

Life Cycle Assessment of Coconut Residue Valorization via Pyrolysis

Alessandra da Rocha Duailibe Monteiro

`alessandra_duailibe@id.uff.br`

Federal Fluminense University (UFF), Niterói – Rio de Janeiro State, ZIP CODE

Mariana da Silva Teixeira

Federal Fluminense University (UFF), Niterói – Rio de Janeiro State, ZIP CODE

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Authors:	Alessandra da Rocha Duailibe Monteiro – <i>Department of Chemical and Petroleum Engineering, Federal Fluminense University (UFF), Rua Passo da Pátria, 152, São Domingos, Niterói - Rio de Janeiro State, Brazil. ZIP CODE 24210-240</i> ORCID ID: 0000-0002-3114-4133 Mariana da Silva Teixeira – <i>Department of Chemical and Petroleum Engineering, Federal Fluminense University (UFF), Rua Passo da Pátria, 152, São Domingos, Niterói – Rio de Janeiro State, Brazil. ZIP CODE 24210-240</i> ORCID ID: 0009-0005-8082-656X
Corresponding Author:	Alessandra da Rocha Duailibe Monteiro Phone Number: +55 21 992631295 E-mail Address: alessandra_duailibe@id.uff.br
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ABBREVIATIONS

ACPF, Activated Carbon Polymer Foam; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; CFC, Chlorofluorocarbon; CML, *Centrum voor Milieukunde Leiden* (Leiden Center for Environmental Science); DCB, Dichlorobenzene; EPE, *Empresa de Pesquisa Energética* (Energy Research Company); GHG, Greenhouse Gases; GWP, Global Warming Potential; ISO, International Standard Organization; SCS, Spent Coconut Shells; PAH, Polycyclic Aromatic Hydrocarbons; FU, Functional Unit.

ABSTRACT:

The environmental performance of coconut waste management via pyrolysis was evaluated using Life Cycle Assessment (LCA) and compared with conventional landfill disposal. The assessment followed ISO 14040/14044 standards, adopting a cradle-to-cradle approach with a functional unit of 100 g of coconut husk. Experimental data were obtained from batch pyrolysis under inert atmosphere at 400–600 °C, and modeling was conducted using *OpenLCA* supported by the *Ecoinvent 3.6* database and laboratory data. Results demonstrated that pyrolysis provides superior environmental performance, primarily due to avoided impacts from substituting activated carbon, diesel, and natural gas. For every 100 g of residue treated, 0.081 kg CO₂ equivalent emissions were avoided and 2.02 MJ of non-renewable energy were saved. The agricultural stage was identified as the main contributor to environmental impacts, largely driven by fertilizer and pesticide use. Landfill scenarios, even when considering biogas energy recovery, consistently showed higher environmental burdens. Sensitivity analysis indicated that natural drying improves overall system performance. These findings indicate that pyrolysis is a more sustainable alternative for coconut waste management, reducing greenhouse gas emissions and fossil resource use while supporting circular economy strategies.

INTRODUCTION

Throughout the 21st century, the predominance of fuels derived from fossil sources such as oil, coal, and natural gas, responsible for more than 80% of energy production, has generated growing concern and intensified discussions about the sustainability of industrial processes, driving a significant wave of scientific research in the field [1]. The environmental impacts associated with this industry are numerous, including the emission of greenhouse gases (GHGs)

that influence the health of the population and the environment. In parallel, population growth has stimulated not only industrial modernization but also a greater demand for food, resulting in the generation of large volumes of agro-industrial waste. In this context, the reuse of biomass as a raw material for energy conversion processes emerges as a promising alternative, arousing increasing academic and technological interest [2].

Biomass, composed mainly of carbon, hydrogen, and oxygen, is an organic material originating primarily from agricultural and forestry activities and animal residues and, as a renewable energy source, represents a promising alternative for reducing environmental impacts compared to traditional energy sources [3]. In view of this scenario, coconuts emerge as an alternative for energy generation, since approximately 75% of the fruit is discarded after its water consumption [4]. The issue related to the destination of coconut waste is inserted in the context of the current solid waste management. Sanitary landfills, in turn, continue to be the main form of final disposal of solid and organic waste, corresponding to about 60% of total destination in Brazil, for example [5]. In addition, less than 3% of the waste generated in the country is properly recycled, including organic waste, which ends up being sent to landfills together with solid waste, without any possibility of reuse [6].

The coconut palm (*Cocos nucifera*) is a tropical species of high cultural and economic importance, originating in South Asia and widely cultivated for its versatile fruit, which can be harvested in green or fully mature [7]. Coconut cultivation requires appropriate soil conditions, efficient irrigation, and adequate nutritional and pest management practices [8]. While coconut processing generates valuable products such as coconut water, oil, and milk, it also produces large amounts of husk waste. In Brazil, where annual production exceeds 2.34 million tons, up to 80%

of the fruit's weight may become residue [9]. Despite national policies that prohibit disposal in open dumps and promote reverse logistics and circular economy practices and promote reverse logistics and circular economy practices [10], improper disposal remains common, causing environmental, public health, and economic impacts [11]. Given the slow biodegradation of coconut husks and their contribution to methane emissions when landfilled [12], the reuse of these residues for composting, energy generation, and new materials represents a sustainable environmental and socioeconomic opportunity [10].

Thermochemical processes are promising routes for converting waste into value-added materials and chemicals, with pyrolysis, gasification, combustion, and torrefaction being the main solid waste valorization techniques [13]. Pyrolysis is a thermochemical decomposition process carried out in the absence of oxygen under an inert atmosphere, preventing combustion and enabling the breakdown of complex polymers into useful products [14,15]. Operating at temperatures between 350 and 1000 °C, pyrolysis produces three main fractions: bio-oil, biochar, and non-condensable gases, and can be applied to diverse feedstocks such as biomass residues, municipal solid waste, and plastics [14,16].

Coconut husk is particularly suitable for pyrolysis due to its high lignin content, calorific value of, approximately, 20 MJ/kg, year-round availability, low cost, and low ash content [17]. Although its energy content is lower than that of fossil fuels, coconut husk can be converted into value-added fuels and blended products, contributing to reduced fossil fuel consumption. Despite its favorable properties, limited studies address the yields and environmental feasibility of coconut husk pyrolysis, highlighting the need for further investigation compared to conventional residue disposal practices [18].

One of the approaches to evaluate the environmental viability of emerging technologies is the Life Cycle Assessment (LCA) an internationally standardized methodology (ISO 14044) used to quantify environmental impacts associated with products and processes throughout their entire life cycle, including material and energy flows, emissions, and waste generation [19,20]. LCA evaluates multiple impact categories, such as global warming potential, acidification, eutrophication, resource depletion, and toxicity, supporting environmental improvement and decision-making. In the context of coconut husk pyrolysis, LCA enables the comparison between residue valorization and conventional disposal, assessing impacts from biomass production to final disposal [18].

Few studies in literature specifically address the life cycle analysis itself of coconut residue pyrolysis. Arena, Lee, and Clift (2016) [21] present the life cycle assessment of activated carbon produced from coconut shells in Indonesia. Ran et al. (2024) [22], in turn, present LCA applied to the joint production of green biodiesel and activated carbon from spent coconut shells (SCS), with special focus on China. Finally, Saleem et al. (2025) [23] present the study from Qatar of the production of activated carbon polymer flakes (ACPF) from coconut shell pyrolysis, which is subsequently dispersed in a solution of polyethylene dissolved with xylene. The studies adopted the cradle-to-gate approach and used the CML impact methodology.

Therefore, the aim of this study is to evaluate the environmental feasibility of reusing coconut waste via pyrolysis by quantifying the impacts associated with the proposed technology. Additionally, the study assesses the environmental implications of disposing of coconut waste in a sanitary landfill, and, finally, compares both scenarios from an environmental perspective, discussing the advantages and limitations of each alternative.

