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Research Article

Cradle-to-gate analyses of biochar produced from agricultural crop residues by vacuum pyrolysis

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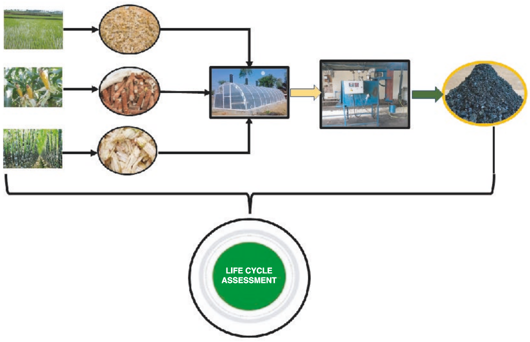
Abstract

Agricultural waste, if not managed efficiently, can pose significant environmental threats. Biochar production, a cost-effective solution, offers a potential to significantly reduce carbon dioxide emissions and thereby combat climate change. However, the environmental impact of this process is not uniform and varies depending on the agricultural residue used. These impacts, spanning the entire lifecycle from cultivation to disposal, underscore the necessity of a thorough assessment before biochar can be widely adopted for practical applications. This study employs a cradle-to-gate approach to evaluate the life cycle assessment (LCAs) of producing biochar from various agro-residues, such as rice husk, sugarcane bagasse (SB), and corn cob (CC). The LCA was conducted using SimaPro software, version 9.5.0.1, and the ReCiPe impact assessment method. The results indicate that CC cultivation has the highest impact across most categories, while rice husks exhibit higher water consumption (2.8×10^3 m^3). Using diesel, electricity, and fertilizers significantly contributes to global warming potential (GWP). SB shows the most negligible impact during biomass cultivation. However, pyrolysis processes exhibit high implications on various indicators. Applying biochar to soil for carbon sequestration and improvement can reduce GWP. Sensitivity analysis demonstrates a notable reduction in GWP and cumulative energy demand, approximately 10%–24% and 4–11 MWh, respectively. Paddy cultivation and rice husk biochar production have a lesser environmental impact. Changing energy sources during biomass growth and biochar production significantly influences environmental factors.

Graphical abstract



Keywords: biochar; life cycle assessment; agriculture residues; pyrolysis; global warming potential

1. Introduction

There has been a surge in biochar manufacturing using waste materials, including tree residues and agricultural and animal waste. This approach addresses waste management by offering a sustainable alternative [1]. In particular, crop wastes represent a potentially significant resource, yet most of these residues are rarely utilized, and disposing of them frequently harms the ecosystem. Large amounts of gaseous and particle pollutants are released into the atmosphere during biomass burning in the field, which is detrimental to the population's health and the climate [2]. Burning rice residues poses a risk to human health because most particulate matter with a diameter of <10 μm (PM10) can quickly enter the lungs and cause cardiac and respiratory issues [3]. It has also been discovered that open-burning rice residues are a major source of polycyclic aromatic hydrocarbons (PAHs), which have noteworthy toxicological characteristics and may be carcinogenic [4]. Therefore, effective waste management strategies must be adopted. Pyrolysis provides an answer for lowering

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air pollution emissions from open burning of biomass, including PM10, PAHs, and sulfur dioxide (SO_2). This has environmental and human health advantages [5].

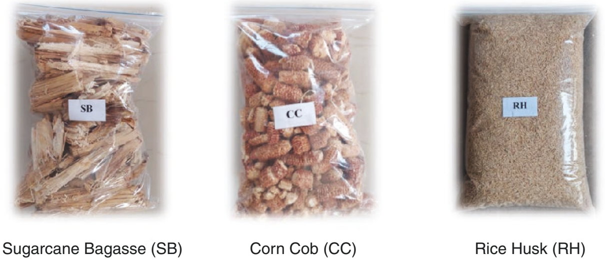
Biochar is a carbon-rich substance created when biomass is subjected to pyrolysis in an environment with restricted oxygen. Applying biochar can promote soil health by improving fertility, reducing pollution, and increasing the population of living organisms. It can also help reduce carbon sequestration and climate change [6]. While biochar may experience some degree of degradation under different field conditions, its capacity for long-term carbon storage is universally acknowledged and indisputable [7]. Hence, biochar technology can enhance the exploitation of sustainable energy sources and the valorization of agricultural residue.

