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Environmental assessment of energetic valorization of textile waste *via* fluidized bed combustion with post-combustion catalytic treatment, thermal plasma application, and carbon capture

Walter Fernández Benítez, [iD][a] Einara Blanco Machin, [iD]*[b] Carlos Labra Fierro,[c] Nestor Proenza Pérez [iD][d] and Daniel Travieso Pedroso [iD][c]

The textile industry is one of the most polluting sectors worldwide, generating large amounts of post-consumer and industrial waste with limited recycling options and significant greenhouse gas emissions. This study assesses the environmental viability of energy recovery from textile waste through fluidized bed combustion and oxycombustion, followed by post-combustion catalytic treatment, thermal plasma application, and carbon capture. A gate-to-gate life cycle assessment (LCA) was performed using process simulation data for textile waste with a composition of 50% cotton and 50% polyester, integrating selective catalytic reduction for NO_x abatement, CaO-based treatment for CO_2 capture, and also incorporating real thermal plasma data for the destruction of dioxins and furans. Environmental impacts were quantified using the ReCiPe 2016 Midpoint (H) method. Results show that combustion with carbon capture and thermal plasma application achieved a global warming potential (GWP) of 3.6 kg CO_2 eq. per kg textile. In comparison, oxycombustion with carbon capture and thermal plasma application achieved 4.3 kg CO_2 eq. per kg textile, representing reductions of 27–57% compared to textile waste disposal in landfills, incineration, or mechanical/chemical recycling. CO_2 capture and thermal plasma were the primary contributors to environmental burdens, whereas steam generation provided significant offsetting credits. Oxycombustion increased NO_x and particulate emissions but reduced eutrophication and aquatic ecotoxicity. Overall, combustion and oxycombustion with post-combustion catalytic treatment, thermal plasma application, and carbon capture offer a promising route for the energetic valorization of non-recyclable textile waste, combining greenhouse gas reduction, energy recovery, and lower environmental impacts, supporting circular economy strategies.

1. Introduction

The textile industry is among the most polluting industries in the world due to its high consumption of resources and the massive generation of industrial and post-consumer waste, much of which ends up in landfills or is incinerated without adequate environmental control.[1]

[a] *Departamento de Ingeniería de Procesos y Bioproductos (DIPROB), Facultad de Ingeniería, Universidad del Bío–Bío, Av. Collao 1202, Concepción, Chile*

[b] *Departamento de Ingeniería Mecánica (DIM), Facultad de Ingeniería, Universidad de Concepción, Edmundo Larenas 219, Concepción, Chile. E-mail: eblanco@udec.cl*

[c] *Departamento de Ingeniería Mecánica (DIMEC), Facultad de Ingeniería, Universidad del Bío–Bío, Av. Collao 1202, Concepción, Chile*

[d] *School of Engineering and Sciences, Guaratinguetá (FEG), Department of Chemistry and Energy, São Paulo State University (UNESP), Av. Ariberto Pereira da Cunha, 333, Guaratinguetá/SP, Brazil*

The textile industry is responsible for nearly 10% of global carbon emissions.[2] The production of virgin fibers, such as cotton, consumes between 7000 and 29 000 liters of water and 0.2 to 1.1 kilograms of oil per kilogram produced, resulting in soil degradation and loss of biodiversity. Seventy percent of global textile production consists of synthetic fibers derived from petroleum.[3] Final disposal in landfills releases toxic methane and ammonia, while incineration emits dioxins, heavy metals, and acid gases. More than 8000 chemicals are used in processing, with up to 23% of these persisting in the final product, making recycling difficult and potentially harmful to health.[4]

Between 2000 and 2020, global textile production nearly doubled, rising from 58 to 109 million tons, and forecasts indicate that it will reach 145 million tons by 2030.[5] However, most textiles at the end of their useful life are landfilled or incinerated, with recycling rates often below 15% worldwide.[6]

In Europe, the average annual consumption is 26 kg per person, and 87% of discarded textiles are either burned or buried.[5] Chile mirrors this upward trend, with *per capita* purchases quadrupling over two decades and generating more than half a million tons of textile waste annually, a significant portion of which ends up in informal landfills.[7]

Given the complex composition of textile waste—a mixture of natural and synthetic fibers, such as cotton and polyester conventional waste treatment methods face limitations in terms of environmental impact and energy recovery efficiency.[8] Therefore, advanced technologies that enable simultaneous energy recovery and pollutant mitigation are urgently needed.

Conventional treatment methods, such as incineration without CO_2 capture or mechanical recycling, present technical and environmental limitations. Incineration of mixed textiles (*e.g.*, cotton/polyester) emits pollutants such as NO_x, volatile organic compounds, dioxins and furans, and fine particles.[9] Furthermore, current energy recovery strategies often overlook the potential of integrating carbon capture systems, which are crucial to achieving global climate neutrality goals.[10–12]

Faced with these limitations, the combustion in fluidized bed reactors with post-combustion catalytic treatment, combined with CO_2 capture technologies and thermal plasma application, has become a promising alternative for recovering value from textile waste and minimizing greenhouse gas (GHG) emissions and other harmful pollutants such as NO_x, dioxins, and furans.[1,11–13] These processes can generate valuable products, such as superheated steam, which contributes to circular economy goals and reduces dependence on fossil fuels.

However, to assess their actual environmental viability, it is essential to subject these processes to life cycle assessment (LCA), which allows for the consideration of environmental burdens and benefits from waste treatment to the generation of valuable products such as superheated steam, as well as the management of emissions, ash, and byproducts such as carbonates.[13] LCA is a robust and standardized tool for quantifying environmental impacts, enabling objective comparisons between technologies and supporting intelligent decisions towards more sustainable models.[14]

Despite growing interest in fluidized bed carbon capture technologies, including circulating fluidized beds, oxycombustion, and calcium looping, the systematic application of life cycle assessment (LCA) to evaluate their environmental performance remains limited.[15,16] While comparative life cycle assessments have been developed for incineration plants with CO_2 post-combustion systems,[17] as well as general reviews on the use of fluidized bed reactors for CO_2 capture,[18] the integration of LCA into combustion processes of textile waste with post-combustion catalytic treatment, carbon capture, and thermal plasma is still an emerging and largely unexplored field.

Various industrial sectors have been the subject of comprehensive LCA studies that integrate carbon capture and other mitigation technologies, revealing significant environmental improvements. For example, the cement industry has been evaluated in scenarios that include oxycombustion and the use of biomass as fuel, resulting in GWP reductions of 75–90% in some cases.[19] In steel production, recent studies have modeled alternative pathways, including carbon capture and storage (CCS), hydrogen-based direct reduced iron (H_2-DRI), and electrified processes, finding that these technologies can reduce steel-related emissions by up to 90–95%.[20] Even in the steel slag sector, research is being conducted that applies life cycle analysis (LCA) to mineral carbonation as a means of CO_2 capture, assessing whether the net benefits outweigh the environmental costs of the process.[21] Compared to these sectors, the textile industry lacks comprehensive studies that explore energy recovery with carbon capture and advanced technologies, such as thermal plasma. This gap highlights the need for specific research, such as that in the present study.

Recent advances in material science have yielded innovative solutions for environmental applications, such as biomass-derived porous carbons for efficient CO_2 capture[22] and molecular reconstruction techniques for upcycling waste fluororubbers.[23] While these material-centric approaches enhance individual process efficiency, they underscore a broader research gap: the lack of holistic environmental assessments of integrated technological systems for complex waste streams. This study addresses that gap by shifting the focus from material innovation to system-level integration.

This study aims to evaluate the environmental performance of energy recovery from textile waste (50% cotton and 50% polyester) through combustion and oxycombustion in a fluidized bed reactor with post-combustion catalytic treatment, integrating selective catalytic reduction (SCR) with zeolite for NO_x abatement, CaO-based CO_2 capture, and application of thermal plasma for the treatment of dioxins and furans. The analysis follows a gate-to-gate approach,[24,25] from waste feeding to the production of useful steam, based on process simulations in Aspen Plus that provide material and energy flows, gaseous emissions, and solid waste, as well as information on pilot-scale testing for the destruction of dioxins and furans using thermal plasma.[26]

2. Methodology

2.1 System boundary

The system is divided into the following subsystems:

(i) Feeding and preparation: includes storage, handling, and feeding into the reactor.

(ii) Combustion and oxycombustion: thermal oxidation processes of waste and different atmospheres (air and enriched oxygen) and catalytic NO_x reduction (SCR).

(iii) Gas treatment: CO_2 capture through adsorption with CaO and thermal plasma.

(iv) Steam generation: recovery of thermal energy for process steam production.