METHODOLOGY

The environmental impacts of the pyrolysis process were evaluated through laboratory-scale experiments using green coconut residues. After crushing and natural drying, 100 g samples were pyrolyzed in a batch quartz reactor under an inert nitrogen atmosphere. The system included a furnace, condenser, separator, and gas scrubbers for product collection and gas treatment. Experiments were conducted at 400, 500, and 600 °C, with temperature stabilization followed by one hour of residence time. The heating rate used in the experiments was 10 °C/min. Solid, liquid, and gaseous products were collected and weighed after controlled cooling, while gas characterization was limited and not the focus of the study. Figure 1 presents a flowchart of the experimental procedure.

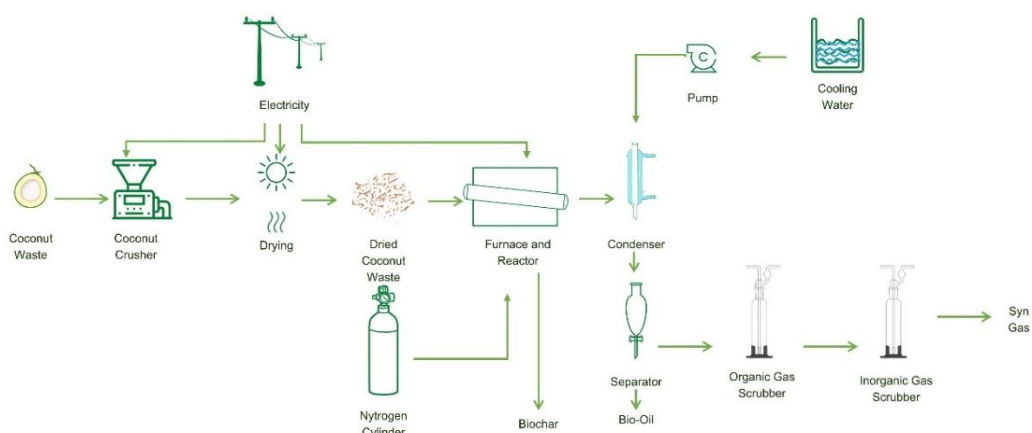


Fig 1 Flowchart of the Pyrolysis of Coconut Waste in laboratory scale.

Then, the Life Cycle Assessment (LCA) was performed, following ISO 14040 and 14044. The first stage of the life cycle assessment involves the definitions of the study goal and scope [24]. The main reference for the modeling framework adopted was the work by Arena, Lee and Clift (2016) [21], which served as the basis for presenting an experimental modeling comparable to that proposed herein, with activated carbon as the product focus. However, differently from the article that focused solely on the life cycle assessment of pyrolysis for biochar production, the

present work presented three distinct analysis: LCA of the thermal reuse of coconut residues; LCA of the method currently used in Brazil for waste destination, which consists of direct sending to sanitary landfills with the reuse of part of the generated biogas for biomethane generation; and the comparative LCA between the two destination routes for coconut residues.

For comparison purposes, the functional unit (FU) was defined as the treatment of 100 g of coconut shell residue. Considering that the average shell mass of one coconut is approximately 900 g, the reference flow required to produce 100 g of coconut shell corresponds to 0.11 units of green coconut [25]. The definition of the system boundaries is a critical step at this initial stage of the LCA [24]. Accordingly, two distinct scenarios were developed to construct the life cycles and to evaluate their respective boundaries, assumptions, and methodological considerations.

To enable a comprehensive assessment, a “cradle-to-cradle” approach was adopted for the first scenario. This approach encompasses coconut cultivation, transportation, consumption, waste disposal, and the subsequent pyrolysis process to produce new raw materials. The process of coconut residue pyrolysis illustrated in Figure 2 by the system boundaries of the thermal reuse route, comprises Processes 1 to 6.

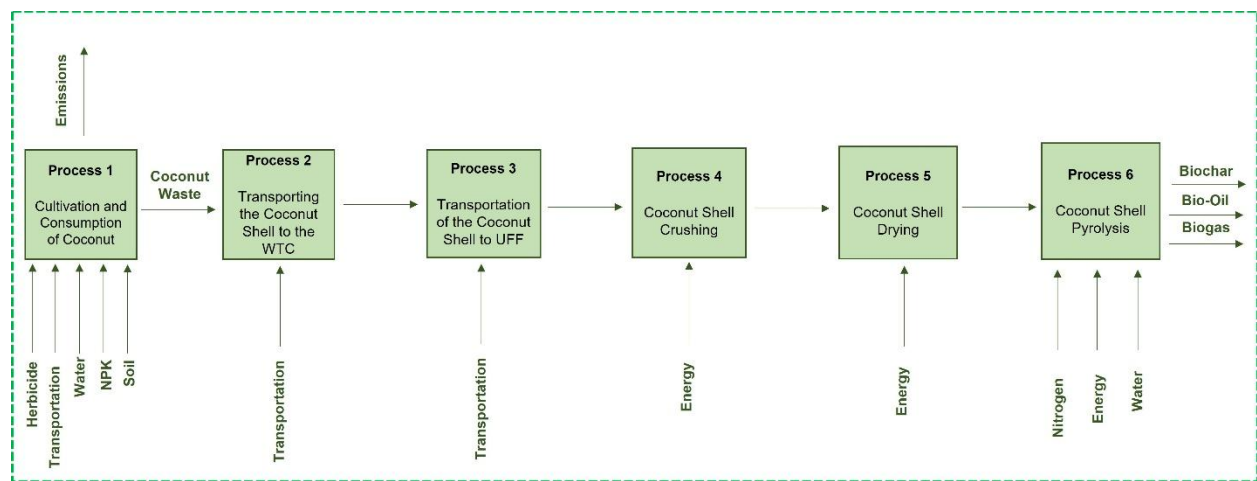


Fig 2 Boundaries of the system of pyrolysis including inputs and outputs of each of the six processes

For the life cycle evaluation and model construction, some premises and hypotheses were considered, as follows: road transport, with the shortest mileage routes, according to estimates provided by Google Maps; electricity consumption in the crushing process is estimated as the maximum nominal power of the equipment within the operating time. Electricity consumptions related to the submersible pump and the fume hood were disregarded because they are not very significant for the total calculation. For the drying stage, a mass loss of 40% related to material moisture was adopted, according to data obtained at laboratory. Drying was carried out in open air using sunlight. To estimate the energy consumption of the furnace used in the reaction, the enthalpy of coconut residue pyrolysis, calculated by Miranda (2013) [26], with a value of 273.5 J/g, was employed.

The estimate of water consumption was calculated exclusively based on the capacity of the tank used in the condensation stage, which operated in the recycle regime. The equivalent to 2% m/m of the total tank capacity was considered, corresponding to losses generated during the heating process and to the make-up volume necessary to maintain the tank level.

The destination of coconut residues in sanitary landfill, the “cradle-to-cradle” approach was also modeled for the comparative analysis beginning from planting, transport operations, waste to landfill and its treatment stages and the production of a new product, in this case the biogas captured and converted into biomethane. The diagram is presented in Figure 3, in which the dashed line represents the system boundaries and the processes 1, 2 and 7.

Rocha (2025) [27] was used as a basis for the estimates of input and output flows for the life cycle modeling. Moreover, some premises were considered, as the non-consideration of landfill construction, for consistency with the pyrolysis scenario, in which the impacts of equipment manufacturing (furnace and crusher) were also not considered. Road transport was

chosen as the transport mode, considering for the traveled distance the routes of shortest mileage to the Seropédica (RJ) landfill, according to estimates provided by Google Maps.

