribution to the avoided emissions because cellulose was the material with the highest rate of recovery (16.75%*w*/w), whereas the items of the process with the highest impacts were the dryer unit, followed by the wastewater treatment and AHP-waste collection. The high impacts of the dryer unit and wastewater were due to the high moisture content of the AHP-waste (Liza, 2019).

For all the considered impact categories, the recycling process proved that to achieve a negative impact it is mandatory that the rate of material recovery must be able to counterbalance the impact of the whole process. This result agreed with the document “Environmental analysis of the collection and recycling of absorbent sanitary products” conducted by Fater (2019) which exhibited similar technology, the same functional unit, and boundary conditions.

In the recycling process, the avoided emissions for climate change

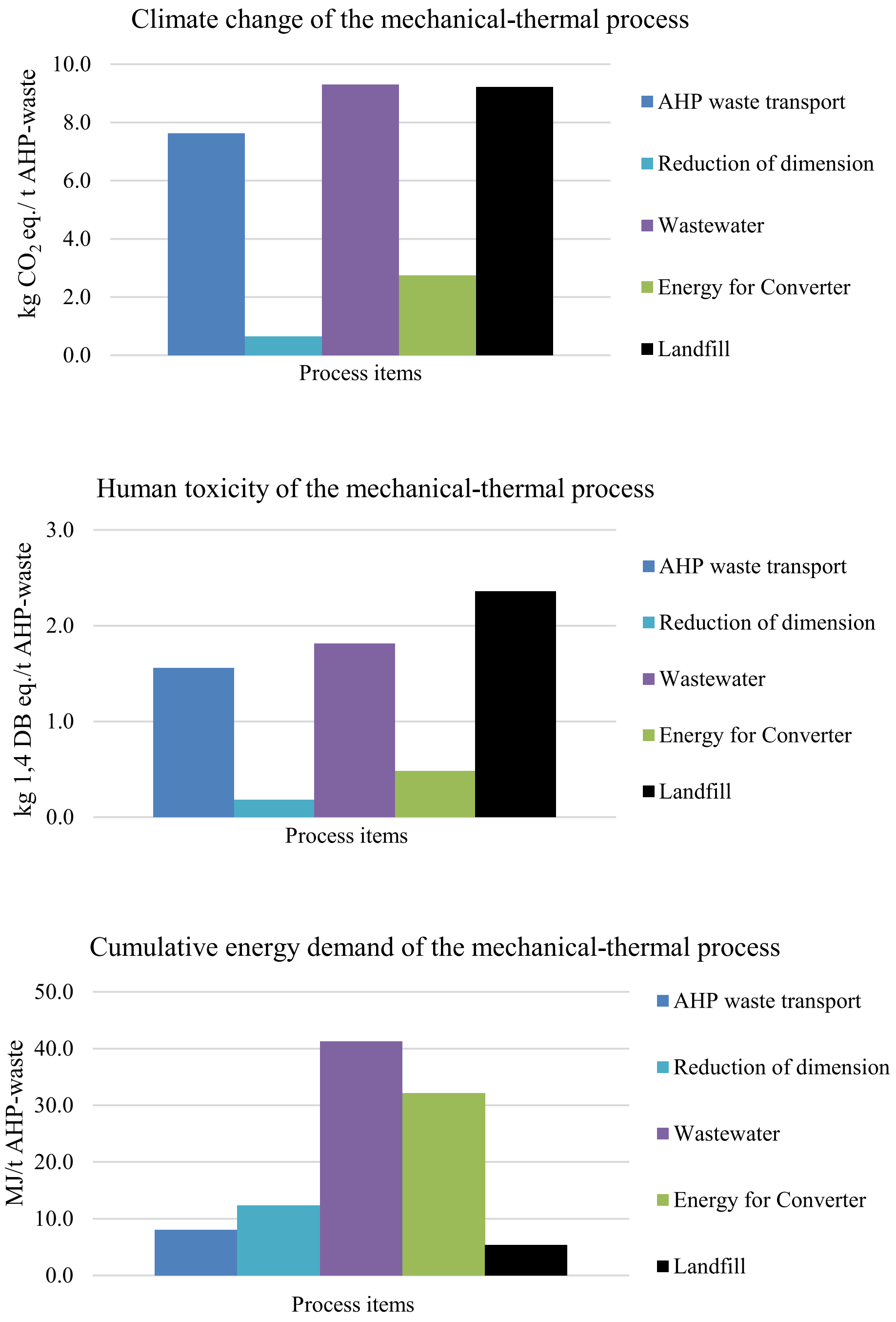

Fig. 3. Contribution of each process item to the environmental impacts in the mechanical-thermal process of AHP-waste, considering the impact categories climate change, human toxicity, and cumulative energy demand.

