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Life Cycle Assessment of Biochar from Residual Lignocellulosic Biomass Using Kon-Tiki Kilns: Applications in Soil Amendment and Wastewater Filtration

Roxanna Pamela Ramírez López, Diana Cabañas Vargas *, Erick Alberto Aguilera-Cauich and Julio César Sacramento Rivero *

Faculty of Chemical Engineering, Universidad Autonoma de Yucatan, Periférico Norte Km. 33.5, Tablaje Catastral 13615, Chuburna de Hidalgo Inn, Merida 97302, Yucatan, Mexico; erick.aguilera@correo.uady.mx (E.A.A.-C.)
* Correspondence: cvargas@correo.uady.mx (D.C.V.); julio.sacramento@correo.uady.mx (J.C.S.R.)

Abstract: Producing biochar from residual biomass is an opportunity for health, environmental, and economic benefits to farmers in small traditional parcels, which are widespread in Latin America. This study presents a life cycle assessment of biochar in two circular economy scenarios: soil amendment and wastewater filtration. Seven mid-point environmental impact categories were assessed using the CML-IA method: acidification (AP), abiotic depletion (ADP), fossil fuels depletion (ADP-FF), eutrophication (EP), global warming (GWP), human toxicity (HTP), and smog formation (POCP). The soil amendment scenario showed lower impacts per tonne of biochar in all categories, especially for GWP (−801.3 kg CO_2eq) and ADP-FF (−374.3 MJ), compared to the filtration scenario (−123.54 kg CO_2eq and 827.85 MJ). Negative GWP values reflect reduced emissions from avoided fertilizers and carbon sequestration. However, POCP and HTP increased due to air emissions (CH_4, NOx, NMVOC, and PM_{10}) from the kiln. In both scenarios, biochar production contributed to 40–90% of the total impacts. Indirect emissions from electricity used for water pumping were identified as a hotspot in the filtration scenario.

Keywords: carbon sequestration; circular economy; wastewater filtration; biomass valorization

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1. Introduction

Biochar (BC) is a carbon-rich material produced through the pyrolysis of biomass. Pyrolysis is the thermochemical decomposition of biomass in low- or no oxygen environments between 150 °C and 950 °C. The resulting material has high porosity and surface area, with various potential uses [1]. BC has been primarily studied for its uses in soil amendment [2–4], pollutant adsorption [2,5,6], and for atmospheric carbon sequestration.

In agricultural systems, BC improves soil aeration, may increase crop yields, and reduces fertilizer and water requirements due to its retention capacity of nutrients and water, as well as its synergistic effect with soil microbial activity [7–9]. However, quantitative results are mixed. For instance, one study [10] reported a 10–29% increase in corn yield in tropical clay ferralsols in Australia with different BC application rates, while another [11] found no significant yield differences in temperate climate despite improved nitrogen retention. Specialized reviews [12] agree on the benefits of BC in soil but emphasize the need for case-by-case assessments considering soil type, crop, and climate [13].

Due to its low cost and ease of production, BC is also a good material for tertiary wastewater treatment and as a filter media [14]. Its high surface area and water retention capabilities make it effective in removing organic and inorganic pollutants from water [15]. Biochar has comparable adsorption efficiencies to membrane capacitive deionization for the removal of fluoride and chromium from water [5]. Additionally, BC has demonstrated removal efficiencies of over 50% for total suspended solids (TSSs), heavy metals, nitrates, and phosphates, as well as about 25% for heavy metals from urban wastewater [16].

While BC in soil is intrinsically good for long-term carbon sequestration, its production can emit greenhouse gases (GHGs), criteria contaminants, polycyclic aromatic hydrocarbons (PAHs), and other contaminants. These emissions vary greatly depending on biomass composition, technology, and operating conditions, underscoring the need for life cycle assessments (LCAs) to quantify environmental trade-offs [17,18]. LCA has been applied to biochar systems in various regions [4,19], revealing the importance of region-specific evaluations to better understand the environmental impacts and benefits [20].

LCA has been used to evaluate the BC's environmental impacts as a soil amendment [4]. However, variability in biomass sources (e.g., crop residues, sewage sludge, and urban solid waste), transformation technologies (slow or fast pyrolysis, gasification, and auger reactors), and impact assessment methods (e.g., CML-IA, ReCiPe, and IPCC) leads to inconsistent or non-comparable results. Despite this, a common conclusion is that BC application has several environmental benefits, in particular, a low global warming potential (GWP). Table 1 shows a summary of LCAs that used comparable impact assessment methods, including the categories acidification potential (AP), eutrophication potential (EP), photochemical oxidants creation potential (POCP), and human toxicity potential (HTP).

Table 1. Examples of cradle-to-grave LCA results for 1 t of biochar applied in agricultural systems.

Reference/Method	AP (kg SO_{2eq})	EP (kg $PO_4{}^{3-}{}_{eq}$)	GWP (kg CO_{2eq})	POCP (kg C_2H_{4eq})	HTP (kg 1,4-DB_{eq})
[21]/CML-IA	0.82	0.29	−499.4	n.r.	n.r.
[22]/CML-IA	0.89	2.66	−2089	−0.03	97.42
[19]/ReCiPe	n.r.	−0.004	−2736	n.r.	−4.7

n.r. = not reported.

A less studied system is water filtration using BC, for which LCA studies are scarce. Some studies suggest that the GWP of activated carbon for tertiary treatment of wastewater is lower when produced from woody BC instead of coal [23]. Quispe et al. [24] reviewed BC filters for graywater reuse, reporting 99% removal efficiencies, depending on the filtering method and reuse strategy. Two LCAs found that the main environmental benefits of using BC-based activated carbon instead of coal-based activated carbon were in GWP (8.6 against 18.3 kg CO_2eq/kg) [23], while its main impacts were on EP and carcinogenic HTP due to BC production emissions and electricity use [25]. Another LCA study [26] analyzed BC filters for wastewater from oil sands in Alberta, Canada, reporting a GWP of 80 kg CO_2eq/m^3, which includes carbon credits from the coproducts, syngas and bio-oil. No LCA studies have been conducted on BC for pig farm wastewater, which is the focus of this research.

The Context of This Research

The state of Yucatan, in southeastern Mexico, lies on a karstic plateau dominated by leptosols, shallow soils with high rock content that are permeable but have limited agricultural potential. The soil's permeability also makes the region's underground aquifer, its only freshwater source, vulnerable to pollution [27,28]. Nevertheless, agriculture remains a key economic activity, covering 20% of the territory, although 55% of that territory suffers from chemical degradation and 19% suffers from physical degradation due to intensive farming practices, leading to soil compaction and reduced fertility [29].

In Yucatan, traditional farming practices, such as *milpa* (a long-fallow system of intercropping maize, beans, squash, and other crops), are widespread and crucial for food security in rural areas. This system is typical across southern Mexico and Central America. According to official data [30], around 31,000 t of residual biomass are produced annually in Yucatan, most of which is burned in open fields, leading to health impacts from particulate and volatile organic compound emissions. In turn, this biomass could be used to produce BC, offering an alternative solution with environmental benefits. The Kon Tiki open-flame pyrolizer is an affordable, patent-free device suitable for small-scale BC production. Operating at 650–700 °C, it can produce 1 m^3 of BC in about eight hours using biomass as fuel and water or soil for quenching [31]. This method also generates fewer emissions compared to traditional charcoal kilns due to better combustion and heat retention [32].

This study aims to quantify the environmental trade-offs of BC production in Kon Tiki kilns using residual biomass from small-scale *milpa* plots. The focus of this study is on two applications: soil amendment and filtration of treated wastewater from pig farms. Both systems were assessed using the mid-point environmental-impact categories, using mostly primary data gathered from the study region.