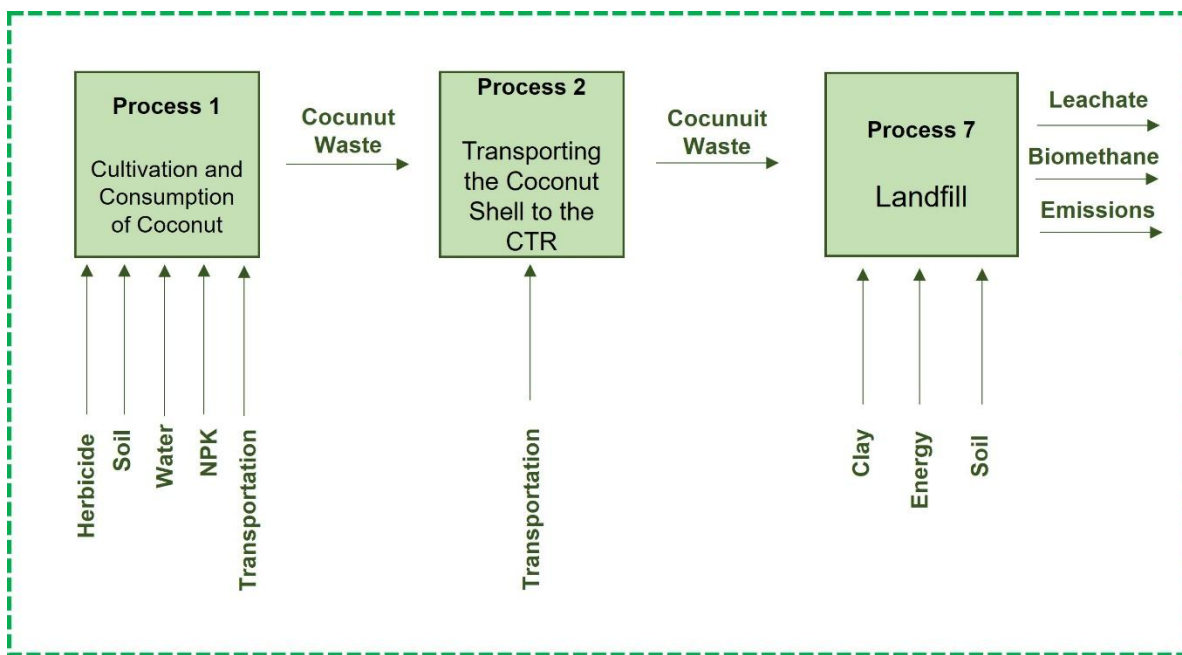


Fig 3 Boundaries of the system of landfill destination including inputs and outputs of each of the processes

From the biogas generated by residue decomposition, 50% were treated as direct emission (discarded) and the other 50% were directed to biomethane production, of which 33% was effectively converted into biomethane, while the remainder was also treated as direct emission. The biogas composition considered was: 64% methane, 18.3% carbon dioxide, 15% nitrogen, 1.7% oxygen and 1% hydrogen in volume, as well as estimates of electricity, clay and diesel consumption associated with the compaction machinery [27].

A combination of primary experimental data from the pyrolysis carried out at laboratory, and secondary data, extracted from the *Ecoinvent* database (version 3.6) was used to construe the Life Cycle Inventory (LCI). The entire LCA modeling was supported using the *OpenLCA* software

(version 2.5) from *GreenDelta*. All inputs and outputs of the processes of cultivation and landfill destination are available on the supplementary material.

The inventory referring to impacts from coconut cultivation up to its consumption was built from secondary data available in the database. The reference process adopted was “*coconut production, dehusked | coconut, dehusked | Cutoff, U*”, and all input and output data in the software for the reference process were adapted to the FU. A process called “*coconut husk – consumed*” (Process 1) was created, in which the output product corresponds to 0.1 kg of husk and all inputs and outputs of the base process were adjusted according to this factor.

The transport of the coconut from the post-cultivation stage to the consumption point was also considered and incorporated. Literature information indicates Quissamã as the municipality with the highest coconut production in the state of Rio de Janeiro and, as data do not refer to a single producer but to several producing communities, the central location provided by Google Maps was used as an average reference for the producing properties in the city [28]. In addition, Recreio Beach was considered as the point for coconut commercialization on the coast of Rio de Janeiro, since it is a region with high demand for coconut water and, because it is the beach farthest from the cultivation location, it represents the most conservative scenario in terms of transport and logistics.

The process of transportation were also created for the intermediate collection station, which, in Rio de Janeiro, is in Seropédica at the Santa Rosa Waste Treatment Center (WTC), representing the destination of the waste (Process 2) and for a hypothetical pyrolysis plant located at the UFF Praia Vermelha campus, in Niterói, where the experimental studies were conducted at laboratory scale from the WTC (Processw 3). For the transport flows, the supply process “*transport, freight, lorry 16-32 metric ton, EURO4 | transport, freight, lorry 16-32 metric ton, EURO4 |*

Cutoff, U - RoW” was chosen from the database, which represents a medium to large truck, with capacity between 16 and 32 tons, considering fuel consumption and direct and indirect emissions, according to the global average

For the crushing energy stream (Process 4), the coconut crusher model TRC 40, as shown in Figure 4. The power of 3.7 Watts during 5 seconds of operation was considered, generating a required energy of 18.4 kJ (0.0184 MJ). For this stream, the input flow “*electricity, medium voltage*” from the energy matrix of the Brazilian southeast region was used.



Fig 4 Coconut Crushing (a), Coconut Waste Sample after crushing (b) and (c)

For the drying stream, it is observed that, of the 100 g of coconut husk from Process 4, only 60 g leave the drying stage and are directed to the furnace (Process 6), due to moisture loss. Thus, by mass balance, 40 g are lost and, in the LCA modeling, were considered as a water emission to air.

Process 6 was considered as the final block of pyrolysis modeling. For this process, three product flows were created: biochar, pyrolysis biogas and bio-oil, with masses defined from the yields obtained experimentally. In addition, three output flows classified as avoided impacts were included, corresponding to the substitution of commercial products: commercial activated carbon, natural gas (low pressure) and diesel, associated, respectively, with the same masses of the biochar, pyrolysis biogas and bio-oil products. These impacts were considered as “avoided impacts”, since it is assumed that the materials can be fully reused in the market, substituting a commercial material. In this context, the entire production route of virgin material can be eliminated, and this impact is accounted for as a negative sign, indicating that it is being avoided. This methodology, called System Expansion, is recommended by ISO to avoid the need for allocation. It is important to highlight that, for analysis purposes, the assumption of 100% yield in the valorization processes of pyrolysis products was adopted, so that the mass of the generated product was fully considered as equivalent to the mass of the avoided commercial product.

Also, for Process 6, water and nitrogen consumption were evaluated. In the case of water, it was considered that, of the 18 liters of tank capacity, only 2% of water (tap water) would be used as make-up water, totaling 0.36 kg of water, and the rest would be recycled. For nitrogen, considering a flow rate of 40 mL per minute and an operating time of 6 hours per experiment, a consumption of 14.4 liters per process is estimated. For the furnace consumption (Process 6), as informed in the premises, the reaction enthalpy for coconut husk pyrolysis was determined according to the study by Miranda (2013) [26], resulting in 273.5 J/g; therefore, 60 g of coconut husk as furnace input, required 0.0164 MJ of energy.

For the sanitary landfill modeling, the inputs and outputs proposed by Rocha (2025)²⁵ were considered, who modeled the Seropédica sanitary landfill in the *SimaPro* software using the

Ecoinvent 3.6 database. Electricity, clay and diesel consumption were calculated for the municipal solid waste (MSW) generated in one year and adapted to the mass of the functional unit, 100 g of coconut husk (residue). To model the generated biomethane, an auxiliary process called “Biomethane (landfill)” was created, which accounts for the composition of biomethane produced in the landfill [27].