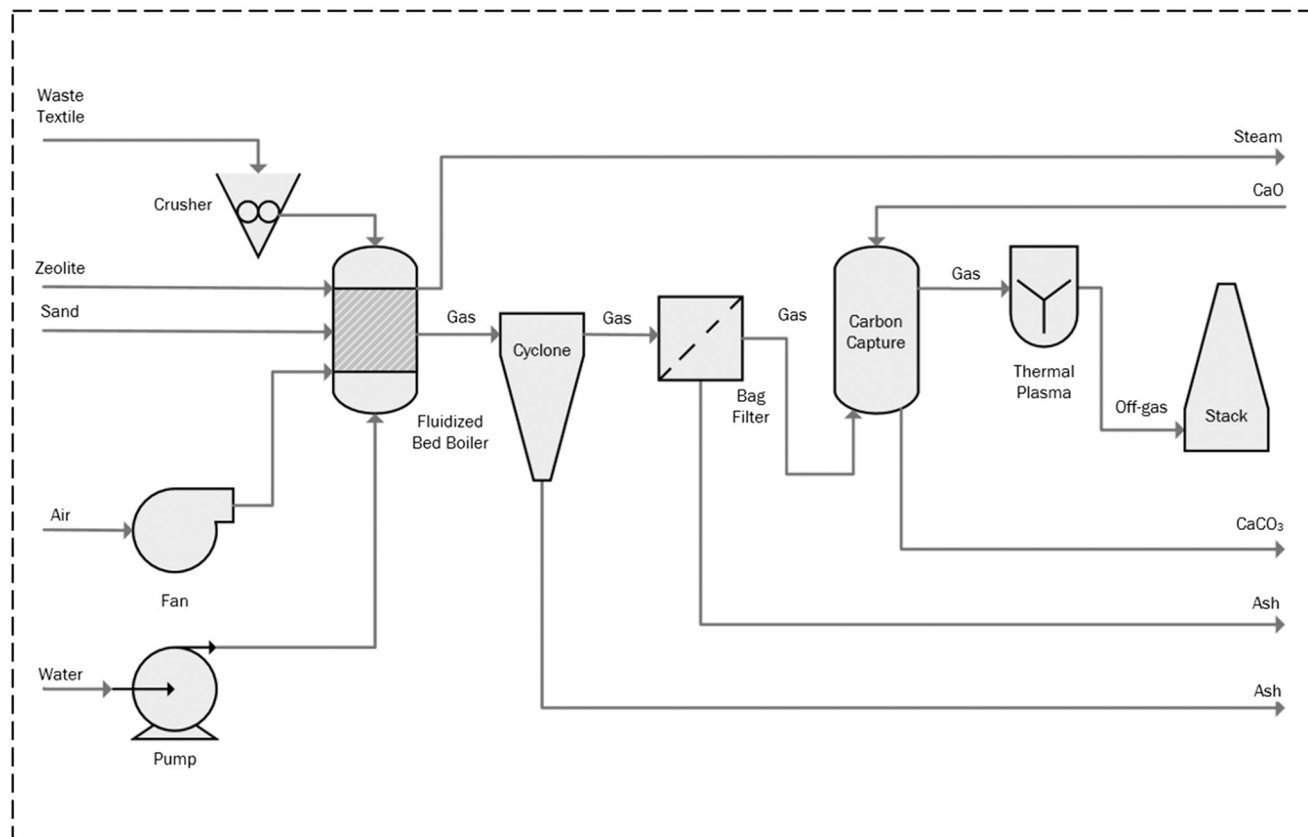The system boundaries for the combustion case are shown in Fig. 1.

Fig. 1 System limits for combustion of textile waste with post-combustion catalytic treatment, thermal plasma application, and carbon capture.

The system boundaries for the oxycombustion case are shown in Fig. 2.

2.2 Functional unit

The functional unit (FU) is 1 kg of textile, valued by combustion and oxycombustion in a fluidized bed reactor with post-combustion catalytic treatment, and thermal plasma application with carbon capture.

2.3 Process simulation and data collection

The combustion and oxycombustion process flows were modeled in Aspen Plus® v14 using a combination of thermodynamic equilibrium and kinetic models for combustion and catalytic reduction of NO_x. The results were balanced in terms of mass and energy and cross-validated with data from the literature.[27]

2.4 Requirements and data sources

The primary data was obtained directly from the process simulation and information reported in the literature, including:

(i) Elemental and thermogravimetric composition of textile waste.[27,28]

(ii) Flows and compositions of combustion and oxycombustion gases.

(iii) Measured the electricity consumption of auxiliary systems and leading equipment.

(iv) Amounts of ash and solid waste generated.

(v) Efficiency of the CO_2 capture system.

The secondary data includes the Ecoinvent 3.9 database for auxiliary processes.

2.4.1 Feedstock and material characterization. The main inputs considered in combustion and oxycombustion processes are textile waste, zeolite as a selective catalytic reduction (SCR) catalyst, and calcium oxide (CaO) as a CO_2 adsorbent. Their characterization was based on information reported in the literature,[23–27] which was utilized in process modeling and life cycle inventory analysis.

The textile waste corresponds to a representative mixture of 50% cotton and 50% polyester, typical post-consumer fractions.[33] The elemental composition and higher heating value (HHV) were obtained from proximate and elemental analyses reported in previous studies.[28]

The catalyst used in the process is zeolite, widely used in selective catalytic reduction (SCR) systems due to its high surface area, acidic sites, and thermal stability.[29] It is assumed that zeolites are replaced periodically during operation, and their production is accounted for in the life cycle inventory.

Calcium oxide (CaO) was considered as a solid adsorbent for *in situ* CO_2 capture through carbonation, according to the reaction:
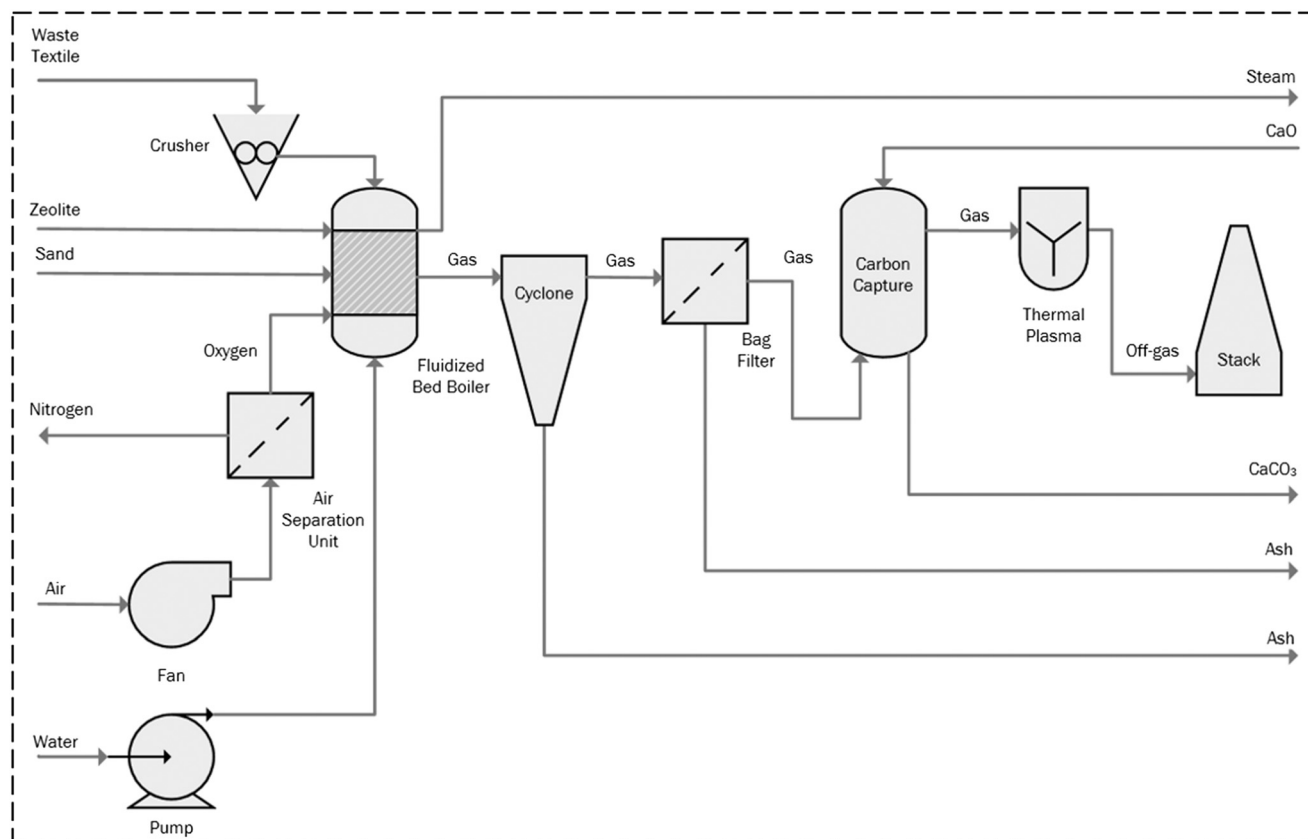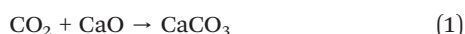
Fig. 2 System boundaries for oxycombustion of textile with post-combustion catalytic treatment, thermal plasma application, and carbon capture.

$$CO_2 + CaO \rightarrow CaCO_3 \qquad (1)$$

The material is assumed to have a purity of around 55% and is considered consumable, requiring periodic make-up addition.[32]

A summary of the main material properties is presented in Table 1.