2. Results and Discussion

2.1. Biochar Production, Characterization, and Emissions

Table 2 compares the measured properties of the BC produced in this study with values from other studies, as well as with the EBC, the IBI, and the Mexican standards. Novak et al. [33] reported on the properties of BC made from pine biomass gasification, while Flesch et al. [34] studied BC made from urban waste biomass produced in a Kon Tiki kiln, a system very similar to the one used in this work. The BC produced here meets all IBI parameters for use in soil and shows general agreement with most property values in the other two studies. Metals such as As, Ca, Cd, Pb, Mg, Zn, Na, and K were found in comparable concentrations to those found in Flesch et al. [34], although some expected variations were observed due to differences in biomass sources.

The specific surface area (SSA) was 258 m^2/g, which is higher than that of biochars derived from pig and cow manure (2–15 m^2/g), straw, and bark, but lower than biochars from high lignin biomass, such as bamboo, soybean stover, and cottonseed hull (300–470 m^2/g) [35]. It is known that in BCs, the larger the pore sizes, the larger the BET surface area. A large number of micropores is linked to a small surface area [36]. In general, BCs from woody biomass (with elevated lignin content) show larger mesopore formation than other common agricultural biowaste, hence a larger BET surface area.

The produced BC also complied with the Mexican normative for biosolids for soil amendment [37], although it is recognized that these criteria are less stringent and specialized than the IBI or EBC standards. Hence, some parameters of concern are not included such as electric conductivity, polyaromatic hydrocarbons (PAHs), and some heavy metals that have been identified as a potential toxicity factors for several organisms [18].

Measured gas concentrations of CO, O_2, CO_2, and NO_x were 751.4 ppm_V, 8.61%, 156.85 ppm_V, and 15.25% ppm_V, respectively; SO_2 was not detected. With these results, the emission factors into the air were calculated using a carbon balance method, as explained in Sparrevik et al. [38], obtaining 6001.9 kg CO_2, 15.72 kg CO, and 5.39 kg NO_x per tonne of BC. Since these emission factors matched reasonably well with those reported by Cornelissen et al. [39], the emission factors of unmeasured gaseous emissions (6 kg NMVOC, 57 kg CH_4, and 15.4 kg PM_{10}) were taken directly from the latter reference.

Table 3 shows the metal content in water before (well water) and after (quenching water) the biochar quenching process. The final column presents the estimated amount of metals desorbed from the biochar into the quenching water before ultimately being discharged into the groundwater. Most metals show negative net emissions to groundwater, indicating that they are being removed from well water. However, there is no published evidence confirming that these metals will remain adsorbed in the BC over the long term. Therefore, it was assumed that they would eventually be released into the soil. Given the karstic nature of the soil in the study area, these metals are likely to return to groundwater over time. Hence, the only actual emissions into the water are those metals that were originally in the biomass that desorbed into the quenching water, such as Cu, K, Zn, and P.

Table 2. Biochar properties compared to international standards and other studies.

Parameter	This Study *	Flesch et al. [34]	Novak et al. [33]	EBC Standard [40]	IBI Standard [41]	Mexican Standard [37]
Carbon (%)	77.58 (1.55)	80.4	88.5	>50	n.a.	n.a.
Nitrogen (%)	0.60 (0.03)	0.79	0.49	Declare	n.a.	n.a.
Hydrogen (%)	1.53 (0.00)	0.87	1.64	Declare	n.a.	n.a.
Sulfur (%)	0.07 (0.01)	n.r.	0.011	Declare	n.a.	n.a.
Moisture (%)	23.17 (4.03)	n.r.	n.r.	Declare	Declare	n.a.
Ash (%)	25.46 (2.11)	17.7	3.46	Declare	Declare	n.a.
Volatile organic matter (%)	22.47 (1.22)	n.r.	10.8	Declare	Declare	n.a.
pH	9.54 (0.10)	8.5	7.8	Declare	Declare	n.a.
Electrical conductivity (µS)	485 (77)	617	n.r.	Declare	Declare	n.a
Average pore diameter (nm)	2.13	n.r.	n.r.	n.a.	Declare	n.a.
Specific superficial area (m^2/g)	258	280	n.r.	Declare	Declare	n.a.
Water holding capacity (%)	219.5 (16.4)	149.1	n.r.	Declare	n.r.	n.a.
As (mg/kg)	13.25 (1.06)	13.25 (1.06)	<0.8	13	13	13–300
Ca (g/kg)	35.63 (3.34)	51	n.r.	n.a.	Declare	n.a.
Cd (mg/kg)	n.d.	<0.2	n.r.	1.5	1.4–39	39
Co (mg/kg)	n.d.	n.r.	n.r.	n.a.	34–100	n.a.
Cr (mg/kg)	0.75 (0.35)	<1	n.r.	90	93–1200	1200
Cu (mg/kg)	8.25 (1.06)	15	n.r.	100	143–6000	1500
K (mg/kg)	3487 (502)	9800	n.r.	n.a.	Declare	n.a.
Mg (mg/kg)	988 (131)	2500	n.r.	n.a.	Declare	n.a.
Na (mg/kg)	417.5 (34.6)	910	n.r.	n.a.	Declare	n.a.
Ni (mg/kg)	1.25 (0.35)	<1	n.r.	50	47–420	420
Pb (mg/kg)	29.5 (7.8)	<2	n.r.	120	121–300	300
Se (mg/kg)	189.5 (17.7)	n.r.	n.r.	n.a.	2–200	n.a.
Zn (mg/kg)	8.5 (2.1)	21	n.r.	400	416–7400	2800
Total P (g/kg)	11.7 (0.21)	n.r.	n.r.	Declare	Declare	n.a.
PAH ** (mg/kg)	n.r.	5.3	n.r	12	6–300	n.a
Dioxins/furans (ng/kg)	n.r.	n.r	n.r.	20	17	n.a.
Polychlorinated biphenyls (PCBs) (mg/kg)	n.r.	n.r.	n.r	0.2	0.2–1	n.a.

n.a. = not applicable; n.r. = not reported; n.d. = not detected; Declare = the standard does not set a limit but requires it to be reported; * = average (standard deviation); ** = sum 16 US-EPA.

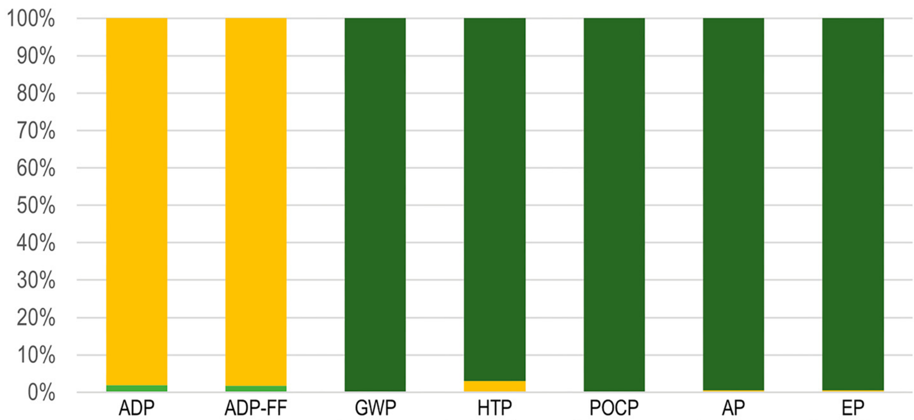
Table 3. Total phosphorous and elemental content in well and quenching water.