Thus, among several impact methods, CML, one of the most used methodologies in the Life Cycle Impact Assessment phase, was chosen for the present study. It should be noted that, for each category, the inventory result presents a series of elementary flows that are emitted to soil, water and air due to the impact of these categories. For the present study, the CML v4.8 2016 method was used, and the comparative LCA were also performed to better evaluate the main differences between these two scenarios.

RESULTS AND DISCUSSION

The results obtained for the performed pyrolysis experiments are presented in Table 1. It should be noted that the coconut fibers subjected to drying and pyrolysis presented, after the crushing process, an average length of approximately 5 cm.

Table 1 Experimental results of the performed pyrolysis experiments including mass yields.

Experiment	1	2	3
Temperature (°C)	600	500	400
Initial Mass (g)	65,00	75,05	41,32
Mass Yields			
Biochar (%)	29,67	31,97	35,56
Biogas (%)	36,25	29,80	18,59
Bio-Oil (%)	34,08	38,22	46,85

A clear trend of increasing biochar yield is observed as the pyrolysis temperature is reduced (from 29.67% at 600 °C to 35.56% at 400 °C). Complementarily, the biogas yield decreases significantly as the temperature is reduced, an expected effect due to the lower formation of volatile compounds under less severe thermal conditions. Bio-oil, in turn, presents its highest yield at the lowest temperature tested (46.85% at 400 °C), which is consistent with the typical regime of slow pyrolysis, in which the evolution of condensable vapors is favored at intermediate temperatures and longer residence times [17].

For comparison purposes with the data reported by Arena, Lee and Clift (2016) [21], who indicate 500 °C as an adequate temperature for obtaining biochar with improved properties, reference yields of 32% for biochar, 30% for biogas, and 38% for bio-oil were adopted for the LCA modeling.

The results of the Life Cycle Impact Assessment (LCIA) for the 11 impact categories evaluated using the CML impact method are presented in Table 2.

Table 2 LCIA results for each impact category.

Impact Category	Result	Unit
Ecotoxicity in freshwater	3.61764	kg 1,4-DCB-eq
Human toxicity	1.9141	kg 1,4-DCB-eq
Terrestrial ecotoxicity	1.5541	kg 1,4-DCB-eq
Eutrophication	0.00079	kg PO ₄ -eq
Material resources (metals/minerals)	2.5680 E-7	kg Sb-eq
Depletion of the ozone layer	-8.4990 E-9	kg CFC-11-eq
Formation of photochemical oxidants	-3.6862E-5	kg Etileno eq
Acidification	-0.00014	kg SO ₂ -eq
Climate Change	-0.08137	kg CO ₂ -eq
Non-renewable energy resources	-2.0239	MJ
Marine ecotoxicity	-105.42	kg 1,4-DCB-eq

It can be observed that, among the 11 categories evaluated by the CML method, Scenario 1 (Pyrolysis) presented positive contributions (impacts) in only five categories, while in the remaining six categories the results were negative and, therefore, accounted as environmental credits. It should be noted that the categories material resources (metals/minerals), ozone depletion, and photochemical oxidant formation were not further analyzed in this study, as their results were lower than 0.0001 and considered numerically insignificant for the present work. Negative results represent avoided impacts, i.e., environmental benefits or credits generated by the process.

The impact categories with the highest contributions were freshwater ecotoxicity, human toxicity, terrestrial ecotoxicity and eutrophication. Process 1 is the main source of environmental impact across categories. In freshwater ecotoxicity, it contributes more than 95% of the total impact, mainly due to the application of cypermethrin in coconut cultivation, which can migrate from soil to groundwater and aquatic environments. This same substance is also responsible for nearly 100% of the terrestrial ecotoxicity impact.

In the human toxicity category, the largest contribution (around 94%) is associated with the production and treatment of wooden support structures used in plantations, particularly due to the use of creosote in wood preservation. Creosote is a highly toxic mixture of polycyclic aromatic hydrocarbons (PAHs), such as pyrene, acenaphthene, and fluorene, which drive the results in this category. This process also contributes significantly to freshwater ecotoxicity. Eutrophication impacts are mainly linked to fertilizer use in Process 1, with emissions of ammonia and nitrates leading to nutrient enrichment in ecosystems and promoting algal growth. Additional contributions come from nitrogen oxides, phosphorus, and increased chemical oxygen demand (COD) related to the treatment of wood residues disposed of in landfills.

Although there are environmental credits associated with substituting conventional production of activated carbon, diesel, and natural gas, these are not sufficient to fully offset the impacts. Overall, the results show that the highest environmental burdens are concentrated in the agricultural stage prior to pyrolysis, especially due to the use of fertilizers and pesticides, wood treatment processes, and diesel-based transportation, rather than the pyrolysis process itself.

The impact categories that resulted in negative values in the inventory analysis, i.e., avoided impacts, were marine ecotoxicity, non-renewable energy resources, climate change and acidification. The largest negative contributions arise from avoided impacts associated with the production of commercial activated carbon. All avoided impacts are primarily associated with the replacement of conventional commercial activated carbon by biochar-derived material. In the non-renewable energy resources category, the negative contributions are mainly linked to avoided coal extraction, as the production of commercial activated carbon is displaced. In addition, reductions in fossil diesel consumption contribute to avoided crude oil extraction, further enhancing the environmental benefits.

In the climate change category, emissions generated during coconut cultivation, particularly those related to fossil fuel-based transportation and the production of wooden support systems, are offset by the benefits of substituting conventional activated carbon with biochar. As a result, emissions of fossil-based CO₂, methane, and nitrogen oxides that would normally occur throughout combustion and supply chain processes are avoided in the modeled system. For the acidification category, positive impacts are mainly driven by ammonia (NH₃) and nitrogen oxide (NO_x) emissions from fertilizer use and diesel combustion in agricultural activities and transportation. However, these impacts are more than compensated by environmental credits associated with the substitution of conventional processes such as activated carbon production,

diesel use, and natural gas consumption. The avoidance of SO_x, NH₃, and NO_x emissions from these conventional routes leads to a net negative impact, indicating an overall environmental benefit in this category.

The results of the comparative LCA between Scenarios 1 and 2 are presented in the normalized bar chart shown in Figure 5.

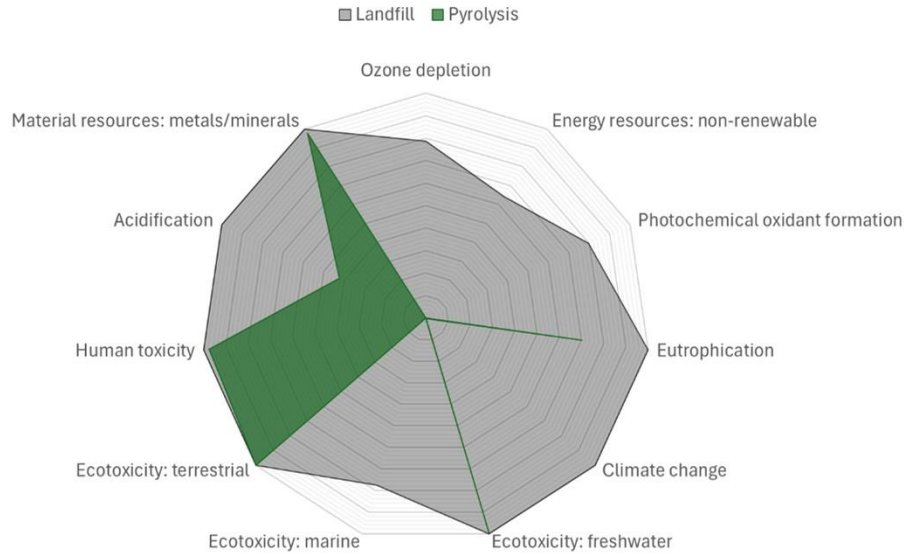


Fig 5 Radar Chart with comparative LCA results of pyrolysis and landfill by impact category relative to the scenario with the highest contribution

For each impact category, the scenario with the highest impact was set as 100%, and the other scenario was expressed proportionally. The green area corresponds to Pyrolysis, referred to here as Scenario 1, whereas the black area corresponds to landfill disposal, referred to as Scenario 2. Based on the results, the comparative analysis demonstrates that pyrolysis is significantly more environmentally advantageous than landfill, since the environmental credits obtained lead to the neutralization of several impacts. Notably, the categories of non-renewable energy resources and climate change stand out, in which the energy recovered through pyrolysis products fully replaces

the need for fossil fuels or other non-renewable resources required for operation. In addition, the credits obtained from substituting high-carbon products, such as commercial activated carbon, completely offset the greenhouse gas (GHG) emissions of the entire pyrolysis chain (cultivation and transport) for the mass defined as the functional unit, resulting in a more environmentally favorable scenario. The comparison between the two scenarios for these categories is shown in Figure 6.