The CaO consumption in the process (2.5 kg per kg of textile) and the corresponding CO_2 capture efficiency (~40%)

are based on a detailed mass balance obtained from the simulation and on the capture capacity reported in the literature for practical systems.

The theoretical CO_2 capture capacity of pure CaO is 0.786 g CO_2 per g CaO. However, under real operating conditions, this capacity is significantly reduced due to kinetic limitations, sintering, and the progressive loss of activity after successive carbonation-calcination cycles.[29,30,32] The

Table 1 Properties of materials

Material	Property	Unit	Value	Reference
Textile waste (50% cotton and 50% polyester)	Carbon	wt%	54.5	28
	Hydrogen	wt%	5.6	
	Oxygen	wt%	38.7	
	Nitrogen	wt%	0.4	
	Sulfur	wt%	0.3	
	Moisture	wt%	1.8	
	Ash	wt%	0.7	
	Volatile	wt%	89.2	
	HHV	MJ kg^{-1}	20.5	
Zeolite (VO$_x$/ZSM-5)	Specific surface area	m^2 g^{-1}	361	27, 28
	Pore size	Å	56.6	
	Si/Al ratio	mol mol^{-1}	25	
	Thermal stability	°C	800–1000	
CaO	Purity	%	~55	29, 30
	CO$_2$ capture capacity	g CO$_2$ per g CaO	0.3–0.7	
	Thermal stability	°C	850–900	
	Molar mass	g mol^{-1}	56.1	

literature reports practical capacities in the range of 0.3–0.7 g CO_2 per g CaO for lime-based sorbents.[31] In this study, the calculated effective capacity is ~0.31 g CO_2 per g CaO, a value at the lower end of the reported range and representative of the initial conditions of a fresh sorbent or one with already diminished activity.

This value justifies the amount of sorbent required to achieve a capture efficiency of 40% of the total CO_2 generated. It is consistent with the assumption that approximately 55% of the lime used is "useful" or reactive lime.[32] Optimizing sorbent utilization and strategies to mitigate its deactivation (e.g., through doping or the use of modified sorbents) represents a crucial area for the future development of this process.

The toxic equivalency quantity (TEQ) was applied to assess the combined toxicity of dioxins and furans. Each congener's concentration (C_i) was multiplied by its corresponding toxic equivalency factor (TEF_i). Because the total concentration of dioxins and furans is known, and not the speciation, a conservative value of TEF = 0.01 is considered for the calculation of TEQ. This value is reported by the literature,[35,36] as expressed by:

$$TEQ = \sum_i C_i \times TEF_i \qquad (2)$$

TEF_s were adopted from the World Health Organization,[37] the total mass of dioxins and furans in untreated flue gases (8.3×10^{-10} kg per kg textile).

2.5 Assumptions and limitations

(i) Textile waste was assumed to carry zero environmental burden, as its production impacts are allocated to the original product's life cycle,[24,25] thereby preventing double-counting and focusing the assessment on waste management efficiency.

(ii) A constant moisture content of 2% is assumed, without prior drying pretreatment.

(iii) Combustion is modeled with 10% excess air for conventional combustion and oxygen greater than 95% for oxycombustion.

(iv) The CO_2 emissions generated from the combustion of cotton (approximately 44% of the total) are biogenic and considered carbon neutral.[38]

(v) Adsorbent regeneration and catalyst poisoning are not considered, as this is a snapshot of the process.

(vi) Impacts associated with the construction or dismantling of the pilot plant are not considered.

(vii) The electricity consumption for cryogenic oxygen separation in the oxycombustion scenario was modeled based on data reported in the literature, considering a value of 0.2 kWh per kg O_2.[39]

(viii) The gate-to-gate approach was chosen to isolate the environmental performance of the combustion process itself, avoiding uncertainties from upstream (e.g., textile production) or downstream (e.g., steam distribution) stages.

2.6 Software and databases

Life cycle modeling was performed using SimaPro 8.5.2.0 and the Ecoinvent 3.6 database for auxiliary processes, with a focus on the rest of the world (RoW).[38] The impact assessment method was ReCiPe 2016 Midpoint (H).[40]

2.7 Experimental validation with thermal plasma

To complement the process simulation, experimental validation tests were performed using the thermal plasma system. The system consists of a non-transferred arc plasma torch operating with argon as the plasma gas. The operating parameters of the thermal plasma system, including gas flow, pressure, electrical current, and energy consumption, were incorporated into the life cycle inventory of the process.

The specific operating conditions for the destruction of recalcitrant compounds like dioxins and furans were defined to comply with stringent international standards. Following European Union guidelines for hazardous waste incineration, which recommend a minimum residence time of 2 seconds at temperatures above 1000 °C,[41] our system was configured to operate at temperatures exceeding 1000 °C with a corresponding residence time.

The experimental parameters to achieve these conditions were:
- Plasma arc current: 30 A
- Operating voltage: 220 V AC
- Argon flow rate: 140 L min^{-1} at 90 psi (620 kPa)
- Measured grid current: 16–18 A

Under this configuration, the specific energy consumption of the plasma torch for treating the flue gases derived from 1

Fig. 3 Pilot-scale plasma reactor.

kg of textile waste ranges between 2 and 4 kWh. This energy input is necessary to sustain the high-temperature environment required for the effective thermo-chemical decomposition of trace pollutants over the mandated residence time. For the life cycle inventory, a conservative and representative value of 2 kWh per kg of textile waste was used, values that are in line with those reported in the literature.[42–44] This consumption is a significant contributor to the system's energy balance and is realistically reflected in the impact assessment, particularly in categories such as fossil resource scarcity (FRS) and global warming potential (GWP). Fig. 3 shows the pilot-scale plasma reactor used in this study.

3. Results and discussion

The inventory for combustion of textile waste in a fluidized bed with post-combustion catalytic treatment, thermal plasma application, and carbon capture is shown in Table 2, with values normalized to the functional unit (FU): 1 kg of textile waste.

The inventory for oxycombustion of textile waste in a fluidized bed with post-combustion catalytic treatment, thermal plasma application with carbon capture is shown in Table 3.

Table 4 presents the results of the environmental impact assessment, considering the main impact categories recommended by the ReCiPe 2016 Midpoint (H) method, for 1 kg of processed textile. Where, case 1: combustion + carbon capture, case 2: combustion + carbon capture + thermal plasma, case 3: oxycombustion + carbon capture, case 4: oxycombustion + carbon capture + thermal plasma.

In terms of global warming potential (GWP), the combination of oxycombustion with carbon capture (case 3:

3082 kg CO_2 eq.) shows an increase of 29.8% compared to conventional combustion with carbon capture (case 1: 2376 kg CO_2 eq.). This increase is primarily due to the higher energy consumption required for oxygen separation to feed the reactor.[39] The addition of thermal plasma (cases 2 and 4) further increases the GWP, reaching 3589 kg CO_2 eq. and 4295 kg CO_2 eq., respectively, due to the additional electricity consumption required to generate the thermal plasma.[34–36]

In terms of air quality, the formation of tropospheric ozone for human health (OF-HH) and terrestrial ecosystems (OF-TE) increases in cases with oxycombustion (+25%), and is even greater when thermal plasma is incorporated, reaching values of 0.009–0.010 kg NO_x eq. The formation of fine particles (FP) also follows this trend, showing increases of 16–133% in cases with plasma, associated with electricity consumption and emissions derived from the process.[15,33]

In terrestrial acidification (TA), cases with thermal plasma exhibit a slight increase compared to processes without plasma, whereas oxycombustion alone increases acidification by 7.4%, primarily due to indirect emissions from fossil fuels used for electricity generation.[39,49] For terrestrial ecotoxicity (TET), oxycombustion (cases 3 and 4) has significantly higher values (6080–7319 kg 1,4-DCB eq.), possibly reflecting higher concentrations of trace metals in ash and residual emissions.