This research focuses on producing biochar from various agricultural residues utilizing a pyrolyzer and the slow pyrolysis technique. Biochar, bio-oil, and syngas production have been proposed as a potential approach to mitigate atmospheric carbon dioxide (CO_2) levels, alleviating global warming in future generations [8]. Nevertheless, research must thoroughly examine the holistic environmental consequences of biochar-based bioenergy generation.

Before commercialization and widespread adoption, biochar applications must unambiguously exhibit environmental advantages [9]. Recently, there has been increasing interest in conducting life cycle assessments (LCAs) for biochar's large, small-scale production. LCA, also called life-cycle analysis or eco-balance, is a standardized methodology (ISO 14040: 2006 series) used to evaluate the environmental consequences linked to every phase of a product's life, from its cradle-grave [8]. Each stage of biochar synthesis has material and energy inputs and outputs that might influence the environment, either directly or indirectly.

The utilization of LCA can also function as a technique for decision-making, aiding policymakers, and practitioners in maximizing the efficiency of biochar-producing systems. Thus, the efforts have been undertaken to comprehend the environmental effects of several process stages, including crop cultivation, harvesting, collecting, transportation, pretreatment, and pyrolysis technology [10]. Hence, determining the LCA of biochar production systems is crucial to mitigating harmful environmental effects and enhancing significant economic advantages. Nevertheless, the specific explanations of LCA, including functional units and system limits, may vary in different projects, making it challenging to compare.

However, some available literature shows the LCA result of biochar production. Still, the comparative result of biochar from 3 feedstocks is necessary to identify the most negligible impact on the environment because the LCA result is susceptible to the type of feedstock material used and process parameters or conditions. Thus, this article compares different biochar production using 3 feedstocks and identifies the more or less impact on the environment using the LCA methodology. Ideal research should encompass all production and consumption phases across the product's life cycle. Hence, the primary objective of this research is to gather and examine background data using conventional techniques and construct the framework in which the LCA of biochar and its co-product can be conducted. The article's main objective is to formulate the life cycle inventory for the selected feedstock using databases to evaluate the environmental impact of the life cycle for possible harm in various impact categories. This study discusses the environmental effects caused by the different biomass cultivation and biochar synthesis processes at the midpoint and endpoint levels. Additionally, cumulative energy demand (CED) and cumulative exergy demand (CExD) are calculated. Furthermore, sensitivity analysis is done by changing the 2 variables and then compared.



Sugarcane Bagasse (SB) Corn Cob (CC) Rice Husk (RH)

Figure 1. The selected agriculture crop residues.

2. Material and methods

2.1 Selection of agriculture crop residues

The 3 agricultural crop residues were selected for biochar production, namely rice husk (RH), sugarcane bagasse (SB), and corn cob (CC), because of their large availability locally. Rice husk was chosen because of the growing concern about the environmental issues of burning in paddy fields. However, it was locally available and purchased from nearby areas to minimize transportation distance. The SB and CC were available locally at the field of experimental farm CTAE, Udaipur. The primary characterization of selected biomass was done to identify the potential of biochar production. Figure 1 displays the biomass chosen in this study. Table 1 shows the characteristics of the selected raw material.

2.2 Equipment for pyrolysis technology

The selected biomass was treated at 500 °C in an inert atmosphere at 2 h residence time for biochar production in the fixed bed slow pyrolyzer. The 500 °C is the most widely used process temperature for biochar production in batch-type processes [11].

Vacuum Pyrolyzer Instruments (VPI), designed by Department of Renewable Energy Engineering, MPUAT, Udaipur, were selected for biochar production. Figure 2 shows a pictorial view of VPI.