and human toxicity categories, due to the separation and recovery of cellulose, SAP, and plastic agreed with the ones obtained by the project Horizon EMBRACED (Establishing a Multi-purpose Biorefinery for the Recycling of the organic content of AHP waste in Circular Economy Domain, ID 745746) which adopted similar technology (Horizon, 2020, ID 745746) and boosted the worldwide adoption of this technique. The RECALL project investigated a process similar to this investigated recycling treatment, but in the RECALL project the unsorted streams were considered as feedstock to produce energy through incineration, which means avoided products and reduction of the total environmental impacts. Specifically, the RECALL project achieved −14.9 kg CO$_2$ eq./t AHP-waste, through the energy recovery from refined streams, which means a +5.52 % of reduction of impact compared to the present study. This result underlined the key role of energy recovery to reduce the total environmental impacts.

In this present investigated recycling technology, the recovered materials could be used in different applications: cellulose is used in paper mills to produce cardboard as a substitute for virgin cellulose pulp, and starch and plastic can be further employed as filler for 3D printing (Arena et al., 2016).

The study of Arena et al. (2016) investigated the environmental impacts of AHP-waste treatment through a process partially similar to the one investigated in the present study, but after the sterilisation of AHP-wastes and the separation of cellulosic in a sorting machine, the process of Arena et al. (2016) proposed the new integrated recycling scheme able to employ the cellulose fraction as feedstock for the fluidized bed gasifier to produce the bio-energy and replace the fossil fuel utilised to produce the steam necessary for the sterilisation stages. With this new driving recycling scheme, the climate change impact and CED decreased by 37.5 and 96.3 % compared to the results achieved in the present study. The comparison between the present study and the one of Arena et al. (2016) proved the environmental sustainability of this recycling technology for AHP-waste and its possible further improvement through a proper valorisation of the recovered materials.

The recycling process of wastes of Arena et al. (2016) was proposed in the framework of a "Virgin" project, LIFE 12 ENV/IT/000611, as an evolution of a previous scheme of RECALL project.

Among the available AHP-waste recycling techniques, the most promising were the technologies proposed by the studies performed by Hwang et al. (2018), Takaya et al. (2019a), and Ragaert et al. (2017), but for all these technologies, LCA studies are not available. In detail, in the study of Hwang et al. (2018) AHP-waste was disinfected, shredded, and separated in the same unit. Disinfection was done with acidic electrolysed water, after which water and chemicals are inserted to improve separation into plastic, pulp, and SAP fractions and finally the wastewater was recirculated through a bioreactor system to remove nitrogen and phosphorus. In this analysed recycling technology wastewater was not recirculated and it represented 30 % of impacts in climate change and human toxicity categories. Whereas Takaya et al. (2019a) proposed a process like the one of this analysed recycling technology, but the separated cellulosic material was converted into construction materials like panel boards and wall cladding, with a reduction of energy consumption. The last available recycling technology was the one proposed by Ragaert et al. (2017) which was a process including AHP-waste sterilisation, and plastics were mechanically and chemically processed, SAP was incinerated, and cellulose was purified and dissolved for use in coatings. The recovery of materials and energy allowed to reduce the impact and improve the circularity of the process scheme (Fig. 4).

4.4. *Environmental evaluations of the baseline scenarios*

The current Italian AHP-waste management system consists of 35 % incineration with energy recovery and 65 % in landfill with 30 % CH_4-capture. The main difficulty of the environmental evaluation of the incineration process is the correct calculation of the direct and avoided emissions of the system. The study of Fleischer et al. (2001) proposed to simplifying LCI of the incineration process by using secondary data instead of direct and case-specific data in inventory analysis. However, the present study evaluated the environmental impacts of the AHP-waste incineration with energy recovery and landfill carried out in two working plants available in the North-West of Piedmont and currently involved in the management of AHP-waste.