Regarding resource use, oxycombustion reduces mineral resource scarcity (MRS) and water consumption (WC) compared to conventional combustion, due to the lower amount of steam generated and the fact that less zeolite is used, as fewer gases are generated for treatment in oxycombustion.[50] However, the introduction of thermal plasma significantly increases fossil resource scarcity (FRS), reaching up to 0.687 kg oil eq. in case 4, which is associated with the high electricity consumption of thermal plasma.

Table 2 Life cycle inventory (LCI) data for combustion modeling, FU: 1 kg of textile waste

Subsystems	Category	Description	Value	Unit
i) Feeding and preparation	Textile waste	50% cotton and 50% polyester, dry	1	kg
	Electricity – crusher[45]	Crusher	0.05	kWh
ii) Combustion	Air feed	Air (combustion)	6.765	kg
	Zeolite (SCR catalyst)	Zeolite	0.390	kg
	Sand (fluidized bed)[41,46]	Sand	5	kg
	Ash (solid residues)	Ash removed	0.016	kg
	CO_2 after capture (biogenic)	CO_2 emitted to the atmosphere	0.52	kg
	CO_2 after capture (fossil)	CO_2 emitted to the atmosphere	0.66	kg
	SO_2	In off-gas	0.024	kg
	NO_x	NO_x (after SCR)	~0	kg
	O_2	In off-gas	0.22	kg
	N_2	In off-gas	5.18	kg
	H_2O	In off-gas	0.36	kg
	CO	In off-gas	~0	kg
	Dioxins and furans[47]	In off-gas	8.3×10^{-10}	kg
	Electricity – fan (reactor)	Fan	0.415	kW
iii) Gas treatment	CaO (input to capture)	CaO	2.5	kg
	$CaCO_3$ produced	Carbonate solid	1.785	kg
	CO_2 captured	Captured (as $CaCO_3$)	0.784	kg
	Electricity – thermal plasma	Induced by electric arc	2	kWh
iv) Steam generation	Water (feed to steam circuit)	Water for heat recovery/boiler	3.0	kg
	Steam produced	Superheated steam	3.0	kg
	Electricity – pump	Pumps	0.0025	kWh

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Table 3 Life cycle inventory (LCI) data for oxycombustion modeling, FU: 1 kg of textile waste

Subsystems	Category	Description	Value	Unit
i) Feeding and preparation	Textile waste	50/50 cotton/polyester, dry	1	kg
	Electricity – crusher[45]	Crusher	0.05	kWh
ii) Oxycombustion	O_2 feed	O_2 (oxycombustion)	1.476	kg
	Zeolite (SCR catalyst)	Zeolite	0.125	kg
	Sand (fluidized bed)[41,46]	Sand	5	kg
	Ash (solid residues)	Ash removed	0.016	kg
	CO_2 after capture (biogenic)	CO_2 emitted to the atmosphere	0.52	kg
	CO_2 after capture (fossil)	CO_2 emitted to the atmosphere	0.66	kg
	SO_2	In off-gas	0.024	kg
	NO_x	NO_x (after SCR)	~0	kg
	O_2	In off-gas	0.105	kg
	N_2	In off-gas	0.0075	kg
	N_2	Air separation unit	4.8	kg
	H_2O	In off-gas	0.36	kg
	CO	In off-gas	~0	kg
	Dioxins and furans[47]	In off-gas	8.3×10^{-10}	kg
	Electricity – fan (reactor)	Fan	0.415	kWh
	Electricity – O_2 separation	Electricity for O_2 separation	0.295	kWh
iii) Gas treatment	CaO (input to capture)	CaO	2.5	kg
	CO_2 captured	Captured (as $CaCO_3$)	0.784	kg
	$CaCO_3$ produced	Carbonate solid	1.785	kg
	Electricity – thermal plasma	Induced by an electric arc	2	kWh
iv) Steam generation	Water (feed to steam circuit)	Water for heat recovery/boiler	1.4	kg
	Steam produced	Superheated steam	1.4	kg
	Electricity – pump	Pumps	0.0025	kWh

Table 4 Impact categories for waste textile combustion and oxycombustion

Abbreviation	Impact category	Unit	Case 1	Case 2	Case 3	Case 4
GWP	Global warming	kg CO_2 eq.	2.376	3.589	3.082	4.295
OF-HH	Ozone formation, human health	kg NO_x eq.	0.004	0.009	0.005	0.010
FP	Fine particulate matter formation	kg $PM_{2.5}$ eq.	0.012	0.026	0.014	0.028
OF-TE	Ozone formation, terrestrial ecosystems	kg NO_x eq.	0.004	0.009	0.005	0.010
TA	Terrestrial acidification	kg SO_2 eq.	0.027	0.034	0.029	0.035
TET	Terrestrial ecotoxicity	kg 1,4-DCB	4.703	5.969	6.080	7.319
HnCT	Human non-carcinogenic toxicity	kg 1,4-DCB	2.141	2.887	1.780	2.530
HCT	Human carcinogenic toxicity	kg 1,4-DCB	0.245	0.304	0.121	0.179
MRS	Mineral resource scarcity	kg Cu eq.	0.022	0.022	0.009	0.009
FRS	Fossil resource scarcity	kg oil eq.	0.133	0.471	0.349	0.687
WC	Water consumption	m^3	0.034	0.036	0.024	0.027

Dioxins and furans are highly toxic and regulated compounds, and their aggregate contribution to the total environmental impact of the LCA under our conditions is relatively low. As shown in Table 5, when comparing the scenario with and without dioxins/furans in case 1 (combustion + capture), there is a marginal increase of 0.62% in TET (terrestrial ecotoxicity) and 1.4% in ME (marine ecotoxicity); HCT (human carcinogenic toxicity) remains unchanged. Despite their modest contribution to the LCA,

this does not diminish their importance: dioxins and furans have an extremely high toxicity profile and a high potential for bioaccumulation.[51]

Although aggregated ReCiPe results (Table 5) indicate a marginal contribution of dioxins and furans to midpoint impact categories, this framework does not fully capture their extreme toxicity. To better represent their environmental and health relevance, the toxic equivalency quantity (TEQ) was estimated following the WHO toxic equivalency factors.

Table 5 Environmental assessment of dioxins and furans

Abbreviation	Impact category	Unit	With dioxins and furans	Without dioxins and furans
TET	Terrestrial ecotoxicity	kg 1,4-DCB	4.840	4.810
ME	Marine ecotoxicity	kg 1,4-DCB	0.073	0.072
HCT	Human carcinogenic toxicity	kg 1,4-DCB	0.245	0.245

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The untreated combustion gases exhibited a total emission of 8.3×10^{-10} kg per kg textile (830 ng per kg textile), corresponding to approximately 8.3 ng TEQ per kg textile. After thermal plasma treatment, dioxins and furans were destroyed, with a TEQ $\approx$ of approximately 0.089 ng TEQ per kg textile (0.0107 ng TEQ per Nm^3), which is well below the limits set by the European Union for incineration processes (0.1 ng TEQ per Nm^3).[52] These results are in line with what has been reported by[53,54] regarding the destruction of dioxins and furans by high-temperature heat treatments, achieving reductions greater than 99.9%.

This finding confirms that, although their contribution to LCA impact categories is numerically minor, the complete elimination of highly toxic dioxins and furans through thermal plasma treatment constitutes a critical environmental and health advantage of the proposed process for textile waste valorization.

The incorporation of thermal plasma as a post-treatment for combustion gases has proven effective in degrading these compounds. High-temperature technologies can efficiently destroy dioxins and furans by operating at temperatures above 1000 °C for adequate residence times, allowing for very low emissions (<0.1 ng m^{-3}).[30,37] This represents a significant qualitative benefit in terms of the quality of the gases emitted, even if it is not fully reflected in the overall LCA categories, such as GWP.

Fig. 4 illustrates the contribution of each subsystem to the environmental impact across all categories, enabling the identification of critical points in the process of fluidized bed combustion with post-combustion catalytic treatment, thermal plasma application, and carbon capture.

