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Research Article

Climate-Smart Biochar: Transforming Waste for Climate Action and Disaster Management Planning

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Abstract

This research investigates the transformative potential of biochar, produced through pyrolysis and torrefaction of agricultural waste biomass, in addressing global challenges. Focused on climate change, soil degradation, and environmental pollution, the study underscores four key benefits: long-term carbon sequestration, enhanced soil fertility, renewable energy generation, and effective biomass waste management. The agricultural sector›s significant contribution to greenhouse gas emissions prompts a comprehensive Life Cycle Assessment (LCA) comparing the environmental impacts of pyrolysis and torrefaction. Results reveal nuanced advantages in acidification, eutrophication, and particulate matter for pyrolysis, while torrefaction excels in ecotoxicity, human toxicity, ozone formation, and climate change mitigation. Optimized processes with renewable energy display reductions in acidification, eutrophication, and particulate matter. The study emphasizes the importance of biochar quality for various applications, considering physical, chemical, and biological attributes. Evaluating the intrinsic characteristics of biochar generated by each process is vital for aligning with diverse application requirements. Harnessing biochar›s potential through comprehensive LCAs empowers decision-makers to promote sustainable technologies, actively combat climate change, enhance soil fertility, and encourage resilient agricultural practices for a greener future..

Keywords: Biochar, Waste Management, Life Cycle Assessment, Climate-Smart Solutions.

1. Introduction

The world faces numerous global challenges, encompassing climate change, land degradation, environmental pollution, and water scarcity, which collectively give rise to adverse economic, social, and environmental consequences. Rising global temperatures, altered precipitation patterns, and increased frequency of extreme weather events have resulted in disastrous consequences for ecosystems, regional economies, and human societies [1, 2].

Climate change and soil degradation stand out as pressing environmental issues, necessitating the exploration of solutions. Pyrolysis and torrefaction of biomass, particularly agricultural waste biomass, to produce biochar, emerges as a potential solution to address these challenges. These technologies yield four benefits: long-term carbon (C) sequestration through stable C in the biochar, a high-performance water holding substrate and soil amendment material, renewable energy generation via biofuels and effective biomass waste management [3].

The agricultural sector, coupled with land use and land cover changes, are major contributors to global greenhouse gas emissions [4]. In fact, after fossil fuel use, land use and land use change emerge as the second most significant sources of emissions [5]. These emissions stem from the depletion of carbon stocks in soils due to land use practices, exacerbating the carbon imbalance. Without intervention, land could become a net source of carbon emissions by 2050 [6].

Biochar has shown immense potential in mitigating and adapting climate change and global warming by acting as a carbon sink, along with locking up carbon from biomass, delaying its release back into the atmosphere. When applied to the soil, biochar sequesters carbon for extended periods, enhancing soil fertility and improving crop yields [7]. The

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porous structure of biochar provides habitat for beneficial microorganisms and enhances water and nutrient retention in the soil, creating a favorable environment for plant growth [8]. Moreover, biochar's stability and resistance to decomposition ensure that carbon remains locked away from the atmosphere for hundreds to thousands of years [9].

In addition to its carbon sequestration potential, biochar has been proven effective in alleviating the adverse effects of extreme weather events on soil-plant systems. High temperatures, droughts, floods, and salinization pose significant challenges to agricultural productivity and food security [10]. However, biochar improves soil aeration, reducing the negative impacts of high temperatures and droughts by enhancing water infiltration and soil moisture retention. Biochar also reduces Denitrification and increases the soil's capacity to act as a sink for methane, effectively mitigating greenhouse gas emissions [11]. Furthermore, biochar application in salinized soils helps minimize ion uptake in plants, enhancing their tolerance to saline conditions [10, 12].

The utilization of agricultural waste and biomass for biochar production offers a sustainable waste management solution, reducing greenhouse gas emissions that would otherwise be generated through burning or landfilling. It is noteworthy that the co-production of biofuels during the pyrolysis process contributes to renewable energy production, reducing reliance on fossil fuels. Biochar projects could also participate in carbon credit markets, providing additional income opportunities for farmers. By sequestering carbon and reducing greenhouse gas emissions, biochar projects can generate carbon offset credits that can be traded in these markets. This not only incentivizes the adoption of biochar but also provides economic benefits to farmers, contributing to the viability and scalability of biochar implementation [13].

The adoption of Circular Economy (CE) principles presents an opportunity to mitigate the substantial environmental impact of different industries. While Life Cycle Assessment (LCA) serves as a valuable tool for guiding CE decision-making by pinpointing key opportunities for environmental impact reduction across the life cycles of different products and services, its application alone may not be sufficient in design situations. Therefore, there is a need to leverage aggregated knowledge derived from LCA to enhance decision-making processes [14]. To conduct a comprehensive LCA, it is essential to define the system boundary, functional unit, among other features. Detailed investigations into energy inputs, material usage, greenhouse gas emissions, resource consumption, and further information is necessary for a transparent and complete assessment. LCA can be used as a methodology to evaluate the environmental impacts of biochar production. Two different techniques for biochar acquisition include pyrolysis and torrefaction, thermal conversion treatments that hold promise for both waste management and energy production [15].