Element (Wavelength in nm)	Quenching Water [a] (mg/L)	Well Water [b] (mg/L)	Net elemental Emission [c] (mg)
As (193.695)	0.04	0.18	−37.39
Ba (455.403)	0.03	0.06	−10.74
Ca (430.253)	3.96	98.18	−22,240
Cd (226.502)	0.00	0.33	−76.13
Co (340.512)	n.d.	n.d.	n.d.
Cr (425.433)	n.d.	n.d.	n.d.
Cu (324.754)	0.01	0	<u>1.04</u>
Fe (371.993)	0.29	0.19	−13.82
K (766.491)	12.2	4.62	<u>193.8</u>
Mg (279.553)	0	13.24	−3054
Mn (403.076)	0	0	0.00
Na (588.995)	89.6	76	−8259
Ni (361.939)	n.d.	n.d.	n.d.
Pb (368.346)	0.59	0.29	−5.84
Se (196.026)	1.5	2.86	−504.6
Zn (481.053)	2.86	0.14	<u>263.7</u>
Total P	0.35	n.d.	<u>35.8</u>

[a] Quenching water amount = 102.5 L; [b] well water amount = 230 L; [c] = calculated from a mass balance. A positive value indicated that the element is desorbed to the quenching water, resulting in a net positive emission. These values are underlined. n.d. = not detected.

2.2. Biochar Production

Figure 1 shows the percentual contributions of inventory flows to the environmental impact categories. The table just below the x-axis includes the absolute values of the category indicators relative to 1 t of BC. Inventory flows are grouped into four categories: (1) pyrolysis air emissions (PAEs), which are the direct emissions from the Kon Tiki kiln; (2) pyrolysis water emissions (PWEs), which are the direct emissions from using quenching water to stop pyrolysis (see Section 3.1 for the operation description); (3) indirect emissions from using electricity for water pumping, and (4) indirect emissions from polypropylene (PP) bag production. The PAE flows contribute up to 95% of impacts in all categories except for the ADP and ADP-FF, where the PP bag production dominates. The PP input is often overlooked in LCAs of biochar, leading to a large underestimation of the impacts in these two categories. The effects of electricity for water pumping and the metals content in quenching water (PWE) are negligible.



	ADP g Sb eq	ADP-FF MJ	GWP kg CO_2 eq	HTP kg1,4-DB eq	POCP kg C_2H_4eq	AP kg SO_2 eq	EP kg PO_4^{3-} eq
PAE	0	0	1596	19.34	766.44	2695	700.81
PP bags	4.23	101	3.59	0.56	0.669	12.44	3.53
PWE	0	0	0	0	0	0	0.1096
Electricity	0.084	1.796	0.134	0.033	0.022	0.564	0.219
Total	4.31	102.79	1599.7	19.94	767.13	2708	704.67

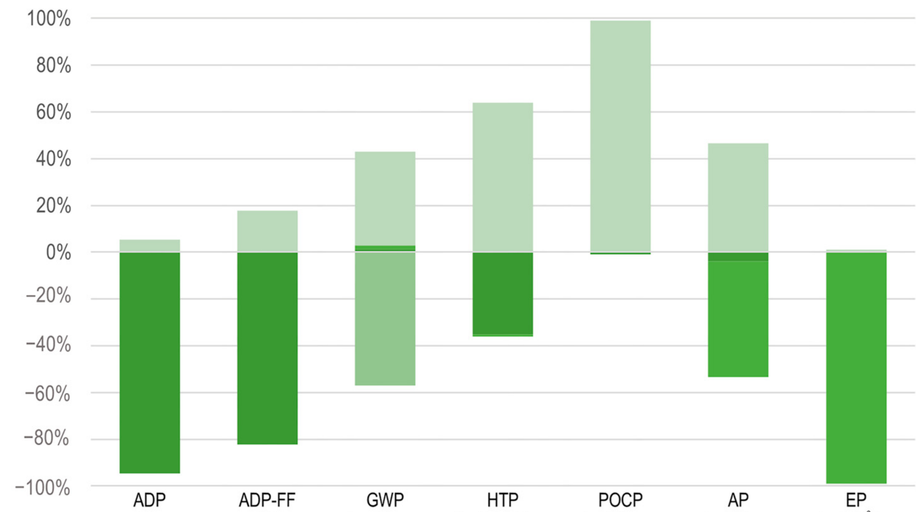
Figure 1. Process contributions to mid-point impact categories. Abbreviations are as follows: abiotic depletion (ADP), fossil fuels depletion (ADP-FF), global warming (GWP), human toxicity (HTP), photooxidants creation (POCP), acidification (AP), and eutrophication (EP) potentials.

The GWP (1599.7 kg CO_{2eq}/t) is largely due to biogenic methane emissions from incomplete combustion in the Kon Tiki kiln's top layer [42]. Other gases, particulates, and products of incomplete combustion contribute to impacts on HTP, POCP, AP, and EP. Although NMVOC flows were included in the inventory, the CML-IA methodology lacks characterization factors for them, so their impact was not accounted for in these results. Identifying specific NMVOC species, which was not in the scope of this work, is crucial to understanding their effects on the POCP. Uncertainty in PAE flows was flagged for sensitivity analysis regarding POCP.

2.3. Biochar as a Soil Amendment

Figure 2 shows the contributions of the life cycle stages to the category indicators in the soil amendment application. Positive emissions come from BC production, while savings come from the use stage, that is, applying BC to soil. Negative contributions in the use stage mean net environmental benefits compared to traditional maize cultivation (no BC application and full fertilization). These savings were grouped into three processes: (1) Emissions abatement (EA): physical reduction in emissions caused by the interaction of

BC with fertilizers and microorganisms in soil, including abated N_2O emissions, reduced NO_3^- leaching, and atmospheric carbon capture as fixed-C; (2) Avoided fertilizer emissions (AFEs): avoided emissions by using less mineral fertilizer, relative to the normal fertilization rate in the region of study; and (3) Avoided background-processes Emissions (ABEs): indirect emissions saved by reducing mineral fertilizer production.



	ADP g Sb eq	ADP-FF MJ	GWP kg CO_2 eq	HTP kg 1,4-DB eq	POCP kg C_2H_4 eq	AP kg SO_2 eq	EP kg PO_4^{3-} eq
BC production	0.004	102.8	1599.7	19.94	0.77	2.71	0.7
EA	0	0	−2284.7	0	0	0	−0.06
AFE	0	0	62.8	−0.22	0	−2.88	−70
ABE	−0.07	−477	53.7	−10.98	−0.007	−0.22	−0.06
Total	−0.06	−374.3	−801.4	8.74	0.76	−0.22	−0.12

Figure 2. Process contributions to the mid-point impact categories—soil amendment scenario (per tonne of BC). Abbreviations are as follows: abiotic depletion (ADP), fossil fuels depletion (ADP-FF), global warming (GWP), human toxicity (HTP), photooxidants creation (POCP), acidification (AP), and eutrophication (EP) potentials.

The production of mineral fertilizers (urea and DAP) is highly fossil-energy intensive. Hence, avoiding fertilizer production (APE) significantly reduces impacts in ADP, ADP-FF, and HTP, due to savings in mining and fossil fuel combustion. These savings lead to net negative impacts in ADP, ADP-FF, GWP, AP, and EP categories. GWP savings are driven by carbon sequestration in BC, and marginally, from the avoided N_2O emissions (EA), while lower N-fertilizer use (AFE) reduces AP and EP. On the other hand, BC production emissions into the air outweigh the benefits of using BC in soil in the POCP category. These results show that the assumption of fertilizer reduction per tonne of BC will have a large impact on many category indicators, and therefore, it must be included in the sensitivity analysis.

The GWP for both systems is dominated by carbon sequestration in BC, which is independent of the LCA assumptions but depends on BC's fixed-C content and application rate. With fixed-C content between 50 and 90%, carbon sequestration ranges from 1.8 to 3.3 t CO_{2eq}/t BC. With an application rate between 10 and 50 t/ha, this translates to 18–165 t CO_{2eq}/ha. This study estimates carbon sequestration at 2.26 t CO_{2eq}/t BC (33.8 t CO_{2eq}/ha). After accounting for pyrolysis emissions (1.6 t CO_{2eq}/t), the net GWP is −0.66 t CO_{2eq}/t, excluding additional savings from the use stage.