For global warming potential (GWP), the gas treatment stage makes the largest contribution (116%), followed by combustion (35%) and feeding/preparation (9%). However, steam generation offsets approximately 60% of this impact,

demonstrating its role as an environmental compensation stage through the substitution of fossil-based thermal energy. This compensatory effect aligns with,[55] which emphasizes the importance of energy recovery in mitigating climate impacts. The high contribution of gas treatment to GWP is primarily explained by the production of quicklime, which requires large amounts of fossil fuels (such as diesel or fuel oil) in rotary kilns,[56,57] and by the additional electricity consumption needed to generate the thermal plasma.[34–36]

For tropospheric ozone formation—both for human health (OF-HH) and terrestrial ecosystems (OF-TE)—the greatest contribution arises from gas treatment (77–78%), followed by combustion (40%) and feeding/preparation (10%). The steam generation stage reduces the impact (−28%), acting as a buffer. This suggests that, although post-combustion cleaning systems are essential for reducing pollutants, they require significant energy and materials, thereby indirectly contributing to the formation of ozone precursors.

Fine particulate matter formation (FP) is dominated by gas treatment (60%) and combustion (46%). Although steam generation slightly offsets this effect (−8%), the total balance remains positive, reinforcing the idea that electricity-intensive abatement technologies contribute significantly to particulate-related impacts, primarily due to the fossil fuel used to produce electricity.

In terrestrial acidification (TA), combustion is the most significant contributor (87%), consistent with the emissions of SO_2 and NO_x during textile waste oxidation. Gas treatment adds 28%, while steam generation partially offsets this increase (−17%). This indicates that the combustion stage itself is responsible for most acidifying emissions, in agreement with previous reports.[58,59]

For terrestrial ecotoxicity (TET), gas treatment (98%) and combustion (81%) are the dominant contributors. However,
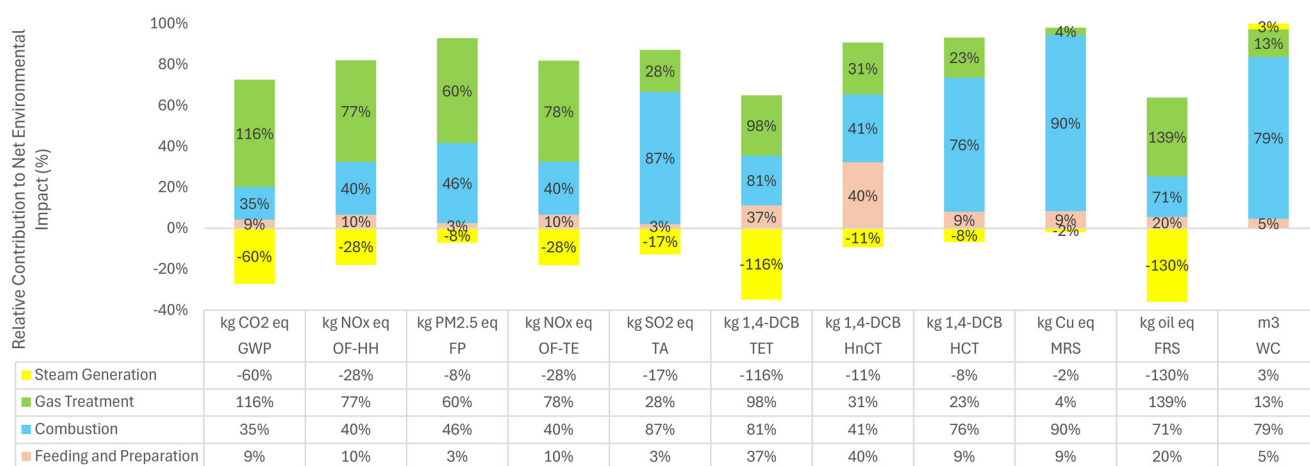

Fig. 4 Environmental impact assessment of the fluidized bed combustion process of textile waste with post-combustion catalytic treatment, thermal plasma application, and carbon capture. Note: in some impact categories, specific processes exceed 100% contribution, due to the presence of negative loads (environmental credits associated with steam production) that reduce the total net value of the category. In these cases, the relative contributions are calculated on a lower denominator and may exceed 100%. This behavior is characteristic of the LCA methodology and does not represent a calculation error.

	kg CO2 eq GWP	kg NOx eq OF-HH	kg PM2.5 eq FP	kg NOx eq OF-TE	kg SO2 eq TA	kg 1,4-DCB TET	kg 1,4-DCB HnCT	kg 1,4-DCB HCT	kg Cu eq MRS	kg oil eq FRS	m3 WC
Steam Generation	-60%	-28%	-8%	-28%	-17%	-116%	-11%	-8%	-2%	-130%	3%
Gas Treatment	116%	77%	60%	78%	28%	98%	31%	23%	4%	139%	13%
Combustion	35%	40%	46%	40%	87%	81%	41%	76%	90%	71%	79%
Feeding and Preparation	9%	10%	3%	10%	3%	37%	40%	9%	9%	20%	5%

steam generation offsets −116%, evidencing the importance of energy recovery in neutralizing part of the heavy metal and trace compound impacts. Despite this, the results suggest that ash composition and residual emissions remain critical drivers of ecotoxicity.

In the case of human toxicity, the non-carcinogenic (HnCT) category is divided among combustion (41%), feeding/preparation (40%), and gas treatment (31%), while steam generation provides only a modest offset (−11%). On the other hand, human carcinogenic toxicity (HCT) is primarily driven by combustion (76%), with gas treatment (23%) and feeding/preparation (9%) contributing less, due to the formation of dioxins and furans during the combustion process.[35,40]

With respect to resource use, mineral resource scarcity (MRS) is primarily driven by combustion (90%), which is associated with the demand for materials such as sand and zeolite for fluidized bed and catalytic systems. In fossil resource scarcity (FRS), gas treatment stands out (139%), followed by combustion (71%) and feeding/preparation (20%). Steam generation, however, offsets a 130% reduction, resulting in a net decrease in fossil fuel dependence. Carbon capture contributes to the scarcity of fossil resources, as mentioned, due to the high consumption of fossil fuels by rotary kilns in the production of quicklime.[56,57]

Finally, for water consumption (WC), combustion is the major contributor (79%), followed by gas treatment (13%) and feeding/preparation (5%), with steam generation adding only 3%. Water use is largely indirect, linked to the production of zeolite (size reduction, washing, crystallization, separation, drying)[60] and the sand production process (size reduction, classification, washing, drying).[61]

Fig. 5 illustrates the contribution of each subsystem to the environmental impact across all categories, enabling the identification of critical points in the fluidized bed oxycombustion process with post-combustion catalytic treatment, thermal plasma application, and carbon capture.

In terms of global warming potential (GWP), the total impact reaches 4.295 kg CO_2 eq., dominated by gas treatment (97%), followed by oxycombustion (19%) and feeding/preparation (8%). At the same time, steam generation provides a compensatory effect of −24%.[62] The strong contribution of gas treatment is consistent with its high energy demand and chemical inputs, which indirectly lead to increased GHG emissions. Additionally, quicklime production, a necessary step for CO_2 capture processes, remains one of the main hotspots due to its intensive use of fossil fuels (diesel or fuel oil) in rotary kilns[56,57] and the electricity consumption required to generate thermal plasma.[34–36]

For ozone formation (OF-HH and OF-TE) and fine particulate matter formation (FP), the trends are similar. In OF-HH (0.005 kg NO_x eq.) and OF-TE, gas treatment dominates (72%), followed by oxycombustion (31%) and feeding/preparation (≈9–10%), partially compensated by steam generation (−12%). Likewise, in FP (0.014 kg $PM_{2.5}$ eq.), gas treatment contributes 56% and oxycombustion 45%, with a modest compensation of −4% from steam. These results align with findings from,[1,9,63] which report that high-temperature thermochemical processes are primary sources of NO_x and PM precursors.

In terrestrial acidification (TA) (0.029 kg SO_2 eq.), oxycombustion is the leading contributor (79%), followed by gas treatment (26%), with steam generation accounting for a reduction of −8%. This reinforces the role of oxycombustion as a key driver of SO_2 and NO_x emissions.