2.2.1 *Brief description of VPI*

The biochar production was done using the most advanced technology available in the department. The VPI is the batch type pyrolyzer having processing capability of 1–5 kg of biomass. The VPI system utilized a biomass cartridge, pyrolysis chamber, loading mechanism, condenser, temperature sensor, pressure

Table 1. Characterization of biomass (RH, SB, CC).

Sr. no.	Biomass	Moisture content (%)	Volatile content (%)	Ash content (%)	Fixed carbon (%)
1	Rice husk (RH)	5.3989	61.4008	21.1896	12.0108
2	Sugarcane bagasse (SB)	9.6455	82.9333	1.5408	5.8804
3	Corn cob (CC)	7.0747	78.8778	1.57272	12.4748

gauge, syngas outlet pipe, vacuum pump, and mounting frame. The pyrolysis chamber was heated to the desired temperature using an electric heater while the vacuum pump sustained a vacuum pressure of 15–20 kPa. The emitted vapors underwent additional condensation in a shell and tube condenser and formed liquid oil. The resulting liquid oil was collected and stored in the bio-oil collection tank, as shown in Fig. 2. Bio-oil was extracted using a valve and weighted. The agitator inside the biomass cartridge was manually rotated every 15 min, resulting in consistent distribution of biomass and heat. The temperature fluctuations were measured using thermocouples and displayed on an attached control panel. The biochar was cooled to room temperature within the pyrolysis chamber and weighed separately after unloading. The yield of biochar, bio-oil, and syngas from RH, SB, and CC are tabulated in Table 2. The biochar made from CC, SB, and RH at 500 °C at 10 °C/min heating rate is denoted as a CC 500, SB 500, and RH 500, respectively.

2.3 Life cycle assessment

LCA assesses environmental aspects of a product, process, or service, including goal and scope, life cycle inventory, impact analysis, and improvement analysis. This study employs LCA to evaluate the environmental effects of biochar production from diverse feedstocks using Simapro software (V 9.5.0.1).

2.3.1 *Goal and scope*

The initial step in LCA involves defining the goal and scope. For this particular study, the purpose and scope of the LCA are to evaluate the greenhouse gas emissions and related environmental effects of a biochar-based bioenergy system. The goal and scope involved the system boundary, set of functional units, assumptions, and allocation of this study, described in the subsequent subsection. Quantification of the environmental effects of the biochar production life cycle is done for the following: global warming potential (GWP), stratospheric ozone depletion (SOD), ionizing radiation (IR), ozone formation, human health (OFHH), fine particulate matter formation (FPMF), ozone formation, terrestrial ecosystems (OFTE), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FET), marine ecotoxicity (MET), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), land use (LU), mineral resource scarcity (MRS), fossil resource scarcity (FRS), and water consumption (WC).

Figure 2. The pictorial view of Vacuum Pyrolyzer Instruments.

2.3.1.1 System boundary

A cradle-to-gate impact study is made possible by the system boundaries in this work, which considers the following subsystems: agricultural crop production and raw material separation (Phase 1); pyrolysis of raw material including pretreatment (Phase 2). Figure 3 shows the life cycle investigation's system boundary, represented by solid lines. The components presented in dotted lines are excluded from the scope of this paper. The system boundary, illustrated by the solid line in Fig. 3, encompasses the entire process, from gathering raw materials to producing biochar. This includes several intermediary stages: collection, transportation, storage, processing, and pyrolysis.

2.3.1.2 Functional unit, assumptions, and allocations of study

The unit of measurement is one tonne of biochar made from agricultural waste biomass [12]. This functional unit is the most beneficial since it is primarily responsible for producing biochar.