For incineration and landfill of municipal waste, the key factors in LCA evaluation were the energy recovery (Čarnogurská et al., 2015) and the collection of landfill gases and leachate (Paes et al., 2020). The energy recovery from incineration and landfill is not broadly adopted in waste management as proved by some LCA performed in different geographical contexts, in Switzerland (Boesch et al., 2014) and France (Déchaux et al., 2017).

In the present study climate change, human toxicity, and CED were 136.17 kg CO_2 eq./ t AHP-waste, 25. 07 kg 1,4 DB eq./ t AHP-waste and 208,43 MJ/ t AHP-waste, respectively. In these above-reported results, the contribution of the landfill was 73 %. The baseline scenario considered in the present study agreed with the current scenario proposed by EUROSTAT 2021: 65 % landfill with CH_4 capture and 35 % incineration with energy recovery. The results obtained from the baseline scenario proved that incineration with energy recovery contributed to reducing the environmental impacts of the current AHP-waste management in climate change category and CED.

In the present study, the recovery of 30 % of CH_4 in landfill allowed to reduce the environmental impact of landfill up to – 2 %, (Thushari et al., 2020; Liikanen et al., 2017). It is worthy of note that in landfills, the degradation of plastic and SAP waste is slow, and it is hindered by the widespread practice of wrapping nappies and sanitary pads in their external plastic layer (Tsigkou et al., 2020). However, these materials affect the environmental performance of the facility, specifically through the production of greenhouse gasses due to the degradation of cellulose and biowaste (Velasco Perez et al., 2021).

With regards to incineration, the study of Liikanen et al. (2017), evaluated that the bottom and fly ashes and CO_2 capture unit represented 93 % of the total environmental emissions, but the energy recovery section reached −4 % of emissions. The study of Beylot et al. (2018) investigated a French municipal solid waste incineration plant with the same FU and boundary conditions adopted in the present study, and stated that energy recovery counted between 33 and 54 %. Whereas, in the present study the incineration of AHP-waste reached a limited energy recovery due to the higher moisture content of the AHP-waste compared to one of the municipal solid wastes. Considering the CED, the recovery of energy in the incineration treatment and the CH_4-capture and its conversion into energy contributed to reducing the energy consumption and impacts of the AHP-waste treatment.

It is important to underline that the CED could be completely different if the energy recovery function was not included because the energy recovery allowed the production of electricity by exploiting the heat from flue gases and it covered part of the energy cost of the plant. Moreover, if the flue gases were not valorised and converted into energy, they produced emissions and impacts.

The recovery of energy was a key parameter that contributed to reducing the impacts in all the considered impact categories, indeed the partial recovery of energy reduced the energy consumption and climate change impact (Scipioni et al., 2009).

The human toxicity obtained by incineration and landfill was in line with the ones achieved by the research of Beylot et al. (2018) and Hait and Powers (2019), respectively for incineration and landfill with energy recovery. Even if the incineration treatment represented only 35 % of the total AHP-waste baseline treatment, incineration mainly contributed to human toxicity due to the production of bottom and fly ashes, (Vakalis et al., 2017). Specifically fly ashes are hazardous waste and represent a dangerous matter for human health (Vakalis et al., 2017). In the human toxicity category both for incineration and landfill, the recovery of electricity achieved an avoided impact which was not able to balance the highest impacts due to the possible effects of solid, liquid, and gaseous waste on human health (Takaya et al., 2019b). However, it is important to underline that incineration has the great advantage to eliminate the risk of dispersion of pathogens, destroying them in the process (Takaya et al., 2019b), whereas human toxicity category due to landfill came from landfill emissions concerning GHS emissions and possible loss of leachate with the pathogen (Fig. 5).