For terrestrial ecotoxicity (TET) (6.053 kg 1,4-DCB eq.), the highest contribution is from gas treatment (80%), followed by feeding/preparation (31%) and oxycombustion (34%), while steam generation contributes a reduction of −45%. The
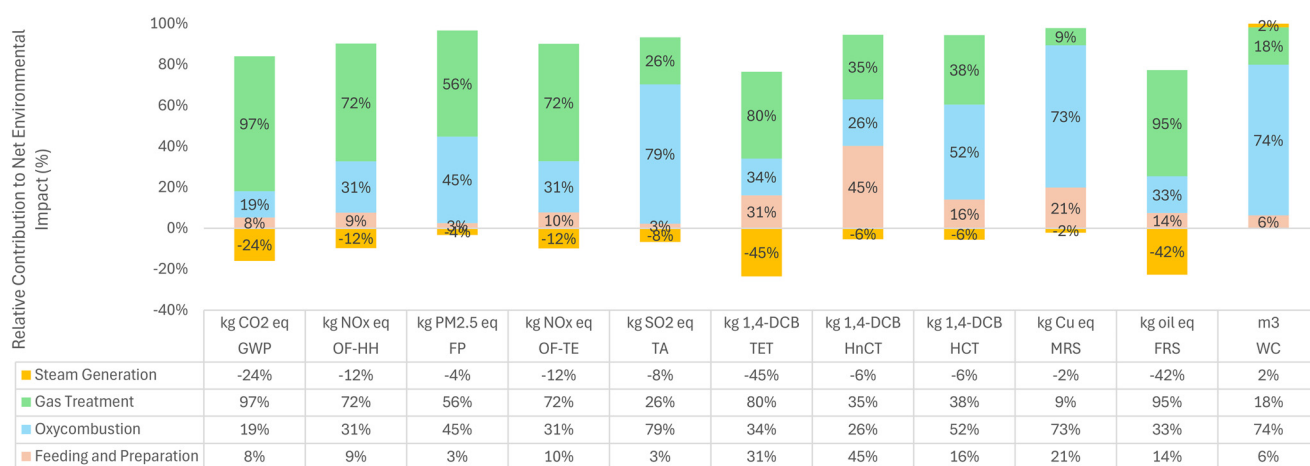

	kg CO2 eq GWP	kg NOx eq OF-HH	kg PM2.5 eq FP	kg NOx eq OF-TE	kg SO2 eq TA	kg 1,4-DCB TET	kg 1,4-DCB HnCT	kg 1,4-DCB HCT	kg Cu eq MRS	kg oil eq FRS	m3 WC
Steam Generation	-24%	-12%	-4%	-12%	-8%	-45%	-6%	-6%	-2%	-42%	2%
Gas Treatment	97%	72%	56%	72%	26%	80%	35%	38%	9%	95%	18%
Oxycombustion	19%	31%	45%	31%	79%	34%	26%	52%	73%	33%	74%
Feeding and Preparation	8%	9%	3%	10%	3%	31%	45%	16%	21%	14%	6%

Fig. 5 Environmental impact assessment of the fluidized bed oxycombustion process of textile waste with post-combustion catalytic treatment, thermal plasma application, and carbon capture. Note: in some impact categories, specific processes contribute more than 100%. This is due to the presence of negative loads (environmental credits associated with steam production) that reduce the total net value of the category. In these cases, the relative contributions are calculated on a lower denominator and may exceed 100%. This behavior is characteristic of the LCA methodology and does not represent a calculation error.

predominance of gas treatment highlights the importance of chemical reagents and residual compounds.

The human toxicity categories show a more balanced distribution. Non-carcinogenic toxicity (HnCT) is driven by feeding/preparation (45%), gas treatment (35%), and oxycombustion (26%), partially offset by steam (−6%). In carcinogenic toxicity (HCT), oxycombustion dominates (52%), followed by gas treatment (38%) and feeding/preparation (16%), again with a modest offset from steam (−6%). These trends suggest that emissions of trace elements and persistent organic compounds during oxycombustion and flue gas treatment play a central role, consistent with.[48]

In mineral resource scarcity (MRS), oxycombustion represents the highest burden (73%), followed by feeding/preparation (21%) and gas treatment (9%), with a small reduction from steam (−2%). This can be explained by the demand for sand and zeolite in the fluidized bed and catalytic systems, which are known to have non-negligible upstream burdens.

For fossil resource scarcity (FRS), the total impact is 0.349 kg oil eq, dominated by gas treatment (95%) and oxycombustion (33%), with feeding/preparation contributing 14%. However, this is partially offset by a 42% reduction from steam credits, reflecting the displacement of external fossil energy. The large contribution from CO_2 capture reagents, particularly lime, again emphasizes the fossil fuel intensity of their production.[56,57]

Finally, in water consumption (WC), the total is 0.024 m^3, dominated by oxycombustion (74%) and gas treatment (18%), with smaller contributions from feeding/preparation (6%), and a negligible contribution of +2% from steam generation. This has to do with the water and energy used directly or indirectly in the oxygen separation processes.[39,50,64] Oxycombustion indirectly contributes to the water used in the production of zeolite and sand.[60,61]

Fig. 6 compares the environmental impacts between the two scenarios evaluated, combustion and oxycombustion,

with post-combustion catalytic treatment, thermal plasma application, and carbon capture.

The results obtained show a differentiated distribution of environmental impacts between conventional combustion and oxycombustion of textile waste, which allows the strengths and weaknesses of each technology to be identified. In terms of global warming potential (GWP), oxycombustion accounts for 54% of emissions, compared to 46% for conventional combustion, primarily due to the high energy consumption required for oxygen separation in oxycombustion.[39]

The tropospheric ozone formation categories (OF-HH and OF-TE) and fine particulate matter (FP) show a slightly higher contribution from oxycombustion (52–52%) compared to combustion (48–48%), which could be associated with the burning of fossil fuels for the production of energy used in the separation of oxygen.[39]

In terrestrial ecotoxicity (TET), oxycombustion accounts for 55% compared to 45% for combustion, indicating a greater terrestrial ecotoxic impact, possibly associated with variations in the composition and concentration of heavy metals in the resulting ash. Conversely, for human non-carcinogenic toxicity (HnCT), combustion exhibits higher values (53%) than oxycombustion (47%), suggesting a more favorable profile of the latter in terms of potential human health risks from non-carcinogenic substances.

In terms of resource use, there are marked differences: for mineral resource scarcity (MRS), combustion accounts for 70% of the impact, more than double that of oxycombustion (30%), while for fossil resource scarcity (FRS), the trend is reversed, with oxycombustion accounting for 59% compared to 41% for combustion, indicating that the use of pure oxygen requires more fossil energy resources for its production. The MRS is lower in oxycombustion because the flue gas flow is lower, and less zeolite is used, which comes from mineral sources.[26]

Finally, water consumption (WC) is higher for combustion (58%) than for oxycombustion (42%), due to the greater steam production.

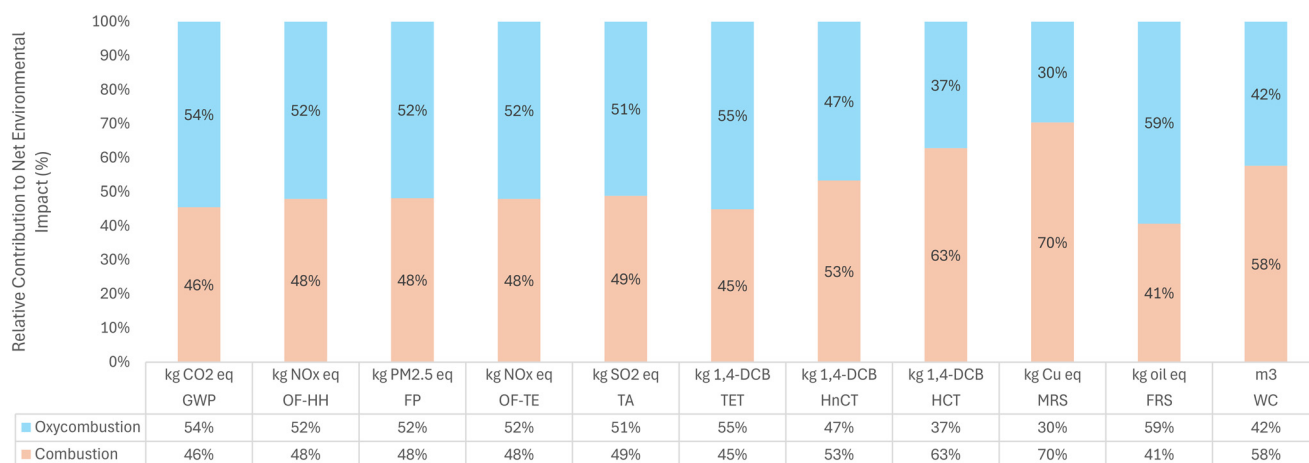|	kg CO2 eq GWP	kg NOx eq OF-HH	kg PM2.5 eq FP	kg NOx eq OF-TE	kg SO2 eq TA	kg 1,4-DCB TET	kg 1,4-DCB HnCT	kg 1,4-DCB HCT	kg Cu eq MRS	kg oil eq FRS	m3 WC
Oxycombustion	54%	52%	52%	52%	51%	55%	47%	37%	30%	59%	42%
Combustion	46%	48%	48%	48%	49%	45%	53%	63%	70%	41%	58%

Fig. 6 Environmental impact assessment of the fluidized bed combustion/oxycombustion process of textile waste with post-combustion catalytic treatment, thermal plasma application, and carbon capture.