To prevent duplication in the decision-making process, several assumptions need to be taken into account in the actual approach:

- The location of the pyrolysis plant and biomass cultivation are thought to be the same. Therefore, the transportation of biomass is not considered.
- Variations in the results are possible because the data was gathered from various sources, including databases, specialists, site surveys, and literature.
- In evaluating the biomass production stage, no watering technique other than the natural rainwater method has been considered.
- This study does not include using or disposing of biochar, oil, tar, and gasses.
- The evaluation does not include the equipment used in the pyrolysis system and the purchase or maintenance of agricultural equipment and machinery.
- The labor involved in the operations included in the various stages assessed in this research is not considered.
- Char, tar, gas, and other pyrolysis system outputs were considered system products.

The mass economic allocation method was used to calculate the allocation percentage of each product and co-products for raw biomass extraction and pyrolysis process (Table 3). The economic price of all products was taken after consulting with the

Table 2. The product of Vacuum Pyrolyzer Instruments at 500 °C temperature.

Sr. no.	Biomass	Biochar (%)	Biooil (%)	Syngas (%)
1	CC 500	30.21	38.71	31.10
2	SB 500	34.59	37.42	27.98
3	RH 500	35.82	25.45	38.73

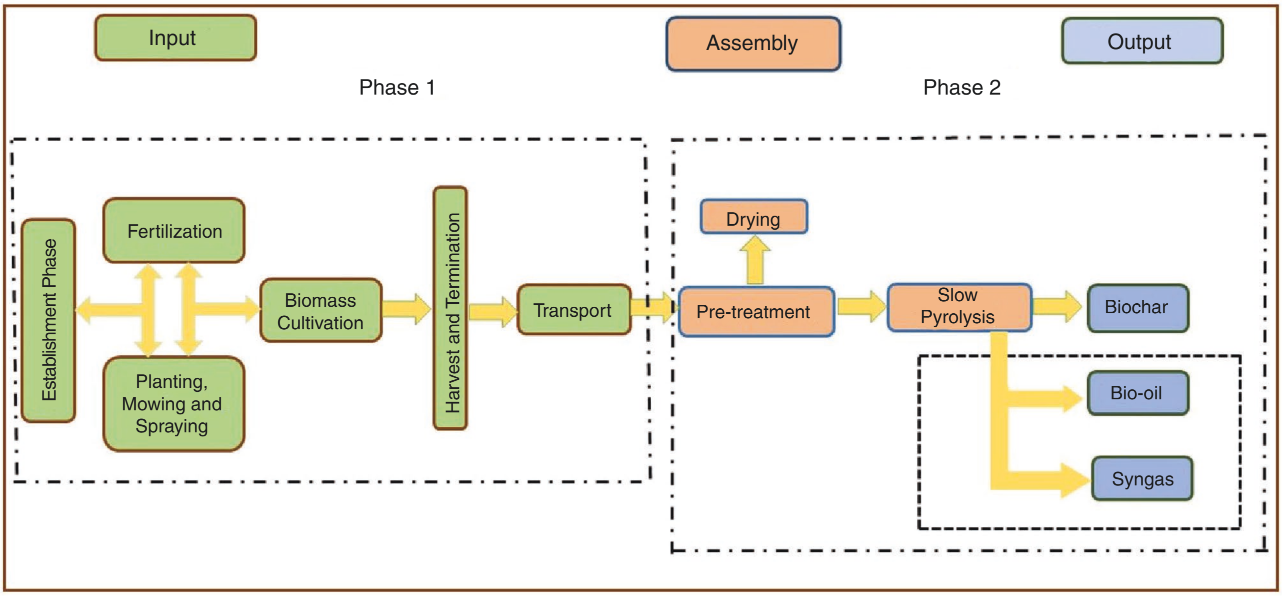


Figure 3. System boundary for life cycle assessment of biochar synthesis using various crop wastes.

industrialist in Udaipur known by (SIYA INSTRUMENTS). These approximate prices may vary depending on the study area, potentially leading to different outcomes.

2.3.2 *Inventory analysis*

The input–output data were acquired from many sources, including experiments, experts, professional communications, literature, the Ecoinvent database, farmers, and subject matter specialists. According to the guidelines set forth by the Intergovernmental Panel on Climate Change for Greenhouse Gas (GHG) inventory related to annual crops, carbon dioxide intake, and emissions from crop development and combustion/pyrolysis were excluded from the inventory. This is because carbon dioxide uptake and return to the atmosphere are assumed to occur within an annual cycle [5].