This research paper aims to assess the environmental impacts of two different technologies in the acquisition of biochar, applying fundamental changes to the traditional approach, specifically on the energy source. Improving these technologies increases the net worth of the process and resources they provide. Therefore, new light can be shed on biochar and its transformative capabilities in addressing climate change challenges and disaster management planning, paving the way for a more resilient and sustainable future.

As we mentioned before, Biochars play a pivotal role in ecosystem restoration when incorporated into soil to enhance fertility and increase carbon content. They sequester carbon in the soil for extended periods, effectively removing CO2 from the atmosphere and mitigating greenhouse gas emissions. As a result, it facilitates carbon-negative practices, where more carbon is taken out of the atmosphere than is released. However, it is crucial to consider the carbon footprint in the generation of pyrolysis, given the potential emissions associated with producing bio-oils and biochars. Therefore, it is relevant to assess the carbon emissions from creating biochars using conventional energy sources and to explore the enhanced application of renewable energy in this process. The objectives of this manuscript are twofold. On one hand, we demonstrated that greenhouse gas emissions could be significantly reduced by applying renewable energies. Simultaneously, we propose the implementation of biochars in areas where agricultural waste is increasing due to the demands of the international market. This not only addresses waste management but also contributes to sustainable practices and the global effort to adapt and mitigate climate change.

2. Methods and Materials

2.1 Technical overview of biochar production processes

Torrefaction and pyrolysis are two distinct thermal conversion techniques utilized in biomass processing, each serving different objectives and operating conditions. Torrefaction involves a mild thermal treatment process applied to biomass in the absence of oxygen. The primary goal of torrefaction is to enhance the properties of biomass for use as a solid biofuel, such as wood pellets or briquettes. During this process, biomass is subjected to temperatures typically ranging from 200 to 300 degrees Celsius, leading to the release of moisture and volatile components. Consequently, the resulting solid material, from here on referred to as torrefaction biochar, attains higher energy content. The biochar exhibits superior storability and combustion characteristics, rendering it suitable for co-firing with coal or as a stand-alone renewable fuel.

In contrast, pyrolysis represents a more intense thermal treatment process wherein biomass is decomposed in the absence of oxygen at higher temperatures. The primary objective of pyrolysis is to produce various valuable products, including biochar, bio-oil and gas. The pyrolysis temperature can vary depending on the desired composition of the products and typically ranges from 300 to 600 degrees Celsius. Pyrolytic biochar serves as a stable carbon-rich material suitable for soil amendment and carbon sequestration, while bio-oil can be further processed into biofuels. Pyrolytic gas, on the other hand, finds application in heat and electricity generation.

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Study area: Forests have long been regarded as invaluable resources, providing timber, biodiversity, and ecosystem services essential for the well-being of our planet and its inhabitants. This industry, encompassing forestry management, wood processing, and paper production, has evolved significantly over time, adapting to shifting paradigms of sustainability, technological advancement, and global demand. As a vital component of industrial activity, it encompasses the physical transformation of wood that yields a diverse range of products.

Beyond its primary wood product manufacturing role, the sawmill industry generates a substantial amount of waste or potential byproducts including wood chips, bark, and sawdust, among others within the various wood treatment processes. From the raw material entering sawmills, approximately 45-55% is eventually transformed into the final product, while the remainder is discarded or open field burnt, accounting for an estimated 3.6 million tons of by-products annually (see Table 1) [16, 17].

Table 1: By-product generation (m3).

Region	Sawdust	Bark	Edging	Trimming	Shavings	Total
Cuyo	9.894	8.419	45.969	17.386	3.391	85.059
Northeastern region	488.014	393.968	2.244.476	883.540	239.812	4.249.810
Northwestern region	16.600	11.641	67.991	22.883	4.621	123.736
Pampas	31.906	16.210	108.023	28.888	8.084	193.111
Chaco Region	56.015	43.744	239.909	87.782	9.662	437.113
Patagonia	27.743	19.773	116.745	40.637	12.821	217.718
National	630.172	493.755	2.823.114	278.391	278.391	5.306.547

In Argentina, according to the latest census data, there are a total of 2,087 sawmills scattered throughout the country. Notably, the Northeastern region accounts for 37% of this total, relying on cultivated forests to sustain its operations [17]. The provinces of Misiones, Corrientes, and Entre Ríos, collectively forming the Northeastern region of Argentina, represent the quintessential geographic hub of sawmills at the national level. The distribution of sawmills within these three provinces reveals distinct patterns (Figure 1).