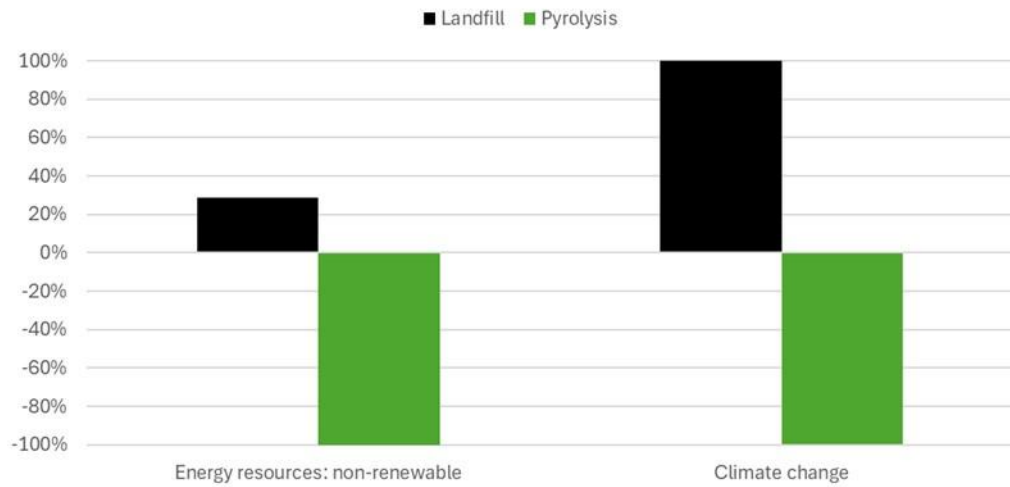


Fig 6 Comparative LCA results for the Non-Renewable Energy Resources and Climate Change categories

The impact associated with the landfill scenario mainly arises from diesel consumption during residue transport, compaction operations, and the use of heavy machinery, without any equivalent compensation. Moreover, within this modeling framework, the greatest environmental vulnerability of landfills lies in the generation of methane from the anaerobic decomposition of organic matter. Crude oil is also a main contributor, largely due to diesel use in transporting fruits, agricultural inputs, and residues, as well as in landfill operating machinery. Moreover, the inventory indicates indirect consumption of coal and natural gas, which are not directly used in the landfill but are embedded in upstream processes such as fertilizer production and agricultural input

manufacturing. Another relevant contributor is the use of clay, whose extraction and processing typically depend on fossil-based energy for excavation, drying, grinding, and transport, thereby incorporating impacts associated with coal, natural gas, and diesel. Thus, even if there is no direct use of these fuels at the landfill, they are internalized in the inventory through the energy burdens of earlier processes in the chain. Even with gas capture systems, fugitive fractions inevitably escape into the atmosphere, making landfills one of the main anthropogenic sources of methane.

Additionally, the landfill itself emerges as a relevant emission source: final disposal emits methane (CH_4) due to anaerobic decomposition of organic matter, and compaction/handling operations also contribute emissions associated with fossil fuel use. Methane (CH_4) has a global warming potential (GWP100) approximately 28 times higher than that of CO_2 .²⁹ Although its atmospheric lifetime is relatively short (about 12 years), immediate reductions in CH_4 emissions produce nearly instantaneous mitigation effects on global temperature. Therefore, controlling methane emissions — such as those originating from sanitary landfills—is considered one of the most effective strategies for reducing global warming in the short term [30].

Figure 7 presents comparative results for the categories of freshwater ecotoxicity, terrestrial ecotoxicity, and human toxicity, respectively. The differences between pyrolysis and landfill for these categories were less than 10%. This is because the main contributors to these categories are associated with Process 1, which is common to both scenarios and refers to coconut cultivation, particularly the use of fertilizers and pesticides. This process emits carbon dioxide (CO_2) due to the combustion of fossil fuels (diesel) used in transporting fruits and inputs and in operating agricultural machinery. In addition, nitrogen oxide (NO_x) emissions from soil are observed, mainly associated with the use of nitrogen fertilizers during cultivation. Transport stages

also contribute significantly to the impact, since the adopted mode is road transport, predominantly using diesel trucks, which release CO₂, NO_x, and particulate matter during operation.

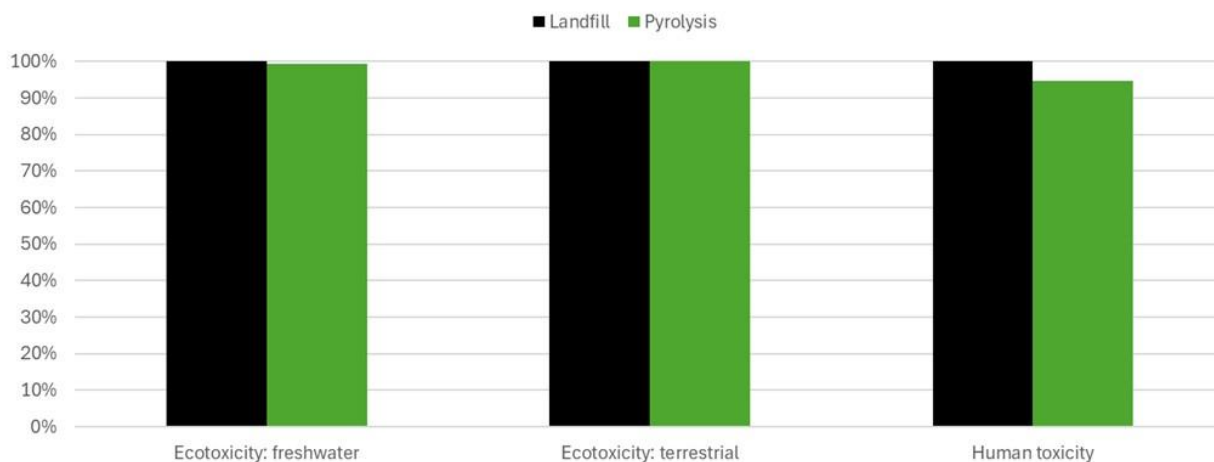


Fig 7 Comparative LCA Results for Freshwater Ecotoxicity, Terrestrial Ecotoxicity and Human Toxicity

For the marine ecotoxicity, acidification, and eutrophication categories, the comparative LCA results are presented in Figure 8. For these categories, the main difference between pyrolysis and landfill lies in the avoided impacts in pyrolysis resulting from the non-production of activated carbon, diesel, and natural gas through conventional routes. Although the positive impacts are primarily associated with fertilizer and pesticide use in Process 1, the pyrolysis scenario presents an advantage over landfill disposal, which fully offsets the impact on the marine ecotoxicity and acidification categories and significantly reduces it in eutrophication.