A material and energy input inventory study, an assessment of air emissions (specifically greenhouse gases), and other environmental considerations were conducted using the SimaPro 9.5.0.1 LCA program, which adheres to ISO standards. This paper utilized inventory data from the built-in databases (Ecoinvent) of SimaPro 9.5.0.1 LCA software and some of the data collected from the literature survey. The data were used for input materials, equipment, processes, and emissions. Tables 4 and 5 indicate the inventory data used for biochar production from agriculture crop residues. The quantities in Table 4 are supported by the literatures and supporting data obtained from literatures are presented in the following paragraph. They have been converted according to the functional unit of the study.

The average maize yield on land is about 3 tons per hectare [13], while the raw material recovery is 47.66% per ton [13, 14]. Twenty-five kilograms of maize seed are required per hectare [15]. The fertilizer requirement per hectare per annum is N-180 kg, P_2O_5-80 kg, K_2O-80 kg, and $ZnSO_4$-25 kg [13]. Approximately 15.6 kg of pesticides and herbicides per annum are also required per hectare. This operation required 196.8 liters of diesel per hectare [15].

The average sugarcane yield on land is about 59.2 tons/hectare [16], while the raw material recovery is 28.0% per ton [17]. The fertilizer requirement per ton of sugarcane per annum is N—2.69 kg, P_2O_5—1.31 kg, and K_2O—0.82 kg. Approximately 0.136 kg of pesticides and herbicides per annum are also required per ton. The 41 kWh of electricity was needed per ton of sugarcane production [18]. Total diesel consumption was 2.8 l per ton of sugarcane production [17]. A significant amount of wastewater was generated during the separation phase, which is excluded from the study. At the same time, 28% bagasse, 10% sugar, and 4.1% molasses were generated [19].

The average rice husk yield on land is about 7 tons per hectare [20], while the raw material recovery is 22.0% per ton of biomass. The fertilizer requirement per hectare per annum is N—45.07 kg, P_2O_5—159.54 kg, and K_2O—86.63 kg. Approximately 13.58 kg of pesticides and herbicides per annum are also required per hectare. 52.8 kWh of electricity is needed to make a 1-ton paddy.

The evaluation study of LCA is divided into two phases:

Phase 1: The cultivation of parent biomass and separation of raw material (Table 4).
Phase 2: biochar production from slow pyrolysis (including pretreatment) (Table 5).

The parent biomass for the corncob, SB, and rice husk is maize, sugarcane, and paddy. The current study is based on the assumption that the parent biomass crop of the 12 months. It was also assumed that fertilizers, pesticides, and herbicides are procured from an average distance of 10 km from the field. Use of farm machinery for plowing, tillage, harvesting, irrigation, harvesting, etc., have been assumed and mentioned if any data are available.

Here, the drying of separated corncob, SB, and rice husk was carried out using a solar tunnel dryer developed and tested by Divyangkumar *et al.* [21], so no conventional energy was used to dry the raw material. Additionally, a size reduction was not done to eliminate the use of traditional resources. It was assumed that the initial moisture content of the maize, sugarcane, and paddy at the time of harvest was not considered in this study because the corncob, bagasse, and rice husk are the byproducts of maize, sugarcane, and paddy, respectively. So, the initial moisture content was assumed to be 12%, and the final moisture content was 7%, 9.645%, and 5.4% for corncob, SB, and rice husk, respectively. Reducing the moisture content of biomass results in a decrease in its weight. Consequently, weight loss is evident in all biomass as it transitions from Phase 1 to Phase 2.

Table 3. The mass-economic allocation of raw feedstock and pyrolysis products.