The GWP can vary greatly depending on LCA assumptions, such as product allocation or system expansion. For example, Rajabi Hamedani et al. [22] credited displacement of grid electricity and natural gas to bio-oil and syngas, which are coproducts in their BC system, yielding a GWP of −2.1 t CO_{2eq}/t. When BC is considered a coproduct of a gasification process [43], GWP was −1.5 t CO_2eq/t, but when using coproduct allocation between syngas for energy and heat, the GWP reduces to −8.3 t CO_{2eq}/t. These differences reflect the effect of LCA methodological choices rather than greater carbon sequestration potentials of the studied technologies. Another important conclusion from these works is that, irrespectively of the final GWP values, using residual biomass for BC soil amendment always results in the mitigation of impacts.

The abovementioned result explains the large differences between the impact factors between other works and those reported here, where air emissions from the Kon Tiki kiln are included, and there is no displacement of electricity or fossil fuels (see Table 4 and Figure 2). Also, using the pyrolysis residual heat as useful energy was not considered in this work either, as this is not feasible in the context of this study (device type and BC production in traditional small parcels). Even when the estimated benefits are smaller in this work's results, the simplicity of the system and its functionality in a rural context make it an option with potential environmental benefits in many categories (based on the negative impact factors), on top of the direct economic benefits for the small parcel's owners.

Table 4. Variations in the category indicators due to LCA assumptions in the soil amendment scenario (per tonne of BC).

Impact Category (Units)	This Study	[22]	[43]	[19]
ADP (mg Sb_{eq})	−60	n.r.	−280	n.r.
ADP-FF (MJ)	−374.3	−16,830	−90,758	n.r.
GWP (kg CO_{2eq})	−801.3	−2063	−8267	−2736
HTP (kg 1,4-DB_{eq})	8.74	n.r.	−1109	−4.7
POCP (kg C_2H_{4eq})	0.76	0.01	−0.51	n.r.
AP (kg SO_{2eq})	−0.40	0.91	−28.37	n.r.
EP (g ${PO_4}^{3-}{}_{eq}$)	−120	580	−7140	−1.23

2.4. Biochar as a Water Filter

Figure 3 illustrates the category indicators and contributions of life cycle stages. Unit processes in the usage stage are grouped into the following: (1) BC transportation from small parcels to pig farms using gasoline trucks; (2) water filtration, including BC rinsing and washing, and wastewater pumping across the filter; and (3) carbon storage, referring to the fixed-C in the BC. The BC production stage is the main contributor (65–95%) to GWP, POCP, AP, and EP due to direct air emissions from the Kon Tiki kiln. The net GWP, dominated by carbon sequestration, results in −123.5 kg CO_{2eq}/m^3 or −444.7 kg CO_{2eq}/t. ADP, ADP-FF, and HTP are primarily caused by the filtration stage, mainly due to grid electricity use for water pumping. Given the large contribution and the estimation of water flow under lab conditions, electricity demand was flagged as a key variable in the sensitivity analysis.

BC transportation significantly contributes only to the POCP, AP, EP, and GWP categories. In this work, the average transportation distance is 34 km, a fair estimation of the distance between small parcels and pig farms in Yucatan. Under this assumption, transportation always contributes < 10%.

LCA studies on wastewater filtration using raw BC are scarce. Moreira et al. [44] reviewed LCAs of BC as a substitute for activated carbon. The best results were for poplar BC, with a GWP of −3890 kg CO_{2eq}/t BC, where pyrolysis accounted for ~80% of the positive impact. Avoiding the use of fossil heat and charcoal led to GWP savings and reduced EP in 1.11 kg ${PO_4}^{3-}{}_{eq}$. These scenarios also include the stages of transportation, chemical usage, and biomass cultivation, though the pyrolysis stage was the main contributor. The GWP savings were larger in their study than in this study due to credits accounted for displacing activated carbon [44].

In contrast, another study [26] focused on GWP in filtration systems very different from WWTP effluent. Filtration of oil sands wastewater in Canada resulted in a GWP of 80 kg CO_{2eq}/m^3, including credits for by-products (syngas and bio-oil), but involved many energy-intensive stages and did not account for BC carbon sequestration.

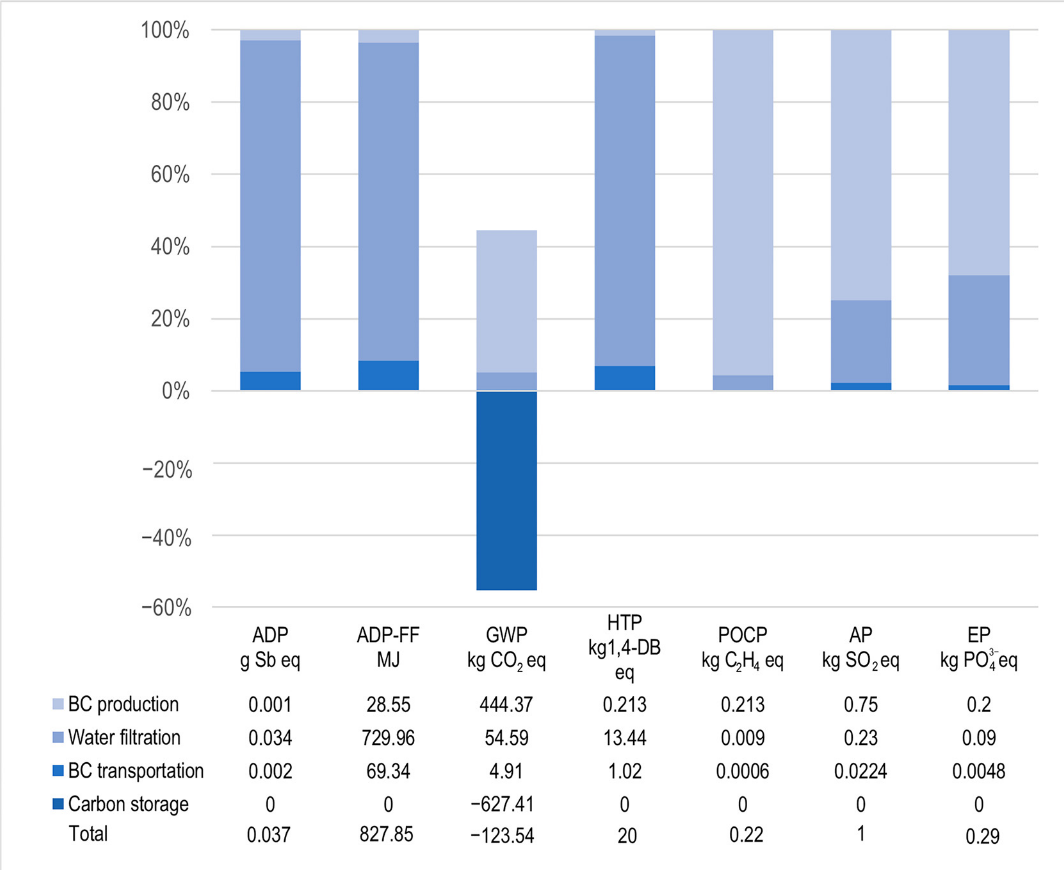


Figure 3. Process contributions to mid-point impact categories—water filter scenario (per cubic meter of filtered water). Abbreviatons are as follows: abiotic depletion (ADP), fossil fuels depletion (ADP-FF), global warming (GWP), human toxicity (HTP), photooxidants creation (POCP), acidification (AP), and eutrophication (EP) potentials.