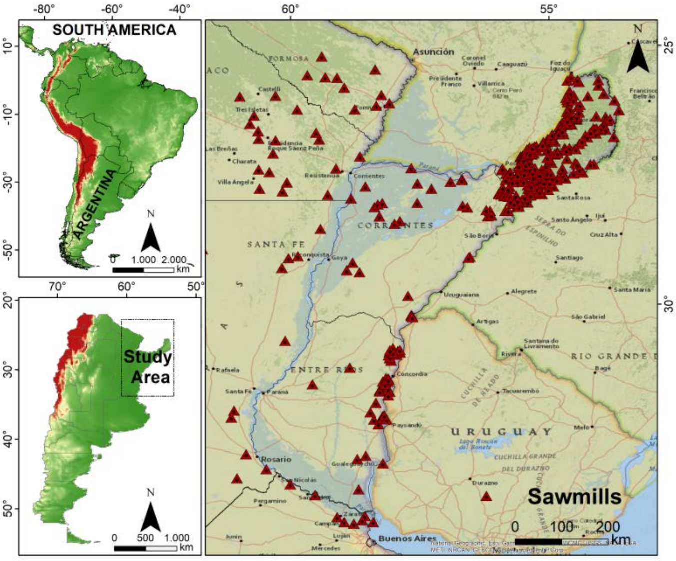

Figure 1: Distribution of sawmills throughout the Northeastern region, Argentina. Modify from [18].

2.2 Life Cycle Assessment

Goal and scope definition: The goal of the LCA was threefold: The first one was to assess and compare life cycle impacts of two different biochar systems to support decision making related to the implementation of producing biochar as a waste management strategy. The second goal was to contrast two technologies for biochar acquisition: pyrolysis and torrefaction. The third goal was to compare emissions from the above-mentioned technologies, both with and without the utilization of renewable energy sources. In this sense, four scenarios were considered:

- Biochar produced through pyrolysis using renewable energy (PyRE)
- Biochar produced through torrefaction using renewable energy (TorRE)
- Biochar produced through pyrolysis using fuel-based energy (PyFE)
- Biochar produced through torrefaction using fuel-based energy (TorFE)

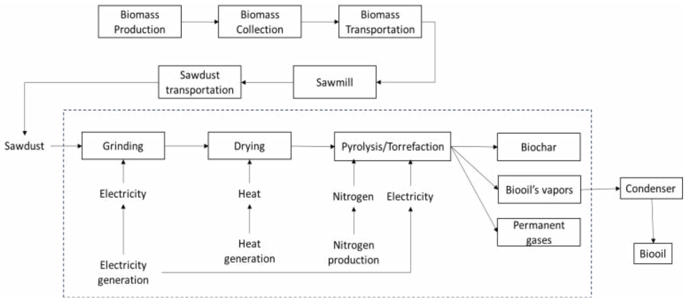

Figure 2: System boundary of pyrolysis and torrefaction processes.

The LCA was carried out following the ISO standards (14040/14044) [19, 20]. The functional unit was defined as “1 t of lignocellulosic waste biomass”. The approach of this study was gate to gate with the focus on electricity consumption and byproducts emissions to produce biochar through pyrolysis or torrefaction (see Figure 2). Therefore, the transport of raw material and chemicals, the construction of reactors and the utilization of biochar were not considered into the system boundaries.

Life Cycle Inventory Analysis: Data for background processes

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are based on generic processes from the IDEMAT (short for Industrial Design & Engineering MATerials database) 2023 database is a compilation of LCI data of the Sustainable Impact Metrics Foundation, SIMF, and a non-profit spin-off of the Delft University of Technology [21].

Sawdust was considered as the waste biomass used in this study to produce biochar. In the northern region of Argentina, the production of sawdust as a residue of the sawmill industry is considerably high. Its production ranged from 940 m3 to 24000 m3 annually (approximately 11000 tons/year). Besides, some data regarding yields were obtained from laboratory experiments (for further details see Casoni et. Al), bibliography and literature [22].

Life Cycle Impact Assessment: Open CA v1.11.0 was used to carry out the assessment. Eco-cost 2023 V1.0 methodology was applied to assess the impacts associated with biochar production through pyrolysis and torrefaction. Although this methodology consists of 14 midpoints, 9 of them have been selected for this study (see Table 2) since their implications are considered more relevant.

Table 2: Impact categories with their respective reference units.

Impact category	Reference unit
Acidification	mol H^+ eq
Climate change	kg CO_2 eq
Ecotoxicity, freshwater	CTUe
Eutrophication	kg $PO_4{}^{3-}$ eq
Human toxicity, cancer	CTUh
Human toxicity, non-cancer	CTUh
Land use (biodiversity change)	bio factor
Particulate matter	kg PM2.5
Photochemical ozone formation	kg NMVOC eq

3. Results

Each technology has been divided into three stages: grinding, drying and thermal treatment (pyrolysis or torrefaction). Even though the biomass is sawdust, the grinding process was considered to accomplish a homogeneous particle size for further treatment.