Products	Quantity (kg)	Price Rs./kg	Allocation (%)
Corncob			
Maize Seed	3841.75	25	84.59
Corncob	3498.24	5	15.40
Corncob biochar			
Biochar	1000	70	42.54
Biooil	1281.36	32	24.92
Syngas	1029.46	52	32.53
Sugarcane bagasse			
Bagasse	2968	5	32.48
Mollases	434.6	10	9.51
Sugar	1060	25	58.00
Sugarcane baggase biochar			
Biochar	1000	70	47.72
Bio-oil	1081.81	32	23.60
Syngas	808.9	52	28.67
Rice husk			
Rice husk	3001.11	8	3.67
Broken rice	272.83	22	0.91
Small rain	150.05	20	0.45
Rice	9548.98	65	94.94
Rice husk biochar			
Biochar	1000	70	46.99
Bio-oil	710.31	32	15.25
Syngas	1081.24	52	37.74

2.3.3 *Impact assessment*

This assessment is based on the scope (system boundary) and the available life cycle inventory database. The ReCiPe midpoint and ReCiPe endpoint methodologies were applied in this study to identify a wide range of impacts connected to each of the presented subsystems and to assess the overall environmental performance. To determine the impact, the midpoint and endpoint approaches differ primarily in considering the various phases of the cause-and-effect chain. The effect is measured using the midpoint techniques on the characterization factor, and the current damages are expressed using the endpoint methods on the indicator [22]. The midpoint characterization comprises 18 impact categories, while endpoint characterization includes 3 categories (human health, ecosystem diversity, and resource availability).

Emissions of carcinogens, respiratory impacts from inorganic and organic material emissions, ozone layer depletion, IR, and climate change are all factors that can harm human health. Disability-adjusted life years (DALYs) are the impact assessment unit used for this category. DALY measures the severity of a condition that considers mortality (the number of years of life lost to an early death) and morbidity (the period when a disease reduces quality of life, such as while a patient is in the hospital). Ecotoxic emissions, the cumulative impacts of eutrophication and acidification, and land conversion all contribute to the degradation of ecosystem quality. Potentially, no species lost per year is the LCA unit for ecosystem quality damage assessment [23]—fossil fuel and mineral extraction results in damage to resources.

2.3.4 *Interpretation of result*

The data obtained from the SimaPro 9.5.0.1 LCA program were subjected to normalization, weighting, and interpretation based on specific impact categories defined throughout the development stages of the system boundary. CED and CExD are also calculated.

Finally, sensitivity analysis was done for the production of biochar. A sensitivity study was conducted to comprehend the impact of modifications on the primary data and the resultant environmental impact. Two variables were adjusted to assess their influence on the ecological impact factors by −20%: the transportation distance traveled and the energy source used to produce power and heat throughout the biochar production process. The changes in the environmental impact of GWP impact categories were found and compared to identify which variable component resulted in the most change of results.

2.4 Economic assessment

Economic indicators in terms of payback period, net present worth (NPW), benefit cost ratio (B/C ratio), and internal rate of return (IRR) were used to check the economic feasibility of biochar production from different biomasses using vacuum pyrolysis unit. Economic indicators were calculated using the formula suggested by Patel and Panwar [24].

3. Result and discussion

This section explains and displays the primary findings from the LCA. Consequently, Section 3.1 compares three distinct agricultural systems for producing crop wastes and separating raw materials for the manufacture of biochar, with an emphasis on environmental assessment during the agrarian stage. Lastly, Section 3.2 assesses the effects of the pyrolysis system used to produce biochar on the environment.

Table 4. Inventory data of Phase 1 for CC, SB, and RH.