2.5. Impact Factors of Both Biochar Applications

Table 5 is a summary of the results of both scenarios, reporting the category indicators referenced to 1 t of BC. These values can be used in case a decision must be made in terms of the most environmentally beneficial use for the produced BC. While the impact factors are lower in the soil amendment system, it should be clear that in several categories, these values are highly influenced by credited savings due to fertilizer displacement and field emissions that are dependent on the cultivated crop. Those issues are not present in the wastewater filtering system. To further understand the influence of these methodological assumptions, a sensitivity analysis is presented in the next section.

Table 5. Category indicators of the two BC application scenarios (per tonne of BC).

Potential Impact Category	Soil Amendment	Wastewater Filtering
ADP (g Sbeq)	−0.064	0.132
ADP-FF (MJ)	−374.3	2980.26
GWP (kg CO_{2eq})	−801.3	−444.72
HTP (kg 1,4-DBeq)	8.74	72.01
POCP (kg C_2H_{4eq})	0.76	0.80
AP (kg SO_{2eq})	−0.40	3.61
EP (kg $PO_4{}^{3-}{}_{eq}$)	−0.12	1.04

2.6. Sensitivity Analyses

2.6.1. Soil System

In the soil system, uncertainty analysis focused on emissions related to reduced fertilization, avoided emissions from fertilizer savings (AFE), NO_3^- and N_2O abatement, and Kon Tiki kiln air emissions. The effects of a ±20% change in these inventory flows are presented in Figure 4.

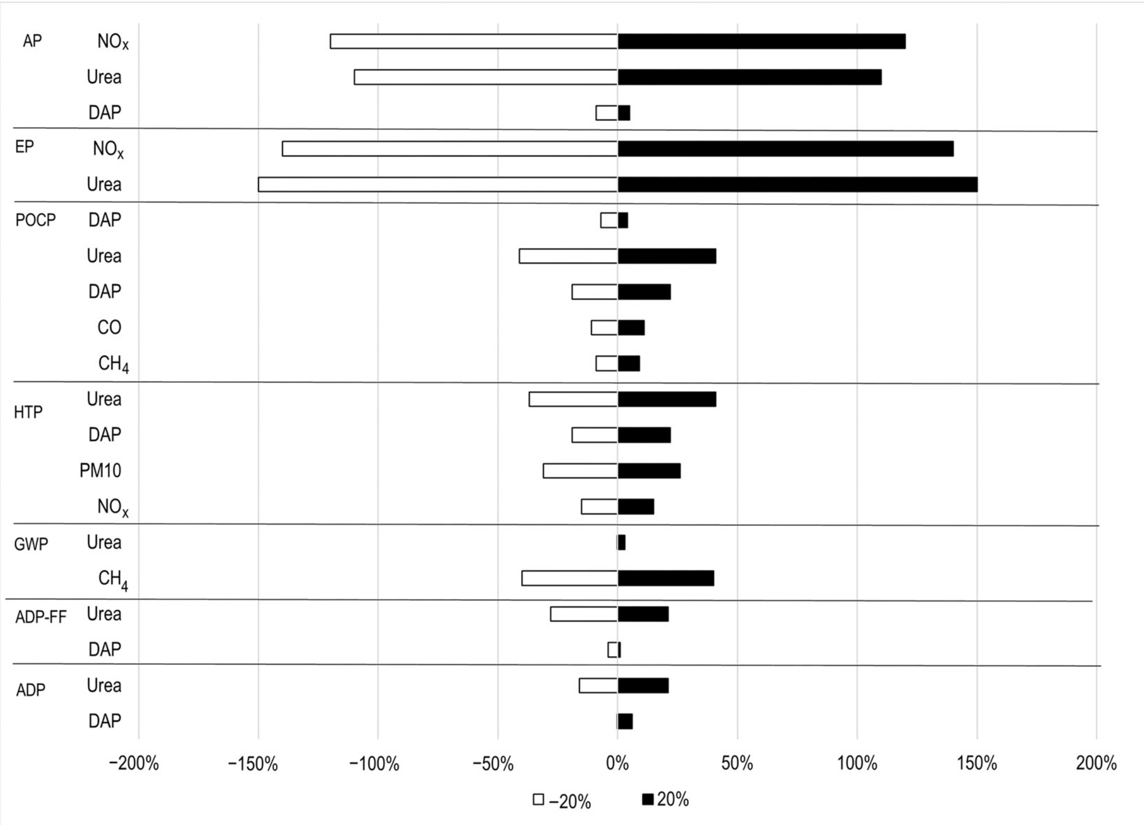


Figure 4. Sensitivity analysis in the soil amendment scenario.

The largest variations are in EP (±121%) and AP (±136%), driven by NOx emissions from the Kon Tiki and urea application (±150% and ±115%, respectively). The LCA model is very sensitive to urea application, which affects POCP (±41%), HTP (±38%), and ADP-FF (±27%). Di-ammonium phosphate (DAP) application affected POCP and HTP by ~50% of the urea impact. Asymmetry in the variations is due to the agronomic model used to estimate the emission fertilizer rates [45].

Methane emissions had a strong impact on GWP (±40%). PM_{10} emissions variations cause significant changes (±32%) in the HTP. This highlights the importance of experimental monitoring of air emissions (especially methane and nitrogen oxides) during pyrolysis for accurate estimations of these category indicators.

2.6.2. Water Filtration System

For the water filtration system, the most uncertain variables were Kon Tiki air emissions and electricity use for pumping. These affect the impact categories plotted in Figures 5 and 6. A ±20% change in air emissions significantly affected EP and AP (~15%) due to NO_x. A ±50% change in electricity use strongly affected GWP (±68%), ADP (±46%), ADP-FF (±44%), and HTP (±34%). This is due to the high fossil fuel contribution in Mexico's electricity grid.

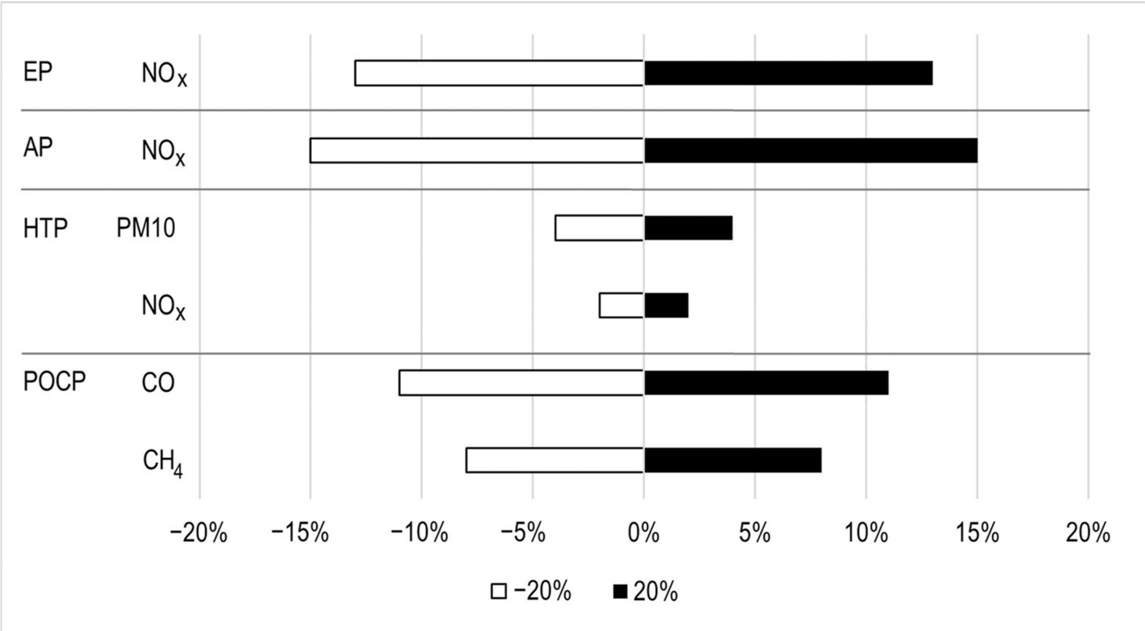


Figure 5. Sensitivity analysis of air emissions on the impacts of wastewater filtration (EP, AP, HTP, and POCP categories).