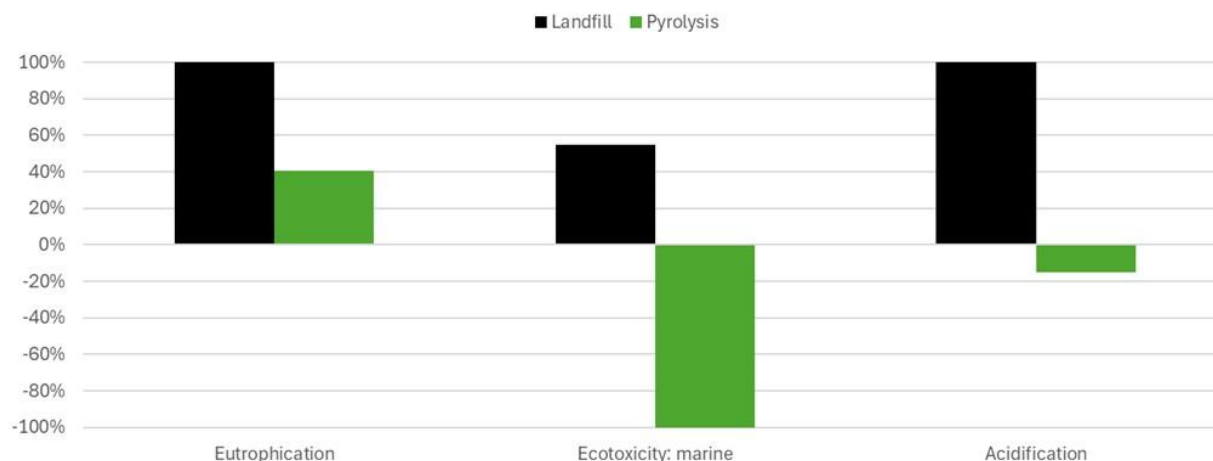


Fig 8 Comparative LCA Results for Eutrophication, Marine Ecotoxicity and Acidification

Thus, the analysis demonstrates that Scenario 1 is more environmentally favorable than Scenario 2. Pyrolysis, as a thermochemical waste conversion technology, enables energy recovery and a substantial reduction in the volume of waste to be disposed of, in addition to avoiding the production of fossil-based fuels. In contrast, sanitary landfills generate high methane emissions and require continuous consumption of environmental resources, resulting in significantly higher impacts across the evaluated categories.

To assess the robustness of the model and the reliability of the results, a sensitivity analysis was performed, which allows the evaluation of how changes in the model influence the outcomes of the different scenarios. Two sensitivity analysis were carried out in this study to evaluate the proposed scenarios. The software inputs and outputs for sensitivity analysis are also provided in the supplementary material.

The first analysis was performed by adding an oven-drying step to Scenario 1. The use of a 40 L laboratory oven with 550 W power was considered for drying 100 g of coconut residue over a period of 24 h, resulting in an approximate 40% mass reduction. A comparative LCA between

Scenarios 2 and 3 was conducted using the CML method. Table 3 presents the comparative LCA results, where Scenario 3 corresponds to the use of oven drying in the pre-treatment stage.

Table 3 LCIA results for each impact category for Scenarios 2 and 3.

Impact Category	Scenario 2	Scenario 3	Unit
Marine ecotoxicity	57.872	1003.0	kg 1,4-DCB-eq
Ecotoxicity in freshwater	3.64265	3.78794	kg 1,4-DCB-eq
Terrestrial ecotoxicity	1.5545	1.56104	kg 1,4-DCB-eq
Non-renewable energy resources	0.57811	8.83067	MJ
Climate Change	0.08175	1.61248	kg CO ₂ -eq
Human toxicity	2.01931	2.61299	kg 1,4-DCB-eq
Eutrophication	0.00195	0.00352	kg PO ₄ -eq
Acidification	0.00092	0.01159	kg SO ₂ -eq
Depletion of the ozone layer	4.8659E-9	4.4462E-8	kg CFC-11-eq
Material resources (metals/minerals)	2.0193E-7	8.83067	kg Sb-eq
Formation of photochemical oxidants	2.1984E-5	7.5617E-4	kg Etileno-eq

Figure 9 also highlights the large differences observed for the scenario that includes oven drying, showing a significant increase in environmental burdens across all evaluated impact categories. This behavior is mainly explained by the high electricity demand associated with continuous oven heating for 24 hours.

Although Brazil's electricity matrix is predominantly renewable, hydropower is not impact-free, as it is associated with hydrological alterations, vegetation loss, and biodiversity impacts. In addition, the complementary use of thermoelectric generation based on fossil fuels increases emissions and the depletion of non-renewable resources, particularly during peak demand or drought periods, raising the carbon intensity of electricity consumption. Consequently, energy use may still represent a significant environmental burden depending on the consumption profile. In this context, the high energy demand of thermal drying amplifies the system's environmental impacts, with electricity consumption identified as the dominant contributor in the

inventory. The results indicate that natural drying is environmentally preferable, as it eliminates this major source of impact. This finding highlights the need to reassess the use of energy-intensive drying methods in experimental, pilot, and industrial applications, especially when strict thermal control is not technically required.

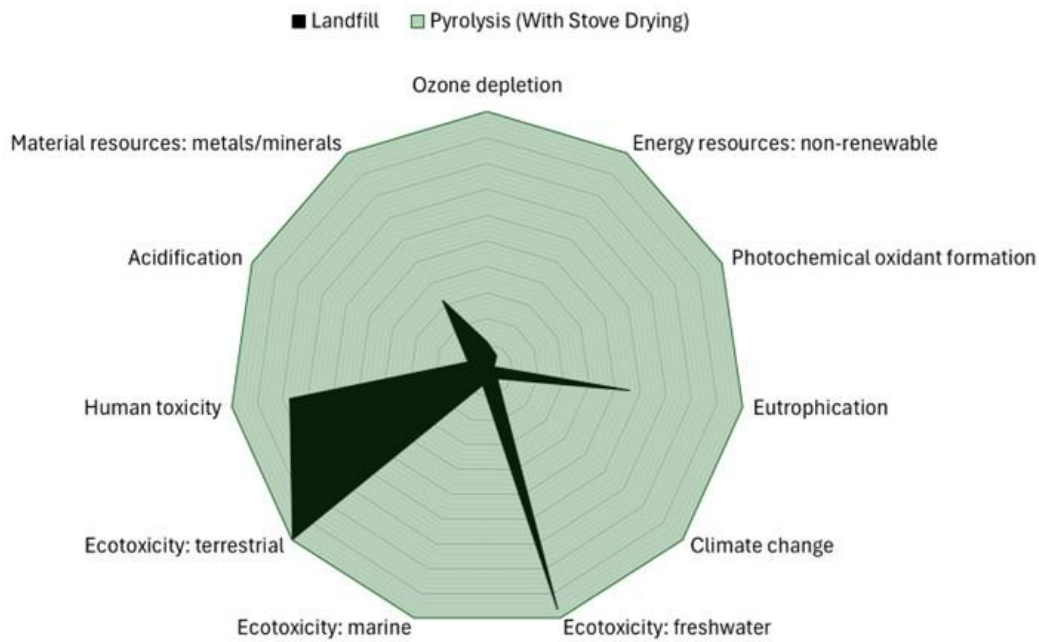


Fig 9 Radar Chart with comparative LCA results of pyrolysis with stove drying and landfill by impact category relative to the scenario with the highest contribution.

The second sensitive analysis was performed by modeling the landfill in Scenario 2 with electricity recovery. Based on the studies conducted by Rocha (2025) [27], an electricity generation unit was considered for modeling the landfill in Scenario 4.1. In this revised modeling, it was assumed that, from the collected gas (corresponding to 50% of the total generated gas), 33% is routed to the biomethane production unit and 27% to the electricity generation unit, while the remaining 40% is considered biogas emissions from the biomethane production process.