	The cultivation of maize and separation of corncob		**The cultivation of sugarcane and separation of baggage**		**The cultivation of paddy and separation of rice husk**	
Unit		**Quantity**		**Quantity**		**Quantity**
	Output to technosphere					
kg	Maize cultivation	7340	Sugarcane	10 600.71	Paddy cultivation	13 641.41
	Input resources from nature					
ha	Transformation to annual crop	2.45	Transformation to annual crop	0.18	Transformation to annual crop	1.95
m^3	Water	1301.63	Water	630.7	Water	75 994.011
	Inputs from the technosphere (materials/fuels)					
kg	Maize Seed	61.14	Sugarcane seed	21.2	Rice seed	389.72
kg	Nitrogen Fertilizer	440.4	Nitrogen Fertilizer	28.514	Organic Nitrogen Fertilizer	77.94
kg	P_2O_5 Fertilizer	195.68	P_2O_5 Fertilizer	13.886	Organic phosphorus Fertilizer	38.97
kg	K_2O Fertilizer	195.68	K_2O Fertilizer	8.69	Organic potassium Fertilizer	116.92
kg	$ZnSO_4$ Fertilizer	61.14	Pesticides,	1.44	Urea Fertilizer	311.697
kg	Pesticides	1.468	Herbicides		Potassium Chloride	311.697
kg	Atrazine	3.67	Fungicides		Pyrethroid compound	1.3
kg	Alachlor (Lasso)	6.11				
kg	Metolachlor (Dual)	4.84				
kg	Pendamethaline	3.67				
kg	Diesel Fuel	404.46	Diesel Fuel	24.93	Diesel Fuel	265.36
tkm	Transport, truck Assumed	9.74	Transport, truck	7.37	Transport, truck Assumed	12.48
kWh			Electricity	434.6	Electricity	1718.766
	Separation of corn cob		Seperation of bagasse		Separation of rice husk	
	Output to technosphere					
kg	Corn cob	3498.24	Bagasse	2968.2	Rice husk	3001.11
kg	Maize seed	3841.76	Sugar	1060.1	Broken rice	272.83
kg			Molasses	434.6	Small grain	150.05
kg					Rice	9548.98
	Input resources from nature					
m^3	NA	NA	Water, river	57.66	NA	NA
	Inputs from the technosphere (materials/fuels)					
kg	Maize cultivation	7340	Sugarcane cultivation	10 600.71	Paddy cultivation	13 641.41
	Inputs from the technosphere (electricity/heat)					
kWh	Electricity	9711.554	Electricity	132.5	Electricity	720.25

Table 5. Inventory data of Phase 2, including pretreatment for CC, SB, and RH.

Unit	**Corn cob**		**Sugarcane bagasse**		**Rice husk**	
Output to technosphere						
	Products	**Quantity**	**Products**	**Quantity**	**Products**	**Quantity**
kg	Biochar (CC 500)	1000	Biochar (SB 500)	1000	Biochar (RH 500)	1000
kg	Bio-oil	1281.36	Bio-oil	1081.81	Bio-oil	710.31
kg	Syngas	1029.46	Syngas	808.9	Syngas	1081.24
	Inputs from the technosphere (materials/fuels)					
kg	Corn cob	3310.162	Sugarcane bagasse	2891	Rice husk	2791.736
	Inputs from the technosphere (electricity/heat)					
kWh	Electricity	12 643.68	Electricity	20 000	Electricity	8629.44

3.1 Environmental impact assessment of agriculture crop residue production and separation of raw material

This study aimed to compare the environmental effects of different agricultural crop wastes at the midpoint and endpoint levels, as described in the following subsections.

3.1.1 *Midpoint analysis*

It is well known that agriculture is an intricate system that requires a lot of natural resources during production, particularly when using land and water. This results in environmental problems. Additionally, the use of plant and soil amendments (fertilizers, insecticides, and pesticides), as well as other cultivation techniques, may be linked to agricultural emissions, which may have an impact on several impact categories, including biodiversity, soil fertility, landscape, climate change, and human health [25].

As demonstrated in Fig. 4, corncob has a maximum impact (100%) on the environment compared to the others in nearly 17 of the 18 mid-categories. The higher environmental impacts in CC cultivation may be due to the higher consumption of fertilizers, plant protection chemicals, diesel fuel, electricity and transformation of higher area. Additionally, Ghasempour and Ahmadi in 2018 observed that, the environmental indicators are most significantly influenced by factors such as fertilizer use, electricity consumption, the use of farming machinery, diesel fuel, and pesticide application [15]. Furthermore, the finding of greater impacts in CC aligns with the CED results presented in Table 6.