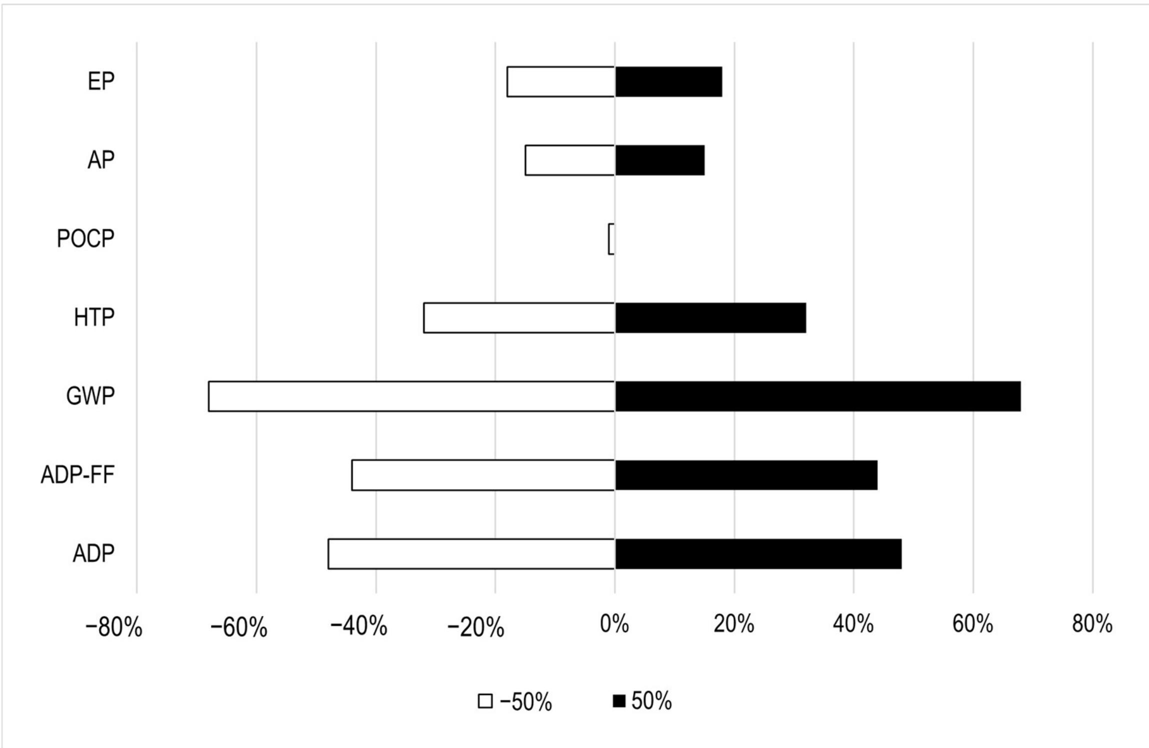


Figure 6. Sensitivity analysis of the electricity usage on the impacts of the wastewater filtration system.

An additional source of uncertainty is the organic matter content in the saturated BC. Although, in this study, it was assumed that it would stay entrained and adsorbed onto the BC, the organic matter would decompose and would add an additional potential for eutrophication. However, considering the effect is expected to be low, it was not considered in this quantitative analysis, recognizing that experimental data are needed to tackle this unknown issue.

3. Materials and Methods

An attributional LCA was performed using the software Simapro v. 9.2 and following the ISO 14040:2006 [46] guidelines. The four phases of the LCA methodology are described below.

3.1. Goal and Scope

The goal of the LCA was to quantify the potential environmental impacts of the production of BC in Kon Tiki kilns from residual biomass originating in small-scale plots and its use in two applications that are relevant in the context of rural areas in Latin America: (i) soil amendment and (ii) treated wastewater filtration. The former is important for residual biomass stewardship, reduction in farm inputs, and carbon sequestration; the latter can aid in reusing wastewater with high turbidity and TSS, such as the effluent of pig-farm wastewater treatment plants (WWTPs), which are ubiquitous in this region.

The two scenarios share the stage of BC production (biomass procurement and pyrolysis). The boundaries of both systems are drawn in Figure 7. The impacts of construction, dismantling, and infrastructure waste management were excluded, as they are expected to be negligible compared to those from the annual operation [42]. The functional unit needed to be defined differently for each scenario, as they served dissimilar functions: (a) As a soil amender, the function of biochar is to improve soil productivity, and this is reflected at the inventory level in avoided fertilizer production and application; the latter also means abating emissions of N_2O and NO_3^- leaching from applied N fertilizer. Given that there is no single variable that reflects all these improvements to soil properties, the functional unit can be expressed as the effect of applying 1 t of BC. A dose of 15 t/ha has been reported to allow for a 50% reduction in fertilization while preserving crop productivity [11]; (b) As a water filtration material, the functional unit is 1 m^3 of filtered water. At some point in the discussions, for comparing the performance of both scenarios, a reference flow of 1 t of BC is used, recognizing that 278.32 kg of biochar can filter 1 m^3 of wastewater down to a final TSS content of 150 g/m^3 (measured under laboratory conditions).

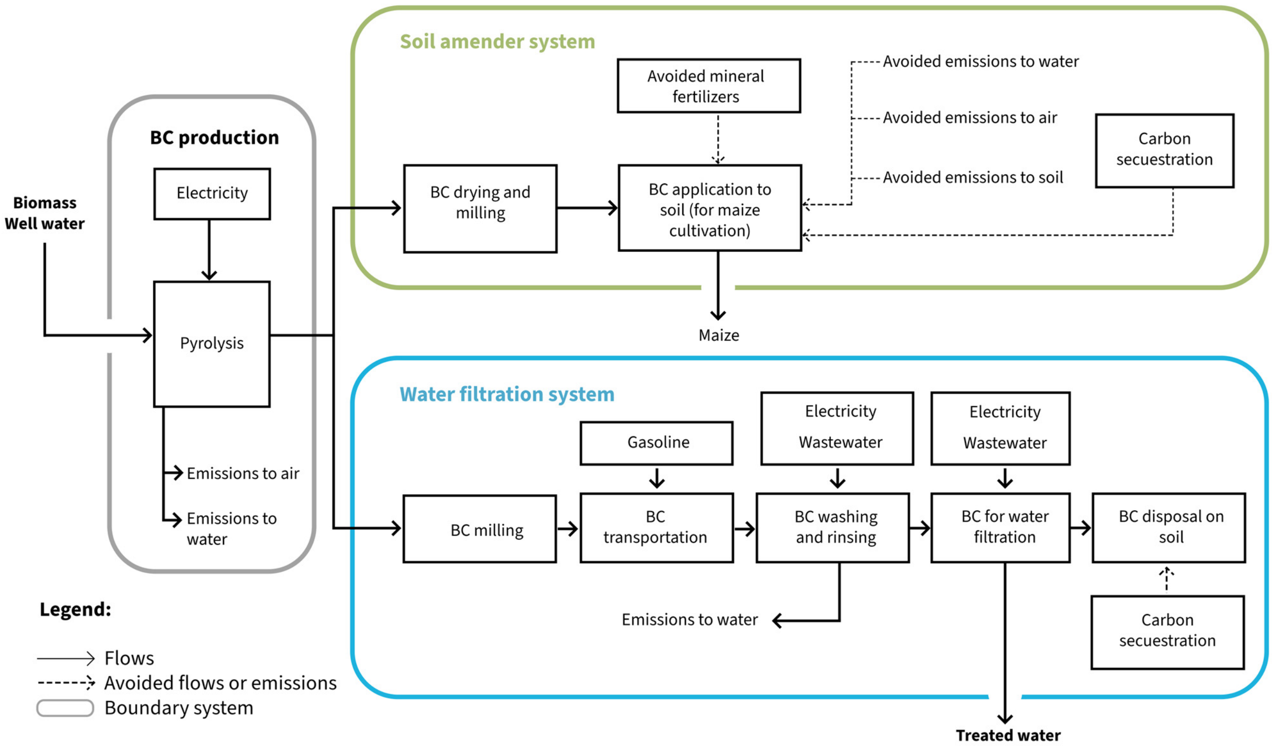


Figure 7. System boundaries of BC production and two scenarios of application. BC = biochar; DAP = di-ammonium phosphate.