4.5. *Sensitivity analysis*

To verify the consistency and robustness of the LCA results, two sensitivity analyses were performed and are depicted in Fig. 6. The first sensitive analysis focused on the collection and transport of AHP-waste to treatment facilities because recent studies underscored that the biomass yield density (t/ha•y) varied with biomass supply distance (km). The transport of AHP-waste was varied by±10 km and the trend of the impacts of the four AHP-waste treatment configurations did not change, but by increasing the transport (km), the climate change increased about 1.5–3.2 %, human toxicity by 2.0–3.3 % according to the study of Demichelis et al. (2022) and the CED increased around 1.8–2.0 %. These results prove the importance to reduce the transport distance of feedstock with high humidity contents (Golecha and Gan, 2016).

The second sensitivity analysis varied the rate of material recovery efficiency by±5% and witnessed that the impact values increased when the recovery efficiency decreased. In detail, climate change increased by 5.8–6.2 % and human toxicity by 2.5–3.8 % according to the study Demichelis et al. (2022) and the CED increased by around 2.12–2.07 %.

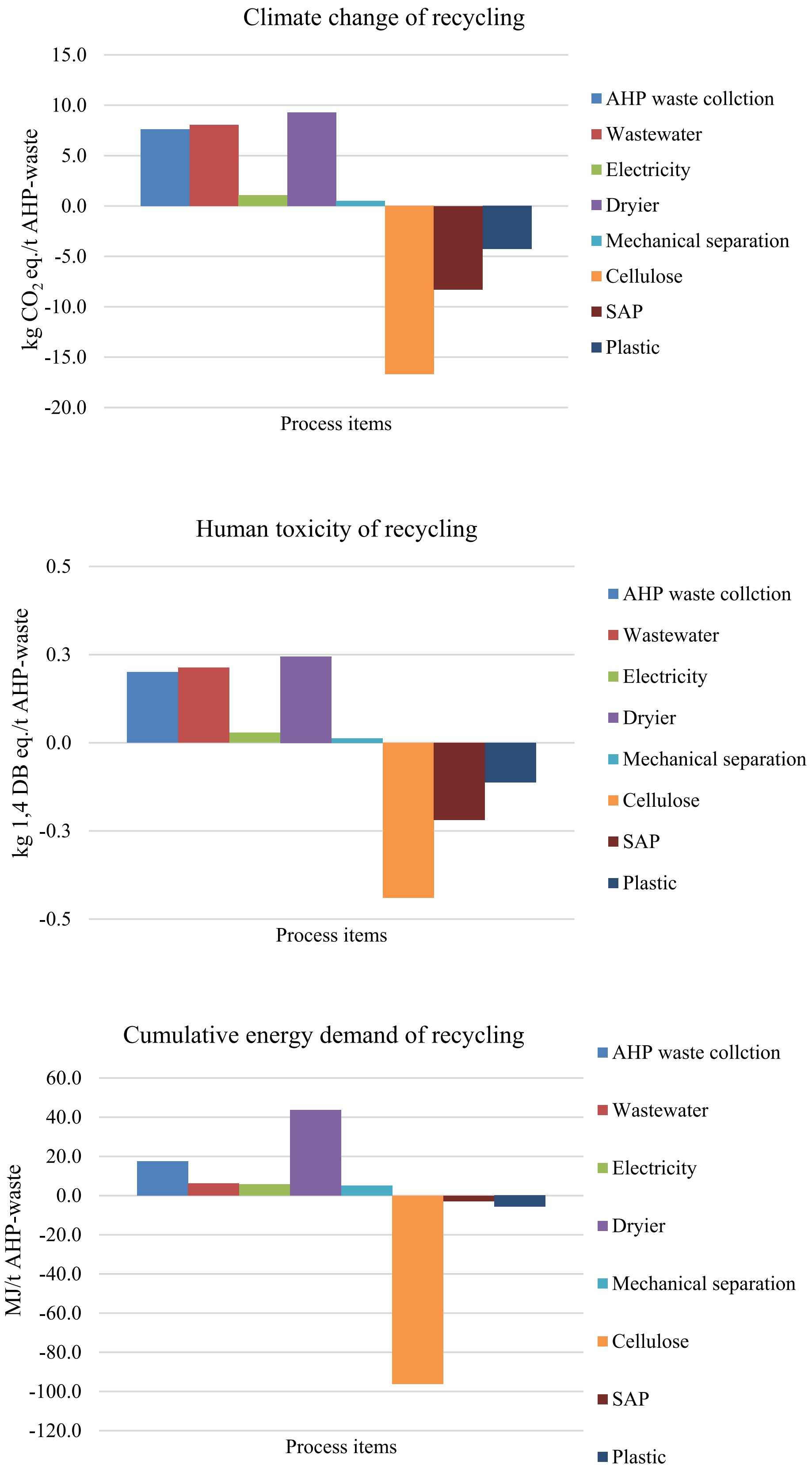

Fig. 4. Contribution of each process item to the environmental impacts in the recycling process considering the impact categories climate change, human toxicity, and cumulative energy demand.