In addition to the revised biogas mass balance, air emissions were considered for the electricity generation unit (NO_x, CO, and particulate matter) [27]. Processes 1 and 2 were kept identical to the Scenario 2 modeling. Finally, a comparative LCA between Scenarios 2 and 4.1 was performed using the CML method. Figure 10 presents comparative results.

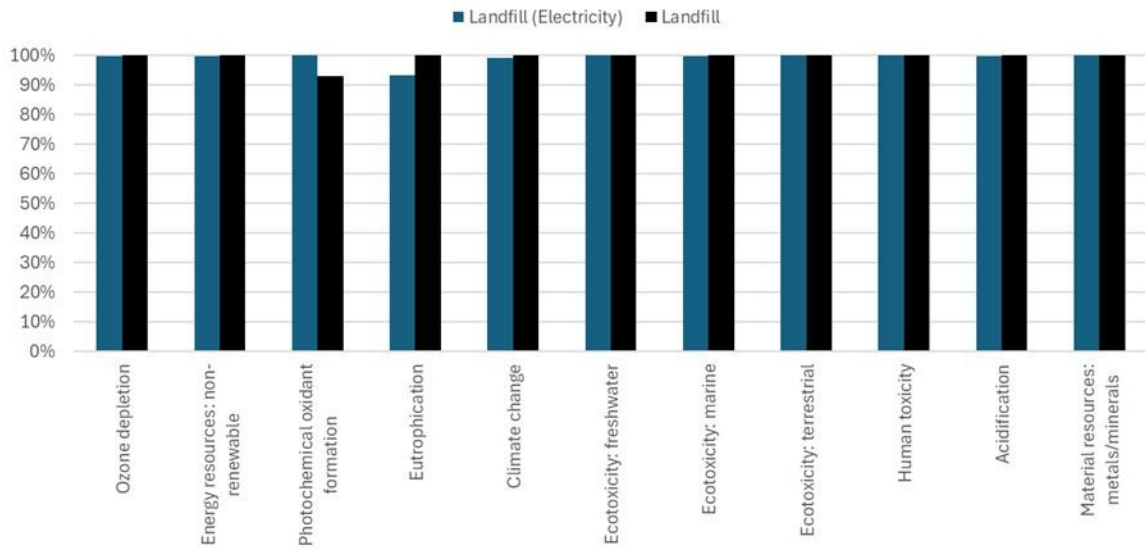


Fig 10 Bar Chart with comparative LCA results of scenarios 2 and 4.1 by impact category relative to the scenario with the highest contribution.

It is observed that, although the landfill model includes capture and combustion of part of the methane for electricity generation which, in principle, should reduce the Climate Change impact through energy credits, the results indicate that there is no effective improvement in this category. As shown, impact magnitudes remain very close to those observed in the reference scenario, indicating that the energy benefit from biogas recovery is insufficient to reverse the environmental balance. The comparison with the pyrolysis scenario also indicates that Scenario 1 remains more environmentally favorable than Scenario 4.1. Figure 11 presents the comparative LCA result between them.

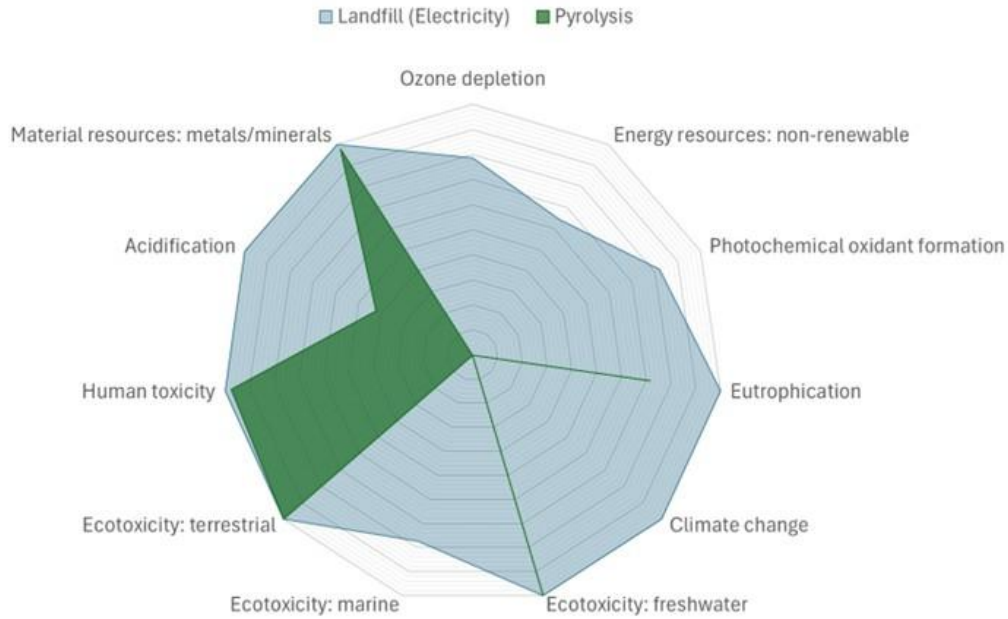


Fig 11 Radar Chart with comparative LCA results of scenarios 1 and 4.1 by impact category relative to the scenario with the highest contribution.

This result can be explained because only about 50% of the biogas generated in the landfill is recovered for conversion, while the remaining fraction — potentially exceeding half of produced methane when process losses are included — is released directly into the atmosphere. Since methane has a higher global warming potential than CO₂ over a 100-year horizon, fugitive emissions can, in practice, offset the expected climate benefit from electricity generation. In addition, the landfill presents additional impacts related to extensive land use, continuous mechanized compaction operations, and leachate formation, affecting categories associated with soil and water health.

To test this hypothesis, a second landfill analysis was conducted assuming that 100% of the generated biogas would be recovered for biomethane production, with no direct emissions associated with the discarded 50% in the baseline. Leachate emissions were maintained, as they

depend on the treated waste mass, and biogas emissions related to losses in the biomethane production unit were recalculated. However, emissions from the electricity generation unit increased, since both consumption and generation enhanced due to the larger amount of treated biogas. Finally, a comparative LCA was performed between Scenarios 2 and 4.2, and the results are shown in Figure 12.

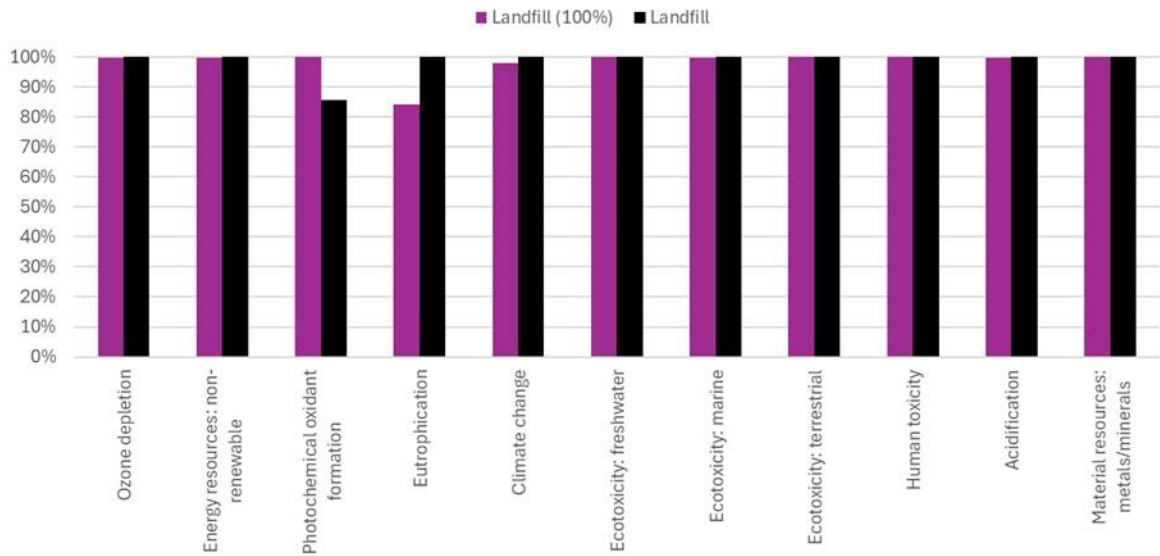


Fig 12 Bar Chart with comparative LCA results of scenarios 2 and 4.2 by impact category relative to the scenario with the highest contribution.