Having a homogeneous and moderately small particle size is crucial when preparing biomass for pyrolysis or torrefaction processes, as it significantly impacts the efficiency and outcome of these thermal conversion processes. First and foremost, particle size plays a pivotal role in controlling the heating rate of the solid biomass material. A smaller and more uniform particle size allows for a more consistent and rapid heating of the biomass. This is essential because the heating rate affects the overall residence time of the biomass within the pyrolysis or torrefaction reactor. If the particle size is too large or uneven, certain parts of the biomass may not receive sufficient heat, leading to incomplete conversion and suboptimal product yields.

Furthermore, the particle size has a direct impact on the proportion and composition of the product fractions obtained during pyrolysis or torrefaction. Research findings have demonstrated that larger biomass particles may hinder the efficient release of volatile gases, leading to increased thermal cracking and char formation. Increasing the particle size from the micron scale (e.g., 53-63 μm) to the hundreds of microns (e.g., 270-500 μm) has been shown to lead to a substantial decrease in the emission of tars, which are undesirable byproducts. This decrease in tar emissions is indicative of a more controlled and efficient pyrolysis or torrefaction process, resulting in a cleaner and more valuable product stream [23].

The energy consumption at each stage is presented in Table 3. The main contributor is electricity consumption, which makes the thermal treatments the most expensive part of the process in terms of energy requirement.

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Table 3: Energy consumption for the different stages of the processes.

Stage	Energy Consumption
Grinding	Electricity: 1.25 kWh [24]
Drying	Heat: 35.2 kWh [25]
Thermal treatment	Electricity Torrefaction: 564.1 kWh [26]
	Electricity Pyrolysis: 281.6 kWh [27]

It is noteworthy that even though the pyrolysis process seems to be the one with the highest energy consumption, the product obtained for this thermal treatment is of a higher quality for the purposes intended. In terms of yields, while the torrefaction has a higher conversion rate, the quality of the biochar obtained is inferior to that of pyrolysis. The milder treatment leaves part of the biomass untreated and unconverted, which leads to a poorer performance in several applications such as carbon sequestration, soil amendment and others of importance for climate change mitigation and or adaptation and waste management purposes.

In Figure 3, the selected impact categories are presented for the two main thermal treatments making use of fuel-based energy sources. Both the reach and limitations for these techniques and the biochar provided from them are significantly different, giving an optimal opportunity for comparison and analysis.

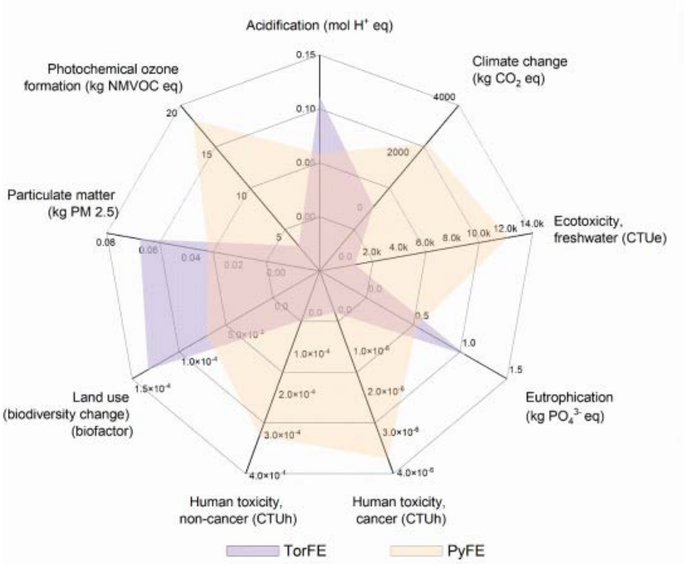

Figure 3: Main impact categories for the different thermal treatments conducted through non-renewable energy sources.

For torrefaction, the main categories where it excels according to this LCA in comparison to pyrolysis, are freshwater ecotoxicity, human toxicity, photochemical ozone formation and climate change.

In particular, the climate change midpoint encompasses the main feature in this analysis due to its contribution from the perspective of gas emissions. It can be clearly observed that the pyrolysis process has a higher environmental impact, due to the methane production amounting to 58.5 kg, which is equivalent to 2152.8 kg of CO_2 (impact factor of 36.8 kg CO_2 eq./kg CH4) out of a total of 2616.7 kg of CO_2 eq. The remaining amount is subjected to electricity and nitrogen use, along with CO and CO_2 emissions. For torrefaction, methane production is due to the drying stage and not the thermal treatment per se, which lowers it to a milder 0.6 kg of CH4, or 21.0 kg CO_2 eq. Moreover, the main contributor to this midpoint is the production of electricity needed for all three stages, with a value of 260.0 kg CO_2 emitted.