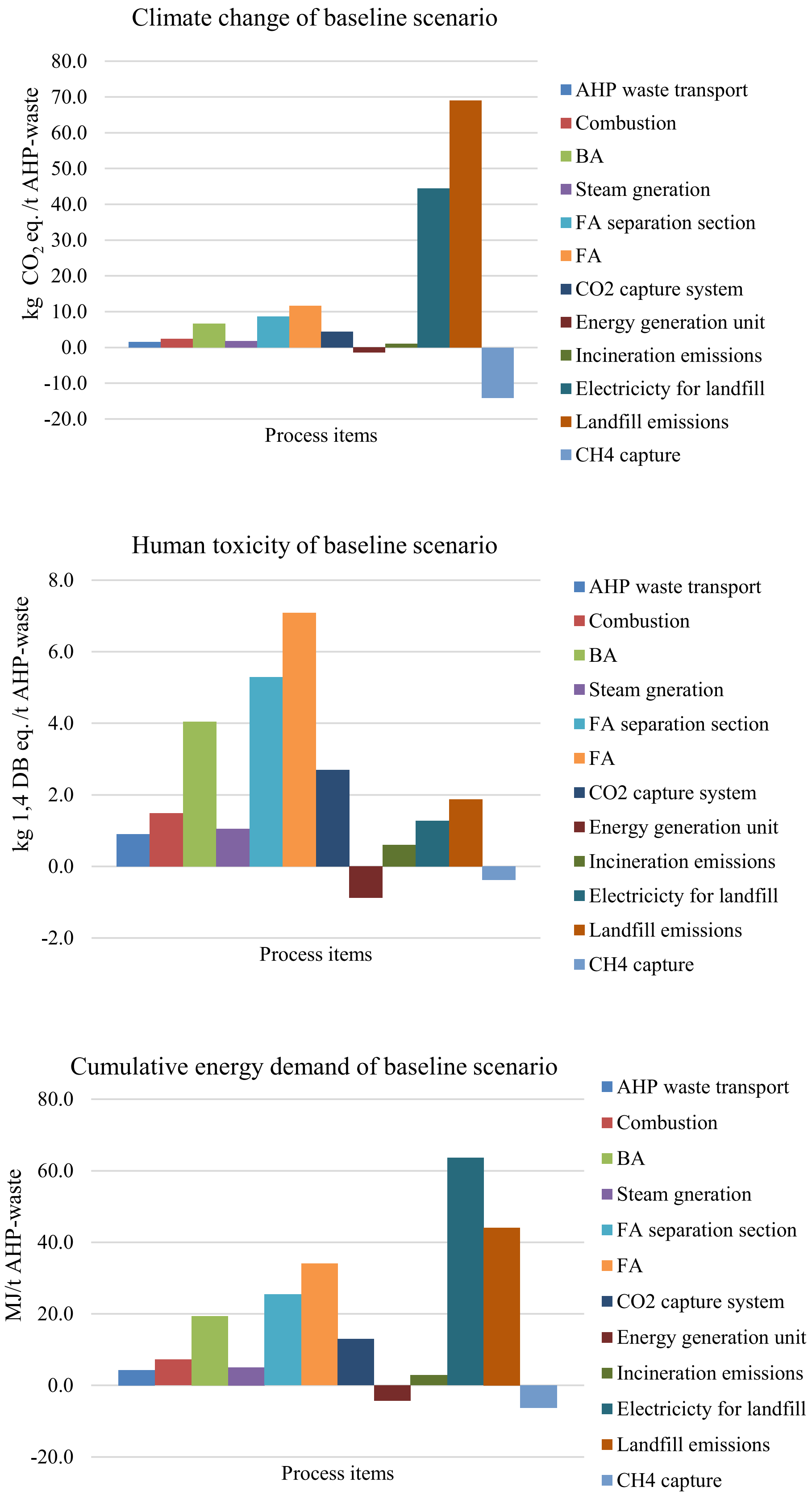

Fig. 5. Contribution of each process item to the environmental impacts in the baseline treatment considering the impact categories climate change, human toxicity, and cumulative energy demand.