Despite the increased energy recovery in the 100% recovery scenario, the impact assessment results remained very close to those obtained for the 50% recovery scenario. This similarity can be explained by the fact that, although greater biogas recovery reduces fugitive methane emissions, the expansion of infrastructure required for full capture and conversion of the gas into electricity seems to imply higher emissions associated with operation and maintenance. Thus, the environmental credit from reduced direct biogas emissions seems to be partially offset by additional impacts linked to increased system complexity and energy consumption. Moreover, the environmental credit obtained from substituting grid electricity, while relevant, is not

sufficiently large to substantially change the overall impact balance, since electricity consumption also increases as more biogas is processed. The comparison with pyrolysis yields a similar conclusion, with thermal treatment remaining environmentally preferable. Figure 13 presents the result for this analysis.

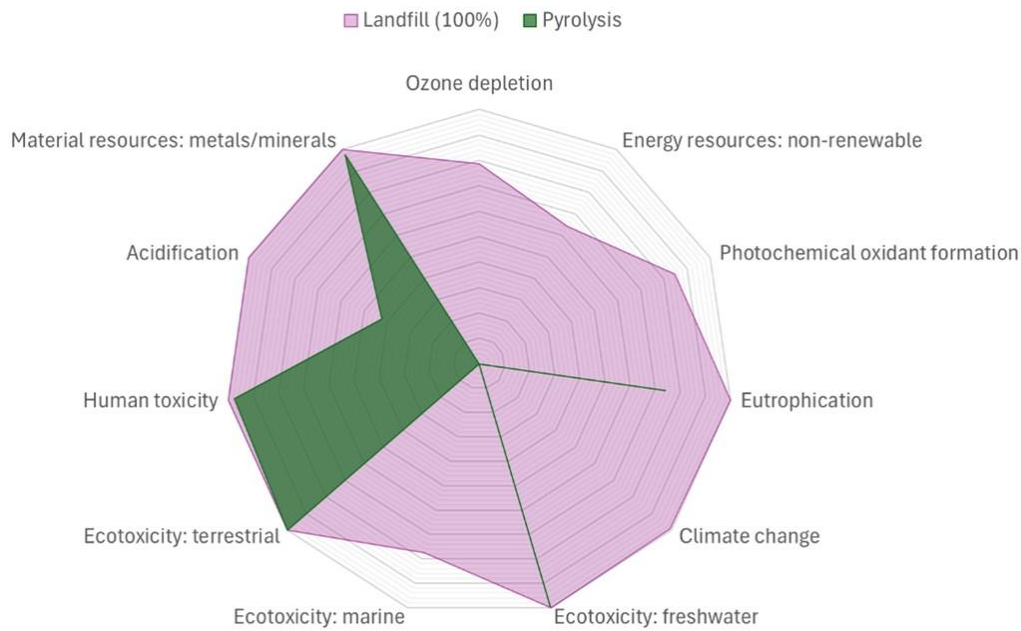


Fig 13 Radar Chart with comparative LCA results of scenarios 1 and 4.2 by impact category relative to the scenario with the highest contribution.

Therefore, for the landfill pathway to become environmentally competitive with pyrolysis, it would be necessary to substantially increase the efficiency of biomethane recovery from biogas, minimizing untreated biogas emissions, and to employ higher-efficiency generators to maximize energy conversion. Another suggestion is integrating anaerobic digestion with landfill disposal, as discussed by Rocha (2025) [27], which could act as a pre-treatment stage enabling greater energy recovery due to a purer gas composition and more efficient operational control, while significantly

reducing methane generation potential in the landfill because the residues would arrive partially stabilized.

It should be noted that, although the adjustments applied to the landfill scenarios were performed according to the mass defined by the functional unit, the LCA results remain relatively small due to the limited quantity of treated coconut husk, which makes differences between scenarios less pronounced. Even with this scale limitation, final disposal in landfills does not present an environmental advantage, confirming that for coconut residues this alternative is not environmentally superior under the modeled conditions.

CONCLUSION

This study evaluated the environmental feasibility of valorizing coconut residues via pyrolysis, using the Life Cycle Assessment (LCA) methodology to compare this technological route with conventional disposal in sanitary landfills. The analyses were carried out using the OpenLCA software, considering cradle-to-cradle scenarios for both alternatives.

Coconut residue pyrolysis proved to be environmentally more advantageous than landfill disposal across all impact categories evaluated using the CML method. The process enabled the generation of significant environmental credits, or net negative environmental impacts, particularly in the categories of non-renewable energy resources and climate change. These benefits result from the substitution of commercial products, such as activated carbon, diesel, and natural gas, by pyrolysis products, namely biochar, bio-oil, and biogas, respectively. It should be noted that this substitution assumed full utilization of the generated products, i.e., without losses during their use as new raw materials.

The results showed that the main positive environmental impacts of the analyzed scenarios are concentrated in the early stages of the life cycle, especially during coconut cultivation. The use of fertilizers and pesticides, such as cypermethrin, and creosote-treated wood for plant support was responsible for most impacts in the freshwater ecotoxicity, human toxicity, terrestrial ecotoxicity, and eutrophication categories. This indicates that improvements in agricultural practices could further enhance the environmental benefits of the pyrolysis route. In contrast, landfill disposal, even with partial recovery of biogas for biomethane or electricity generation, did not prove to be environmentally superior to pyrolysis. The landfill scenario presented positive impacts in all evaluated categories, mainly due to biogas and leachate emissions. No significant environmental credits were observed.

The sensitivity analysis demonstrated that natural drying as a pre-treatment for pyrolysis is environmentally preferable to electric oven drying, due to the high energy demand associated with the latter. Furthermore, even scenarios assuming 100% biogas recovery in landfills were insufficient to reverse the environmental balance in favor of this route, reinforcing the superiority of pyrolysis as an alternative for coconut residue valorization. Further studies are needed to assess the effects of improved biogas infrastructure and larger waste masses on the environmental performance of landfill-based scenarios.

The adoption of pyrolysis as a valorization route for coconut residues contributes to the circular economy by reducing pressure on non-renewable resources, mitigating greenhouse gas emissions, and promoting the generation of valued products. In summary, coconut residue pyrolysis emerges as a more environmentally sustainable alternative compared to landfill disposal, provided that more efficient and less impactful agricultural practices are adopted. This study highlights the importance of public policies and investments in clean technologies for the

management of agro-industrial residues, supporting the transition toward more sustainable production systems.

Supplementary Material

Input and Output data obtained in the *OpenLCA* software for process 1 to 7 and the sensitivity analysis (PDF)

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Statements and Declarations

Ethics Approval

Ethics approval is not applicable.

Consent to Participate and Consent for Publication

All authors read, reviewed, and approved the final manuscript.

Competing Interest

The authors declare no competing interests.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Mariana da Silva Teixeira and Alessandra da Rocha Duailibe Monteiro. The first draft of the manuscript was written by Mariana da Silva Teixeira and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability Statement

The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information files. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request. Source data are provided with this paper.

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