Regarding human and ecotoxicity, the categories are determined mainly by co-production of acetic acid, furfural and p-methoxyphenol during thermal treatments. In the former, the Comparative Toxic Unit for Human Toxicity Impacts (CTUh) metric serves as a quantitative measure that allows a projected escalation in instances of morbidity within the overall human populace, relative to each unit of mass of the emitted chemical substance. In a similar vein, with regards to the latter, the Comparative Toxic Unit for Aquatic Ecotoxicity Impacts (CTUe) functions as an indicator that delineates the estimated fraction of species potentially subjected to adverse effects (Potentially Affected Fraction, PAF), over a defined temporal span and volume of the freshwater compartment [24-28].

On one hand, regarding human toxicity, the pyrolysis process shows a fourteen times higher impact than torrefaction. Both have acetic acid, p-methoxyphenol and furfural emission as main contributors. On the other hand, in the context of ecotoxicity, pyrolysis presents an eighteen times higher impact than torrefaction. The thermal conversion stage in the process leads up to an ecotoxicity of 631.9 CTUe due to acetic acid (94.8%) and furfural (5.0%) production out of a total of 667.6 CTUe, the remaining compounds with a contribution <1% are not considered. Alternatively, the pyrolysis process leads to a total ecotoxicity of 12149.0 CTUe, most of which comprises acetic acid (53.8%), p-methoxyphenol (35.9%) and furfural (10.3%).

The last category in which torrefaction is superior to pyrolysis by a notable margin is the photochemical ozone formation, an impact category that accounts for the generation of ground-level ozone within the troposphere due to the photochemical oxidation process involving Non-Methane Volatile Organic Compounds (NMVOCs) [29]. Elevated concentrations of tropospheric ozone result in detrimental effects on vegetation, human respiratory tracts, and synthetic materials. From the perspective of pyrolysis, this category presents a value of 18.2 kg NMVOC eq., from which 17.8 kg NMVOC eq. are due to acetic acid with only 0.3 kg NMVOC eq. for the NO_2 produced during electricity generation as the second largest contribution. Alternatively, from the perspective of torrefaction, this impact accounts for a total of 3.0 kg NMVOC eq. It presents a similar trend for the main contributors, being acetic acid the highest one with 1.6 kg NMVOC eq., followed by methanol (0.5 kg NMVOC eq.) and lastly, NO_2 produced during electricity generation (0.6 kg NMVOC eq.).

Regarding environmental impacts, there are four categories in which pyrolysis shows a better performance including acidification, eutrophication, land use and particulate matter.

In this methodology, the measurement unit is mol H+ equiv. for the acidification category, which is commonly associated with atmospheric pollution arising from anthropogenically derived sulfur (S) and nitrogen (N) as NOx or ammonia. Torrefaction acidification potential doubles that of pyrolysis (0.11 mol H+ equiv. versus 0.058 mol H+ equiv.), with the main contribution being the SO_2 emitted due to generating energy.

Ecosystems undergo an impact due to substances containing nitrogen or phosphorus, such as manure, slurry, and fertilizer. The outcomes of this nutrient enrichment include heightened production of biomass (organic matter) and diminished biodiversity. This decrease in biodiversity arises from the escalated growth of a limited number of species capable of utilizing the surplus nutrients. For instance, in aquatic ecosystems, this could present itself as an overgrowth of algae at the expense of species that thrive in environments with lower nutrient levels, which could lead to the disappearance of higher plants. Additionally, the decomposition of deceased algae results in a depletion of oxygen, consequently affecting the populations of oxygen-dependent aquatic animals. Similar to the quantification of Climate Change through CO_2 eq., the potential for eutrophication is assessed using PO43- eq. In pyrolysis, this category accounts for a value of 0.54 kg PO43- eq., compared to a 93% higher environmental impact for torrefaction of 1.06 kg PO43- eq. In both technologies, the main contribution is due to the NO_2 emitted during electricity generation.

In LCA, biodiversity is primarily presented as an endpoint category, characterized by a reduction in species richness due to the transformation and utilization of land across various time frames and geographical areas. The broader impacts on biodiversity in terms of function and population are largely overlooked, as the focus remains on the accumulation of species within a constrained geographic and taxonomic scope [30]. The same trend as eutrophication and acidification is observed for this category, with pyrolysis having 86% lower impact than torrefaction.

Typically, a product or process generates air pollution in the form of particulate matter (PM). This pollution can arise from factors such as the transportation of the product by vehicles or the utilization of electricity sourced from fossil fuel-powered plants during the product's manufacturing or usage [31]. Particulate matter is categorized based on its aerodynamic diameter, namely, respirable particles (PM10) measuring <10 µm, fine particles (PM2.5) measuring <2.5 µm, and ultrafine particles (UFP) measuring <100 nm in aerodynamic diameter. The selection of PM2.5 was motivated by the desire to establish consistent international guidelines concerning its health impacts [32]. For the studied processes, the electricity usage is the main contributor to this midpoint, being 0.03 kg PM2.5 for pyrolysis and double this value for torrefaction.