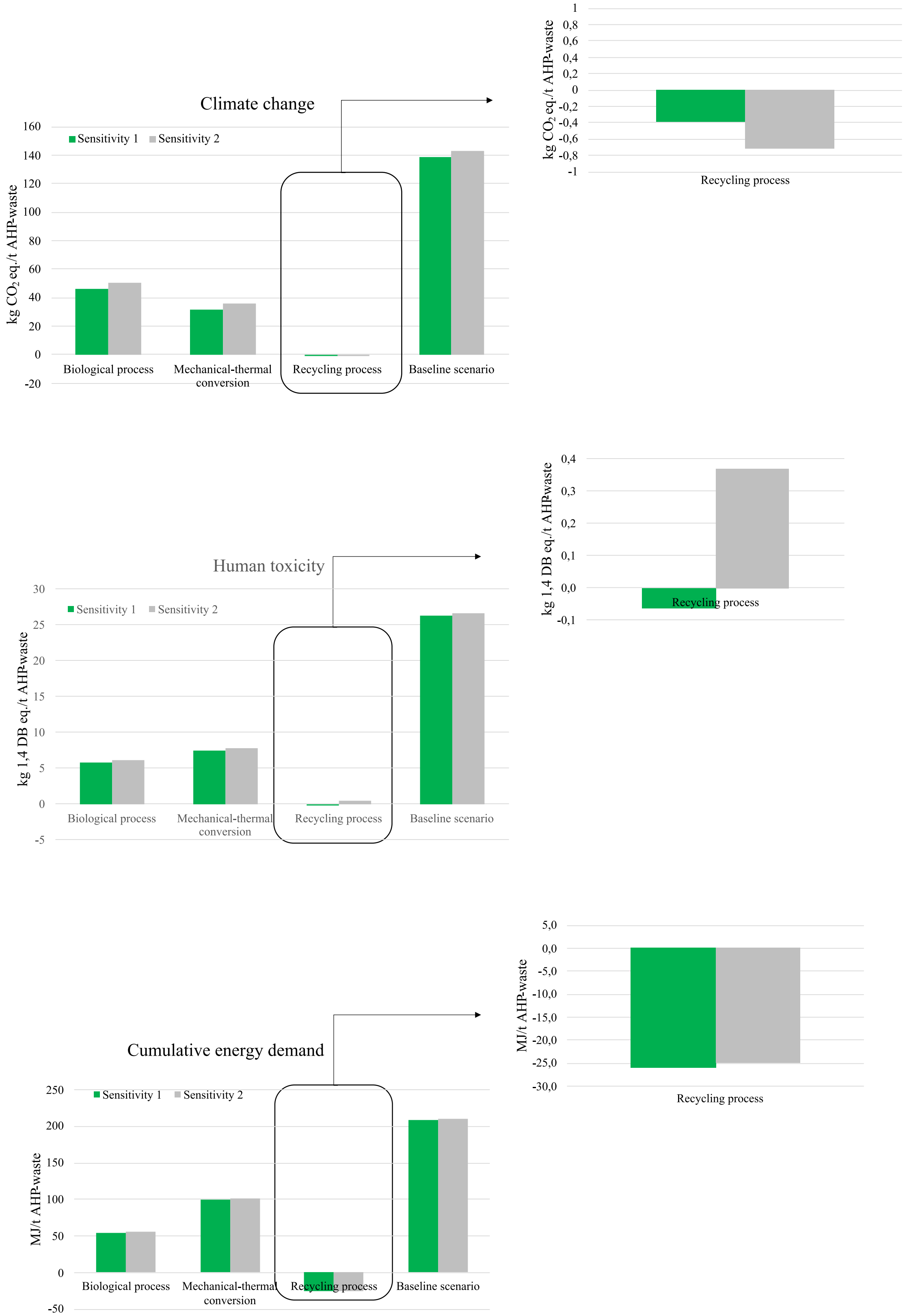

Fig. 6. Sensitivity analysis1 considers the variation of km of collection, transport, and disposal of AHP-waste (green). Sensitivity analysis 2 considers the variation of the process performances (grey). The considered categories are the climate change, human toxicity, and cumulative energy demand (CED).

It is important to evidence that the recycling process had still a negative impact by increasing the transport of +10 km, whereas it became a positive impact in the human toxicity category with a reduction by −5 % of the material recovery efficiency. This result underlined the importance to set the correct recovery rate of material in the AHP-waste or the proper production of energy, which represented an environmental saving impacts, only when the rate of recycling and recovery can overcome the requirement of material and energy to support the AHP-waste treatment according to the studies of Willskytt and Tillman (2019) and Zagklis et al. (2021). To conclude, the environmental analysis proved that by combining the results achieved for climate change, human toxicity and CED, the rank of the most promising AHP-waste treatment technology was; the recycling process which achieved an environmentally avoided impact, followed by biological and the mechanical-thermal process, and last the baseline scenario. Biological and mechanical-thermal processes reached the same position in the ranking of AHP-waste treatments because the biological process reached slightly lower human toxicity and CED impact values rather than mechanical-thermal process, but the climate change impact of biological process was about 1.5 times higher than the one of mechanical-thermal process. It is important to underline that the environmental impacts of the mechanical-thermal process can be minimised through the energy valorisation of fluff.

5. Conclusions

The study compared the environmental impacts of four AHP-waste treatments in the North-West of Piedmont (Italy) to detect the one with the lowest impact and adopt a new environmentally friendly AHP-waste management. The innovative treatments concerned; the biological process which exploited the AHP-waste as a substrate for fungi growth, the second was the mechanical-thermal conversion of AHP-waste into sterilised fluff to dispose of in a