The life cycle starts with BC production (Figure 7). In this system, residual biomass from small parcels' maintenance (e.g., plant and tree cuttings and plot cleaning) is manually recollected. Branches with a diameter of less than 2 cm were selected for BC production, while thicker branches may have other uses, such as firewood for cooking. This is a manual operation, and hence, there is no need for fuel or transportation inputs.

Once enough biomass is available on site, it is transformed into BC in Kon Tiki kilns. The detailed process using this equipment is described elsewhere [39]. The operation of the Kon Tiki kiln consists of starting an initial fire inside the conical kiln (Figure 8) and then adding layers of biomass. As the top layers start combusting, they provide heat and consume oxygen from the lower layers, where pyrolysis occurs. Before combustion consumes the top layer, a new layer is added on top. The temperature gradient in the kiln ranges from 600 to 900 °C (measured with an external surface thermometer), and due to the conical shape of the kiln, vapor recirculation occurs at the kiln's mouth, enhancing the combustion of pyrolysis vapors and incomplete combustion products (see Figure 8).

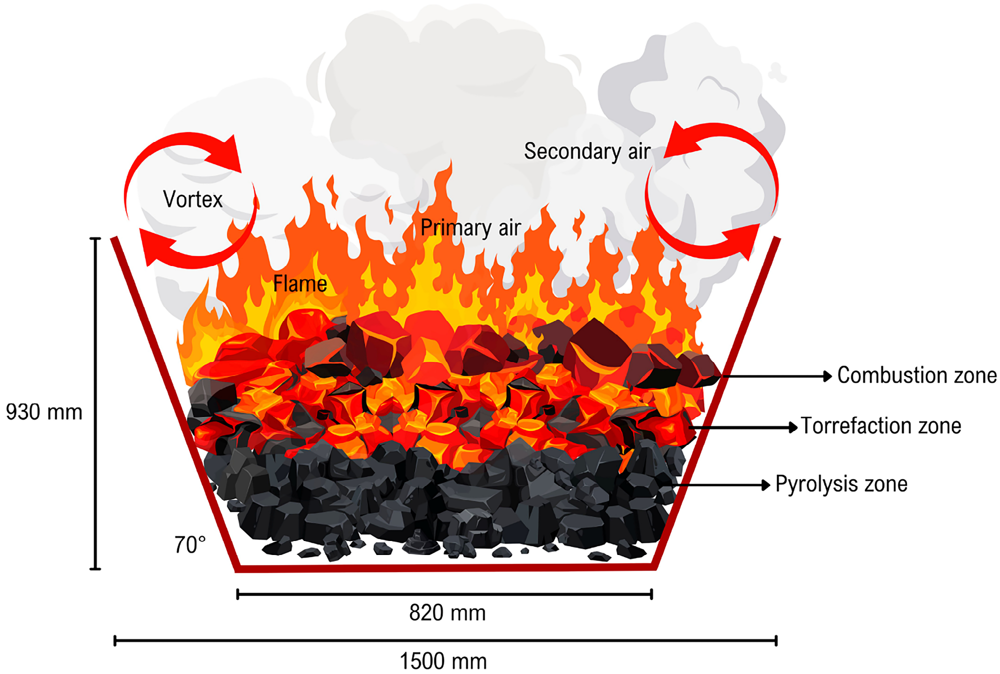


Figure 8. Simplified diagram of the dimensions and operation of a Kon Tiki kiln.

At the end of the process, BC is quenched by pumping well water to fill up the device (approximately 920 L per 500 kg batch). Then, the kiln is drained from the bottom, releasing the water onto the soil. The BC is shoveled into polypropylene (PP) fiber bags (approximately 13.5 kg of BC per bag) and temporarily stored.

When used as soil amender, BC is applied in the same plots where the biomass was collected; hence, no transport is required. In the milpa small parcels in Yucatan, the cultivation of conventional maize is made with no technification (manual plowing and sowing), seasonal irrigation, and application of inorganic fertilizers and pesticides. The BC is unbagged, crushed using a shovel, and mixed with soil at the time of preparing the beds. BC is assumed to stay in the ground for around 1000 years [4], so the fixed carbon in it is effectively sequestered.

Regarding the second application, some pig farms in southwestern Yucatan reuse their wastewater for irrigation or in temperature control systems for the animals. However, the effluent from the wastewater treatment plant (WWTP) may have a high suspended solids content that often blocks the sprayers, thus needing filtering before use. This is where the BC may be used as a filtering matrix. The designed filters consist of vertical PVC columns filled with biochar that has been previously crushed and sized (manually) to an average particle size in the range of 850 µm–4.5 mm. Wastewater is then pumped through the filter continuously. When the BC is saturated with solids, it is discarded on soil or mixed with compost. At this point, no further emissions or positive effects are considered, other than the fixed carbon sequestration.

3.2. Life Cycle Inventory (LCI)

The full inventory data are in Table 6. Most data were gathered from field and laboratory measurements. Background processes (production of fertilizer, fuels, and electricity) were modeled using the Ecoinvent® v.3.6 database. The description of the processes and flows in each stage of the life cycle is detailed below.

Table 6. Life cycle inventory data referenced to 1 t of produced BC.

Concept	Type	Amount	Units	Source
Biochar production in Kon Tiki kiln				
Biochar	Product	1	t	Reference flow
Water from well	Material input	1840	L	Measured
Electricity for water pumping (Mexico mix)	Energy input	0.261	kWh	Measured
CO_2 (biogenic)	Emission to air	6002	kg	Measured
CO (biogenic)	Emission to air	15.7	kg	Measured
NMVOC	Emission to air	6	kg	[39]
CH_4 (biogenic)	Emission to air	57	kg	[39]
PM_{10}	Emission to air	15.4	kg	[39]
NO_X	Emission to air	5.4	kg	Measured
Total P (in quenching water)	Emission to water	0.02	mg	Measured
Zn (in quenching water)	Emission to water	17.4	mg	Measured
Cu (in quenching water)	Emission to water	0.1	mg	Measured
K (in quenching water)	Emission to water	12.1	mg	Measured
Polypropylene (for bags)	Material input	1.26	kg	Interview
Electricity for bag production (Mexico mix)	Energy input	1.38	kWh	Interview
Soil amendment scenario				
N from avoided DAP application	Input	−0.23	kg	[11]
P from avoided DAP application	Input	−0.58	kg	[11]
N from avoided urea application	Input	−4.52	kg	Estimated
C storage in BC, as CO_2	Emission to air	−2258	kg	Estimated
N_2O (abatement)	Emission to air	−98.3	g	[9,47]
N_2O (from avoided fertilizer)	Emission to air	−0.09	kg	[45]
NO_X (from avoided fertilizer)	Emission to air	−0.03	kg	[45]
CO_2 (from avoided fertilizer)	Emission to air	−15.43	kg	[45]
NO_3^- (leaching abatement)	Emission to water	−0.30	kg	[9]
NO_3^- (from avoided fertilizer)	Emission to water	−0.16	kg	[45]
Total P (from avoided fertilizer)	Emission to water	−0.77	µg	[45]
Cd (from avoided fertilizer)	Emission to water	−0.48	µg	[45]
Zn (from avoided fertilizer)	Emission to water	−0.04	µg	[45]
Zn (from avoided fertilizer)	Emission to soil	−0.07	µg	[45]
Pb (from avoided fertilizer)	Emission to soil	−0.05	µg	[45]
Ni (from avoided fertilizer)	Emission to soil	−0.02	µg	[45]
Water filtration scenario				
Biochar transportation	Transport	34	tkm	Estimated
Water from well	Material input	7.18	m^3	Measured
Electricity for water pump (Mexico mix)	Energy input	380.4	kWh	Estimated from pump characteristics (1 hp)
C storage in BC, as CO_2	Emission to air	−2258	kg CO_{2eq}	Estimated
Filtered wastewater	Product	3.59	m^3	Measured

3.2.1. Biomass Procurement

The residual biomass is assumed to have no embedded environmental load or land-use change effects since it would otherwise be treated as waste and left to decompose or burned in open fires to clear space. Recollection, gathering, and selection of biomass were manually made, thus no emissions were considered at this stage.