Considering that in many of the impact categories, both for pyrolysis and torrefaction, the main contributor factors are related to electricity production, an optimization of this particular characteristic and LCA analysis of the process using a renewable electricity source has been carried out. The results are displayed in Figures 4 and 5. The optimized processes show a similar value to that of the fuel-based energy source for climate change, ecotoxicity, human toxicity and photochemical ozone formation midpoints. However, acidification, eutrophication and particulate matter are diminished to almost zero, while land use suffers a drastic reduction.

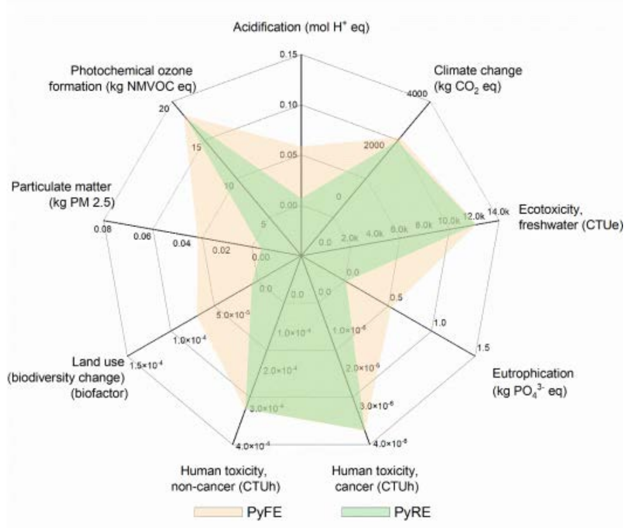

Figure 4: Main impact categories for the pyrolysis process conducted through renewable and non-renewable energy sources.

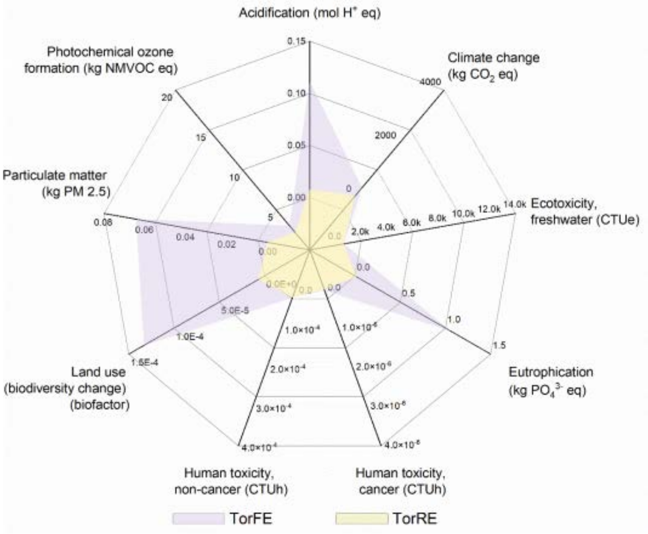

Figure 5: Main impact categories for the torrefaction process conducted through renewable and non-renewable energy sources.

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While the comparison of total effects between optimized and non-optimized processes within the climate change category may not reveal substantive alterations, it is paramount to underscore the pronounced disparity in CO_2 emissions that specifically emanate from pyrolysis and torrefaction. To further elucidate this facet, a graphical representation detailing the distinct CO_2 emissions is provided in Figure 6.

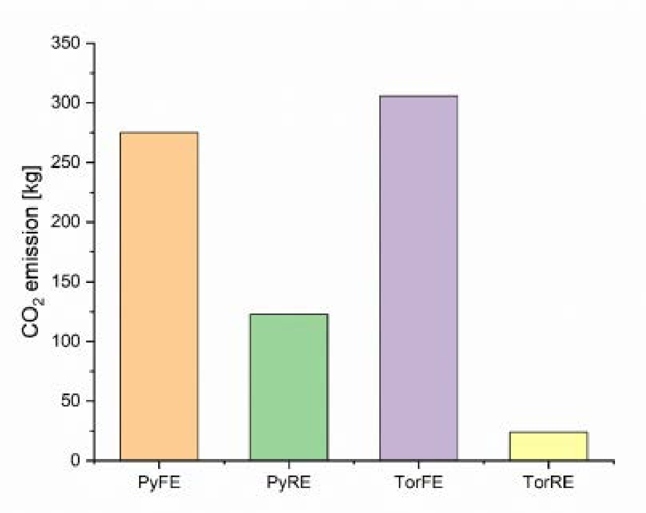

Figure 6: Carbon dioxide emission for different thermal treatments, using renewable and non-renewable energy sources.

It is within this analytical juncture that the strategic integration of biochar applications materializes as a pivotal instrument, a bridge between the theoretical framework of LCA classification and the practical aspects of biochar production techniques. The overarching strategy for global process optimization becomes centered on endowing the biochar outputs with utility that effectively mitigates their impact on climate change dynamics. This strategic pivot revolves around the potential applications of biochar and their profound role in ameliorating climate change, as expounded upon in the subsequent sections and illustrated in Figure 7.