landfill, and the third one was recycling process able to recover plastic, super absorbent materials, and cellulose. The baseline scenario consisted of incineration with energy recovery and landfill with CH4-capture. The analysis was performed with Life Cycle Assessment and evaluated climate change and human toxicity with ReCiPe 2016 Midpoint (H) and non-renewable energy with Cumulative Energy Demand. The functional unit was 1 t of AHP-waste, the approach was from bin to grave and the data came from patents, reports, experimental test and Ecoinvent 3.7 database. Only the recycling of AHP-waste achieved avoided environmental impacts; $-$ 2.68 kg CO_2 eq./t AHP-waste, -0.07 kg 1,4 DB eq./t AHP-waste, and -26.36 MJ/t AHP-waste, because the rate of material recovery counterbalanced the efforts required to treat AHP-waste. The biological and mechanical-thermal conversion of AHP-waste reached the same rank position, but the last one could be further improved through an energy valorisation of the fluff. The study proved the importance of the proper product recovery rate to offset the requirement of utilities of the AHP-waste treatment. To improve these AHP-waste treatments, the detected bottlenecks will solve through the realisation of an eco-design.

Ethical approval

This declaration is not applicable. Tests on human or animal were not done. The manuscript is original study, no submitted elsewhere and it is not divided into several parts.

CRediT authorship contribution statement

Authors ‘contributions are detailed in the following. F. Demichelis carried out Life Cycle Assessment (LCA) studies, contribute to conceptualisation, and wrote part of the paper. C. Martina carried out the inventory phase and part of Life Cycle Assessment (LCA) studies, D. Fino supported the study of LCA, T. Tommasi realised the conceptualization, methodology and supervision of the study, and F.A. Deorsola contributed for the review of the study.

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Declaration of competing interest

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

Data availability

This declaration is not applicable. To carry out LCA study, the authors had a licensee for the used software.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.04.012.

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