3.2.2. Biochar Production, Characterization, and Emissions

Emissions to air from the Kon Tiki kiln operation were measured directly from pyrolysis of thin branches of *Lonchocarpus guatemalensis* Benth, obtained from one parcel from the municipal of Mama, in Yucatan. One batch in a 1 m^3 Kon Tiki can produce 500 kg of BC. The observed yield (biomass to BC) was 19% by weight. The gas concentrations of CO, CO_2, NOx, and SO_2 were determined using standard methods (10-USEPA-2008 [48]; 7E-USEPA-2008 [49]; NMX-AA-055-1979 [50]). Gas fractions were converted to emission factors using the calculations described by Sparrevik et al. [38]. The emission factors corresponding to unmeasured gas concentrations (CH_4, NMVOCs, PM_{10}) were taken from reported emission profiles from a Kon Tiki kiln [39]. Polypropylene (PP) fiber bags were used for BC storing and handling. Polypropylene input (0.068 kg per bag) and the electricity required to make the bag (1.093 kWh/kg) were obtained from interviews with a local manufacturer. Each PP bag can be reused four times on average, as observed in the field.

Emissions into the soil from quenching water were also measured directly from the same tests. A water sample was taken before and after quenching to determine metal contents (As, Ca, Cd, Cr, Co, Cu, Pb, Mg, Ni, Se, Zn, and Na), using atomic emission spectroscopy based on the ASTM C1301-95 (2014) standard [51]; total phosphorous was measured using the vanadomolybdate technique (NMX-AA-029-SCFI [52]).

The BC quality as a soil amender was compared against two standards: the European Biochar Certificate (EBC) [40] and the International Biochar Initiative [41]. The total contents of carbon, hydrogen, nitrogen, and sulfur were determined using an elemental analyzer in a He atmosphere [53]; hydrogen potential (pH), electrical conductivity (EC), proximate analysis (moisture, volatile matter, and ash content), and metal content (same tests that was used for quenching water) were determined. The characterization also included total phosphorus following the IBI specifications. Superficial areas and mean pore diameter were determined using BET analysis.

3.2.3. Soil Amendment

The bagged BC is manually crushed and mixed with soil. In this process, there is an associated material loss of around 12.5% in weight, as observed in the field. To estimate the effects of BC on agronomic inputs, baseline data were taken from recommended inputs for the conventional cultivation of maize in the region of study, assuming a dose of 37.8 kg/ha of DAP fertilizer [11] and 295 kg/ha of urea. Furthermore, an application of 15 t/ha of BC should allow for a reduction of 50% of the inorganic fertilization rate [12], with only seasonal rain irrigation.

The emissions to air, soil, and water from fertilization were estimated using the calculator developed by Navarro Pineda et al. [45], which is based on the roundtable on sustainable biomaterials and the models of the Agroscope Reckenholz-Tänikon Research Station [54]. The input parameters for this model calculator were as follows: type of fertilizer: DAP (macronutrients content: 18% N as NH_4 and 46% P_2O_5) and urea (46% N); the application rate of both fertilizers (18.9 kg/ha and 147.5 kg/ha respectably), type of crop (corn), crop yield (4.2 t/ha), annual precipitation (84.2 mm), group of soil (low activity clay), and climatic region (warm temperate, moist).

The abatement of N_2O emissions from soil due to the interaction of added N with biochar and microorganisms was fixed at 54% [47]. This is true for BC application in similar ambient temperature and C/N ratio in the BC. The same applies to the estimation of NO_3^- leaching abatement, which was fixed at 18% [9]. The potential of carbon storage was estimated considering the dry-weight content of C on the BC (77%, as measured in the elemental analysis), then the fraction of fixed C in the BC was assumed to be 80% of the total C [38,55].

3.2.4. Water Filtration

The pig farms are located an average of 34 km from the parcels where the BC is produced (estimated using Google Maps 2023). BC is transported in 3.5–7.5-tonne gasoline trucks. To minimize the release of fine BC particles into the filtered water, the BC is washed and rinsed before being packed into the filters. Laboratory tests determined that BC washing and rinsing required 7.18 L/kg, based on tests conducted in column filters with varying amounts of BC. The electricity consumption for pumping was estimated using the characteristic curve of a 1 hp centrifugal pump.

The best filtration conditions were selected from laboratory tests. The experiment involved vertical down-flow water filtration in columns packed with different amounts of BC, recirculating the water until steady-state conditions were reached. The best results were achieved using 70 cm tall filtration columns filled with 556.65 g of BC, reducing TSS from 0.25 to 0.15 g/L after two filtering cycles. Each filter can treat up to 2 L of wastewater. After the filter is saturated, the BC can be disposed of in forest land, with carbon sequestration estimated similarly to the soil amendment scenario. No additional benefits from soil amendment were included in this system, as evidence suggested that BC from used water filters performs poorly as soil amendment compared to fresh BC [56].

3.3. Impact Assessment

This study was conducted using SimaPro 9.2. and the CML-IA baseline method. The selected mid-point environmental impact categories were as follows: abiotic depletion (ADP), abiotic depletion of fossil fuels (ADP-FF), global warming (GWP), human toxicity (HTP), photochemical oxidants creation (POCP), acidification (AP), and eutrophication (EP) potentials. Due to the limited availability of LCA results for similar systems, this method provided the best option for comparing mid-point results with existing data [21,22].

3.4. Uncertainty Analysis

During the inventory analysis, the flows with the highest uncertainty or weakest statistical representation were chosen for a basic uncertainty analysis. In the absence of probability distributions or experimental values for these variables, an arbitrary fixed variation of 20% was applied to all selected variables. This approach helps us understand what areas deserve further analysis and supports any comparative conclusions drawn.

4. Conclusions

Two potential applications of biochar (BC), produced in Kon Tiki kilns from residual lignocellulosic biomass, were studied to understand their life cycle environmental impacts: BC filters for wastewater and BC for soil amendment. The main differences between both systems lie on the usage stage. Both scenarios provide benefits in the GWP category due to atmospheric carbon sequestration, after applying the BC to the soil.

In the soil amendment scenario, significant environmental savings were observed due to reduced fertilizer use, leading to negative net impacts in several categories, including ADP, ADP-FF, AP, EP, and GWP. In the water filtration scenario, however, most category indicators were positive due to the lack of input or product displacements. Specifically, electricity use for water pumping was a key hotspot for the ADP-FF, GWP, and HTP categories. This study presents the first LCA results of BC used in this filtration application.

Transforming residual biomass into biochar in small-scale, rural settings offers substantial environmental and economic benefits for farmers, particularly through reduced fertilizer use and carbon sequestration. When BC is sold as a water filtration medium for WWTPs in pig farms, the environmental benefits are smaller. Nonetheless, BC provides a feasible option for the revalorization of residual biomass, promoting a circular economy and offering extra economic income for local farmers.

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