Furthermore, it is important to acknowledge that a comprehensive evaluation of the two acquisition methodologies, torrefaction, and pyrolysis, extends beyond a mere juxtaposition of LCA results. While LCA offers valuable insights into the environmental implications of each process, a multifaceted assessment necessitates an exploration of the intrinsic quality and characteristics of the resulting biochar. This consideration becomes particularly salient when aligning the acquired biochar with diverse application requirements. The nuances of biochar's physical, chemical, and biological attributes, intricately linked to the specific needs of various applications, underscore the essentiality of further deliberation.

The comparative analysis of biochar obtained through pyrolysis and torrefaction reveals distinct characteristics influencing their suitability for various applications. Torrefaction, characterized by a solid biochar yield of 69-93%, exhibits superior energy output and lower ignition temperatures, making it an efficient choice [33]. In contrast, pyrolysis generates a combination of biochar and volatile by-products, resulting in a lower percentage of solid biochar (3.5-20%) but potentially with a higher surface area [34].

The yields and properties of pyrolysis products, including noncondensable gases, biochar, and bio-oil, vary within specific ranges. Bio-oil, with higher heating values in the range of 28.781–29.871 MJ/kg, exhibits a strongly acidic nature. Biochar from pyrolysis, characterized by comparable energy potential to low-ranked coals, offers diverse applications, particularly in adsorption, environmental, catalyst, and agricultural contexts.

FTIR spectra analysis reveals distinctive functional groups in biochars produced at different temperatures. Surface properties, morphology, and elemental composition, examined through SEM and EDX analysis, depict biochar's heterogeneous and amorphous structure. The increase in surface area, pore size, and the presence of essential elements indicate the potential suitability of biochar for various applications, particularly in agriculture.

Inextricably intertwined with the broader discourse on biochar's potential applications, this facet warrants meticulous examination to ascertain how each method aligns with the nuanced prerequisites of intended uses. Thus, in discussing the comparative merits of torrefaction and pyrolysis, the dimension of biochar quality must claim its rightful position alongside the established LCA framework.

Figure 7: Main impact categories for pyrolysis and torrefaction processes conducted through renewable and non-renewable energy sources.

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4. Discussion

The prospect of biochar as a longwave geoengineering solution for climate change mitigation has gained traction since the 60s, with a significant surge in research attention following Crutzen's editorial in 2006 [35]. Projections hint at biochar's potential to sequester atmospheric CO2 on a billion-tonne (109 t yr−1) scale annually within three decades, necessitating a comprehensive risk and reward assessment [36, 37].

The Life Cycle Assessment proves invaluable in evaluating the environmental implications of biochar technology. International standards, ISO 14040 and 14044, define LCA as a comprehensive evaluation of inputs, outputs, and potential environmental impacts throughout the entire life cycle of a product system. It allows for a focused analysis of global warming impact or a broader study of various environmental impacts. Han et al., carried out a LCA which compares two ways of biomass utilization, pyrolysis and open field burning. They concluded that pyrolysis presents lower environmental impacts in several categories of CML 2001 method. Zhu et al., critically analyzes the life cycle assessment (LCA) of biochar production from different agro-residues and compares typical technologies for biochar production. Agro-residues are candidate feedstocks for sustainable production of biochar. They highlighted that pyrolysis is a promising technology for net carbon management of agro-residues and LCA unification facilitates the sustainability assessment of biochar production. Besides, they claimed that biochar has carbon reduction potential in energy and soil applications while biochar technologies with regional characteristics have great development prospects [38, 39].

In particular, the greenhouse gas balance is crucial in biochar technology risk assessment, as its implementation aims to mitigate the risks associated with climate change. However, the GHG balances of biochar systems vary based on factors such as feedstock type, conversion technologies, end-use applications, system boundaries, and reference systems for comparison. GHG emissions occur at different stages of the supply chain, and the extent to which they are offset by carbon sequestration varies from one project to another. Risk assessment strategies tailored to each stage shed light on potential risks and effective management approaches.

The biochar concept is therefore studied through three pivotal stages: biomass feedstock sourcing, conversion technology, and biochar product utilization. The risk profile of biochar aligns closely with waste and bioenergy technologies. Industrial biochar production facilities would navigate risks through process engineering and operational optimization, utilizing engineering risk management tools. Energy efficiency, a key LCA consideration, significantly influences the environmental benefits of biochar production. The transition from combustion to pyrolysis and gasification systems minimizes emissions risks, with pyrolysis demonstrating lower environmental impacts.

Both pyrolysis and torrefaction can be used for biochar production, each with distinct merits and challenges. While both processes provide biochar, the quality and characteristics for each of them are different and can be used for different forms of mitigation systems. Energy efficiency, particularly when incorporating green energies such as hydroelectric power, plays a crucial role in assessing their environmental impact. LCA can be used to show the consequences of using green energy sources instead of fuel-based systems, offering stakeholders insights for informed decision-making that prioritizes sustainability and climate change mitigation.