Table 6 Comparison of the GWP of the proposed technology with conventional treatment methods

Technology	kg CO_2 eq. per kg textile	Reference
Textile deposited in a landfill (garbage)	8.3	65
Chemical recycling of textiles	6.4	65
Textile incineration (without energy recovery)	5.9	65, 66
Mechanical recycling of textiles	5.4	65
Textile recycling (bags or T-shirts)	−8	55
This study – combustion + catalytic gas treatment + thermal plasma + CO_2 capture	3.6	
This study – oxycombustion + catalytic gas treatment + thermal plasma + CO_2 capture	4.3	

To compare the results obtained in this study with those of other textile waste treatment practices, a comparison is made with conventional options reported in the literature, as shown in Table 6.

The results obtained in this study demonstrate a clear environmental advantage of combustion and oxycombustion with post-combustion catalytic treatment, thermal plasma application, and carbon capture over most conventional textile waste treatment technologies. The global warming potential (GWP) for combustion was 3.6 kg CO_2 eq. per kg textile, while oxycombustion reached 4.3 kg CO_2 eq. per kg textile. Compared to the average emissions from textile incineration without energy recovery (5.9 kg CO_2 eq. per kg textile), these values represent a 39.0% and 27.1% reduction, respectively. The reductions are even more pronounced when compared to landfilling (8.3 kg CO_2 eq. per kg textile), achieving 59.6% and 48.2% lower greenhouse gas emissions.

When contrasted with chemical recycling (6.4 kg CO_2 eq. per kg textile), both catalytic processes showed substantial benefits, with decreases of 43.8% for combustion and 32.8% for oxycombustion. Even mechanical recycling (5.4 kg CO_2

eq. per kg textile), which is often considered a low-impact pathway, exhibited higher GWP values than those obtained in this work, by 33.3% and 20.4%, respectively.

An interesting comparison arises with textile recycling into new products such as bags or t-shirts, which can achieve net harmful emissions (−8 kg CO_2 eq. per kg textile) due to significant avoided impacts from virgin material production. While the proposed processes do not achieve carbon negativity, they offer consistent GWP reductions across scenarios involving unavoidable textile waste that cannot be mechanically or chemically recycled.

The presented GWP results (3.6–4.3 kg CO_2-eq. per kg textile) represent a benchmark performance for the specific 50/50 cotton/polyester blend studied. As noted, it is crucial to differentiate between fossil CO_2 from polyester and biogenic CO_2 from cotton, and this is taken into account in our inventory. However, the actual composition of textile waste is highly variable.[67,68] A higher synthetic fiber content would increase the GWP due to higher fossil carbon emissions, while a stream dominated by natural fibers would result in a lower GWP.
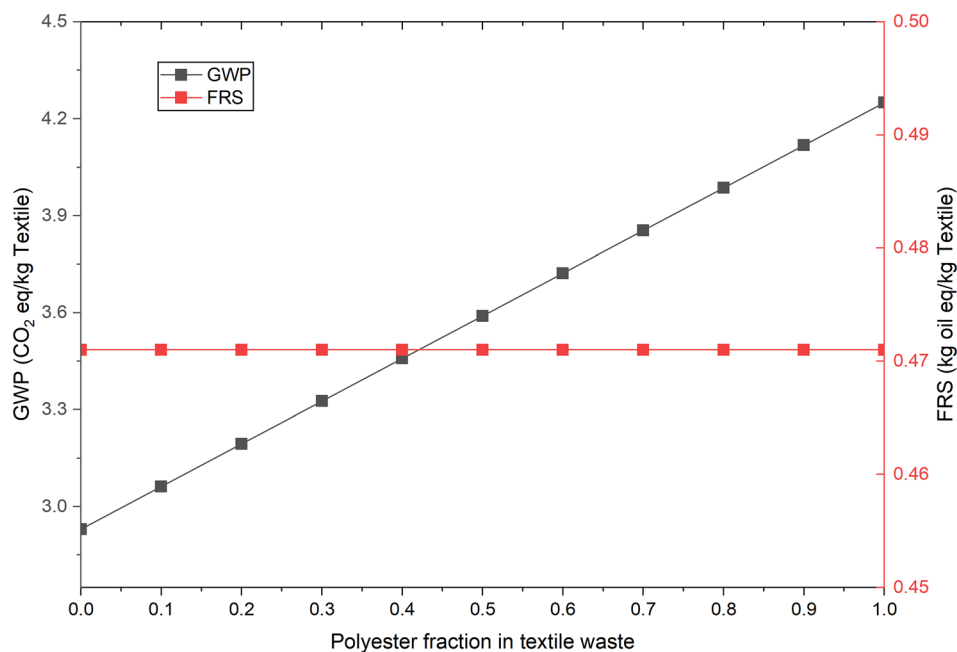

Fig. 7 Polyester fraction vs. GWP and FRS, for the combustion process of textile waste with post-combustion catalytic treatment, application of thermal plasma and carbon capture.

Therefore, these results should be interpreted as a benchmark for a representative blend. The main advantage of the proposed technology lies in the valorization of non-recyclable mixed textiles, offering a more sustainable alternative to landfilling or conventional incineration.

Fig. 7 illustrates a sensitivity analysis in which the polyester composition of the textile waste varies. The global warming potential (GWP) shows a linear response, increasing by 45% (from 2.93 to 4.25 kg CO_2 eq. per kg textile) as the polyester fraction increases from 0% to 100%. Fossil resource scarcity (FRS) remained practically constant (0.471 kg oil eq. per kg textile) as the polyester fraction varied. This is because the analysis considers post-consumer textile waste, and therefore, fiber production is not included within the system boundaries.

Additionally, a sensitivity analysis was performed to evaluate CaO consumption, the energy consumed by the thermal plasma, and steam production by varying these parameters while keeping the other process conditions constant for the combustion process of textile waste with post-combustion catalytic treatment, the application of thermal plasma, and carbon capture.

Fig. 8 demonstrates a strong correlation between CaO consumption and global warming potential (GWP) and fossil resource scarcity (FRS). A reduction in CaO consumption from the baseline case of 2.5 kg kg^{-1} to 1.5 kg kg^{-1} would decrease the GWP by approximately 33% (from 3.59 to 2.42 kg CO_2 eq kg^{-1} textile) and the FRS by 26% (from 0.471 to 0.348 kg oil eq. per kg textile). Conversely, an increase in consumption to 3.5 kg kg^{-1} would increase the GWP by 33% (up to 4.76 kg CO_2 eq. per kg textile) and the FRS by 26% (up to 0.595 kg oil eq. per kg textile).

Fig. 9 shows that the energy consumption of the thermal plasma has a direct relationship with the GWP and FRS, confirming its role as a critical environmental driver. Reducing consumption from 2.0 to 1.5 kWh kg^{-1} of textile decreases the GWP by 8% (from 3.59 to 3.29 kg CO_2 eq.) and the FRS by 18% (from 0.471 to 0.387 kg oil eq.). Conversely, an increase to 2.5 kWh kg^{-1} increases the GWP by 8% (to 3.89 kg CO_2 eq.) and the FRS by 18% (to 0.556 kg oil eq.).

Fig. 10 shows that steam generation has an inverse linear relationship with GWP and FRS, serving as the system's primary environmental benefit. Increasing steam production from 3.0 to 6.0 kg steam per kg textile reduces GWP by 29% (from 3.59 to 2.54 kg CO_2 eq.) and FRS by 63% (from 0.471 to 0.172 kg oil eq.). Conversely, without steam generation (0 kg kg^{-1}), GWP would increase by 29% (to 4.64 kg CO_2 eq.) and FRS by 63% (to 0.77 kg oil eq.). This confirms that efficient heat recovery and maximizing steam production are essential for the process's environmental viability.

4. Conclusions

Combustion and oxycombustion of textile waste, followed by post-combustion catalytic treatment, thermal plasma application, and CO_2 capture, significantly reduce environmental impacts compared to conventional treatments. GWP values were 3.6 kg CO_2 eq. per kg textile for combustion and 4.3 kg CO_2 eq. per kg textile for oxycombustion, representing reductions of 27–57% compared to landfilling, chemical recycling, and incineration without energy recovery.