Biomass waste diversion typically does not exacerbate environmental pressures since it involves materials with no viable beneficial reuse options [40]. When conducting a LCA to assess the environmental risks associated with biochar feedstock sourcing, several factors should be considered. These factors include the impact on habitats, erosion control, changes in carbon and nutrient stocks, water management, and the potential influence of additional income, which may make the production of the primary commodity more economically attractive, potentially leading to land use expansion.

In the realm of biochar technology, the risk profile aligns more closely with alternate waste and bioenergy technologies. Industrial biochar production facilities manage their risks through process engineering principles and operational optimization. Utilizing engineering risk management tools aids in identifying and prioritizing risk management actions, thereby minimizing potential harm and exposure to the environment [41].

The energy efficiency of the chosen biochar production technology significantly impacts the achievable environmental benefits, especially in terms of greenhouse gas abatement. Hence, it becomes a pivotal consideration during the application of life cycle assessment and GHG balance methodologies. Poor energy efficiencies pose risks to the overall GHG abatement potential. The LCA should account for any nonrenewable energy used throughout the life cycle. To accurately calculate the net GHG benefit of bioenergy production, selecting an appropriate fossil reference system for the specific project location is essential. A lower reliance on fossil fuel inputs enhances the ecological impact and potentially improves economic viability [40]. Additionally, biochar technology offers the advantage of producing energy products that can replace fossil fuels or meet increasing energy demands, making it more environmentally friendly [42].

Thermal treatment of biomass serves as a significant option for both energy conversion and waste management. The shift from combustion to pyrolysis and gasification systems has resulted from stricter emissions standards and regulations [43]. Pyrolysis and gasification occur in environments with limited oxygen, and they produce syngas, which burns cleaner and more efficiently than solid biomass due to improved gas-oxygen mixing. These processes operate at lower temperatures, favoring reduction reactions, and exhibit improved emissions profiles compared to combustion systems. Consequently, pyrolysis technology, as employed in biochar production, poses lower emissions risks than combustion

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technologies, even though concerns remain regarding atmospheric emissions from thermal biomass treatment.

The thermal conversion process through pyrolysis has the potential to alter the chemical and biological contaminants in the original waste material. This biological sterilization offers significant environmental advantages, especially when addressing biosecurity concerns related to pathogens and plant propagules. Moreover, heavy metal contaminants are concentrated into the biochar, except for low-temperature sublimating metals like mercury and cadmium, which may be lost to the syngas stream based on the specific temperature profiles of the technology used [44]. Although reductions in organic pollutants are expected to occur, there is currently limited published data on this aspect.

Biochar's applications in climate change mitigation extend to farming systems, where E-LCA studies showcase its potential to reduce carbon footprints, enhance crop productivity, and suppress soil methane emissions. In sponge city construction, biochar-amended green roofs prove effect tive in managing rainwater runoff and mitigating urban heat island effects. Biochar enhances water holding capacity, regulates runoff, and reduces surface temperatures, contributing to improved hydrothermal properties [7, 45-48].

The versatility of biochar technology in addressing biosecurity concerns, modifying chemical contaminants, and contributing to climate change mitigation across diverse applications, including farming systems and urban construction, is evident and underscores its versatility. In adopting biochar, a multifaceted perspective must be used to consider its life cycle, energy efficiency, and environmental implications for informed decision-making, emphasizing sustainability and effective climate change mitigation.

5. Conclusion

In harnessing the potential of biochar as a climate-smart solution and undertaking thorough Life Cycle Assessments, decision-makers gain a nuanced understanding of the intricate trade-offs and potential benefits associated with specific biochar production pathways. This knowledge becomes most valuable in steering the trajectory towards sustainable and environmentally friendly technologies, paving the way for a greener and more resilient future. The proactive adoption of biochar not only represents a forward-thinking approach, but also signifies a commitment to addressing the pressing challenges posed by climate change.

Through strategic decision-making informed by LCAs, stakeholders can actively combat climate change by leveraging the carbon sequestration capabilities of biochar, contributing to the reduction of atmospheric greenhouse gas levels. Simultaneously, the integration of biochar into agricultural systems holds the promise of enhancing soil fertility, thereby bolstering agricultural productivity and promoting sustainable land management practices.

Furthermore, the adoption of biochar aligns with the broader objectives of promoting sustainable agriculture and mitigating environmental impacts. By mitigating the release of harmful substances and pollutants into the environment, biochar emerges as a key player in reducing the ecological footprint associated with traditional waste disposal methods.

The comprehensive exploration and utilization of biochar not only signifies a technological leap forward but also embodies a commitment to fostering a harmonious relationship between human activities and the environment. It is through such conscientious decision-making, guided by scientific assessments and a multifaceted perspective that we can usher in a transformative era of sustainable practices, resilient ecosystems, and effective climate change mitigation.

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