CO_2 capture is the primary contributor to GWP and ecotoxicity due to energy and chemical inputs. At the same time, steam generation provides substantial environmental
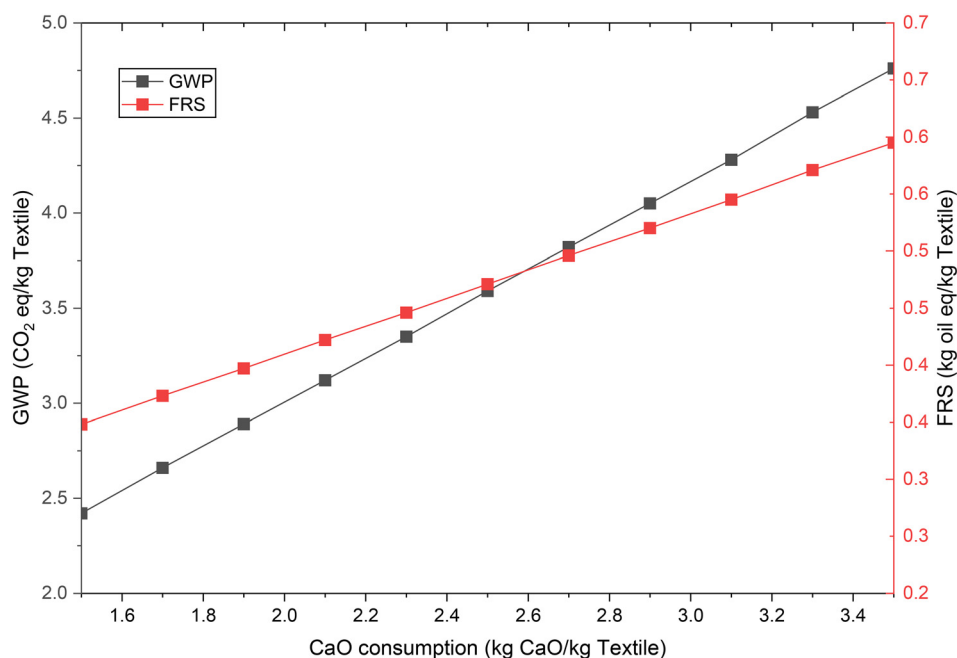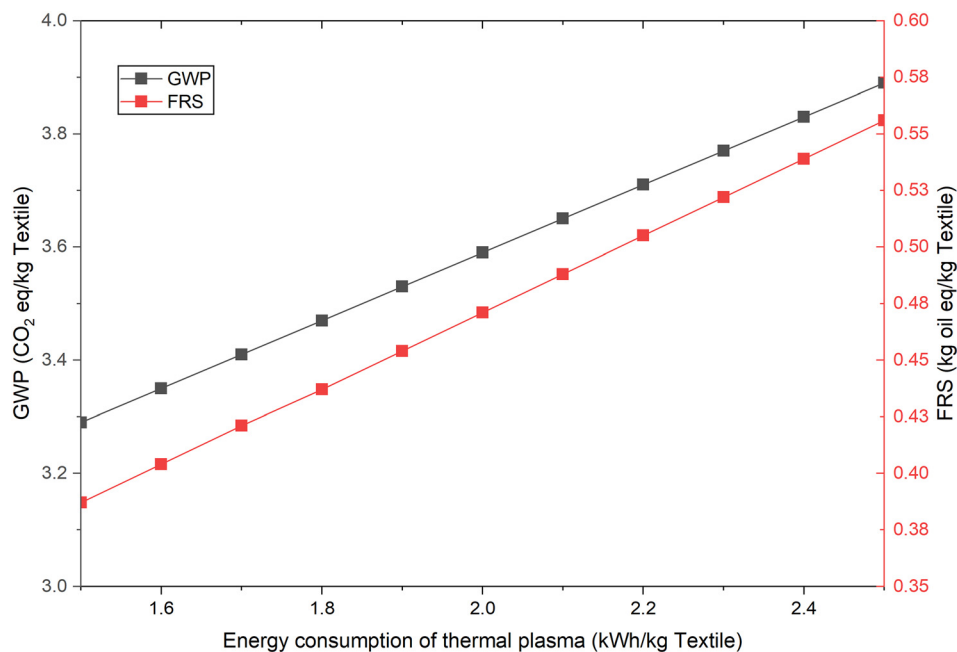

Fig. 8 CaO consumption *vs.* GWP and FRS, for the combustion process of textile waste with post-combustion catalytic treatment, application of thermal plasma, and carbon capture.
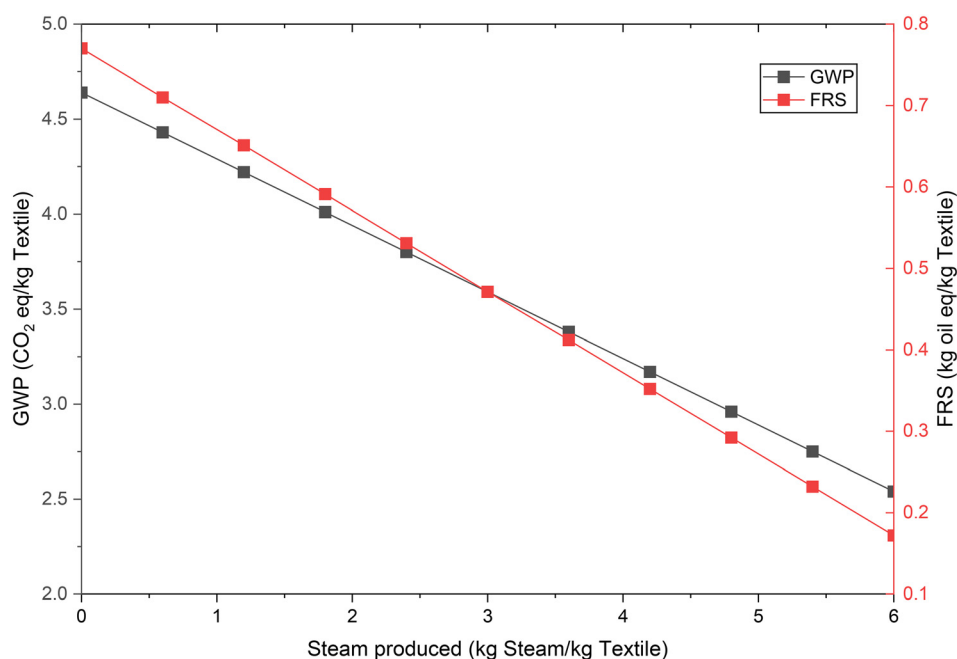
Fig. 9 Energy consumption of thermal plasma *vs.* GWP and FRS, for the combustion process of textile waste with post-combustion catalytic treatment, application of thermal plasma, and carbon capture.

Fig. 10 Steam produced *vs.* GWP and FRS, for the combustion process of textile waste with post-combustion catalytic treatment, application of thermal plasma, and carbon capture.

credits, reducing GWP by up to 60% in combustion and 24% in oxycombustion. In parallel, the application of thermal plasma enhances flue gas purification, enabling the effective destruction of trace pollutants such as dioxins and furans, and strengthening the environmental reliability of the proposed catalytic processes.

Oxycombustion slightly increases NO_x and particulate emissions but lowers aquatic eutrophication and ecotoxicity. Fossil resource use is higher in oxycombustion, whereas mineral use is reduced. Water consumption is lower in oxycombustion due to reduced steam production.

Both processes outperform conventional incineration, mechanical, and chemical recycling for non-recyclable textiles. While net-negative emissions are achievable through textile-to-product recycling, combustion technologies are

suitable for mixed or contaminated waste streams, enabling energy recovery and mitigating greenhouse gases.

The proposed system for recovering textile waste shows significant potential but still presents several challenges. Catalyst deactivation, CaO depletion, the use of energy-intensive electric arc plasma instead of microwave-induced plasma, and the complexity of oxygen separation could hinder long-term efficiency and scaling up. Addressing these challenges is essential for industrial viability.

Combustion and oxycombustion with post-combustion catalytic treatment, thermal plasma application, and CO_2 capture offer a promising and environmentally favorable alternative for managing textile waste, thereby supporting circular economy goals. Optimizing energy efficiency, eliminating dioxins and furans, and capturing CO_2 could further enhance environmental performance.

Sensitivity analysis revealed that the environmental performance of the proposed technology is robust, but three key parameters primarily dominate it. Steam production emerged as the most influential factor, acting as a significant environmental credit; maximizing heat recovery efficiency is therefore crucial for the process's viability. Second, CaO consumption showed a strong linear influence, underscoring the critical need to optimize sorbent efficiency or develop more sustainable materials to reduce the environmental burden associated with CO_2 capture. Finally, the energy consumption of thermal plasma confirmed that, while its impact is moderate, optimizing and integrating it with renewable electricity sources can yield significant additional improvements.

Conflicts of interest

There are no conflicts of interest to declare.

Data availability

The data supporting the findings of this study, including the experimental results and process simulations, are available in the manuscript. The simulation software was Aspen Plus® V14. Additional supplementary data, including process flow diagrams and mass balances, have been included as part of the article.

Acknowledgements

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