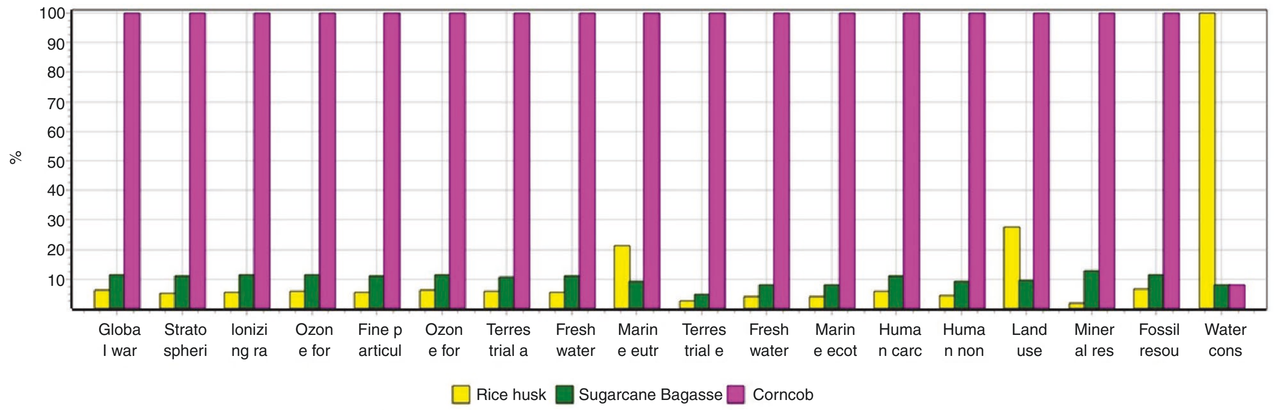
There is a significant variation between the three types of crops in the following impact categories: GW, SOD, IR, OFHH, FPMF, OFTE, TA, FE, ME, TE, FET, MET, HCT, HNCT, LU, MRS, and FRS where the impact value for the other two crops is below 27.5% (6.22, 5.17, 5.67, 6.06, 5.46, 6.12, 5.73, 6.4, 21.5, 2.5, 3.97, 3.99, 5.72, 4.24, 27.5, 1.93, and 6.6%, respectively) for rice husk and below 12.9% (11.4, 11.1, 11.2, 11.3, 10.9, 11.3, 10.8, 11, 9.15, 4.95, 7.96, 7.98, 11.2, 9.33, 9.61, 12.9, and 11.6%, respectively) for SB, As compared to corncob (100%). When it comes to the effects of WC, the rice husk showed a more significant impact value (100%) than the other crops, demonstrating an opposite behavior, for which the impact values for SB are (8.08), and for CC are (7.98%). According to the study, the impacts of TA, FE, ME, and HCT are caused by nitrogen-based emissions (such as nitrogen oxides and ammonia) that result from the usage of mineral fertilizers [22, 26, 27]. Additionally, all cases increase greenhouse gas emissions throughout the fertilizer transportation process, primarily from CO_2 emissions, but also from phytosanitary products, which have an impact on GWP. GWP is majorly affected by a corncob crop, which may be due to the emissions formed in the form of CO_2 and methane by the high usage of diesel fuel, electricity, and fertilizers (Table 4). This statement is in agreement with [15]. Mohammadi et al. (2014) reported a GWP of 1840.8 kg CO_2 per tonne for wheat. They identified diesel fuel and chemical fertilizers as the primary contributors to this indicator [28]. The LCA study revealed that optimizing fertilizer dosages can significantly reduce environmental impacts [29].

In particular, SF_6 and N_2O may be involved in SOD. One possible explanation for the reported values in the TE, FET, and MET effect categories is using phytosanitary products (Table 4) [22]. Furthermore, increased concentrations of some persistent hazardous chemicals in the soil brought on by agricultural treatment may also impact these categories [27]. The application of agriculture may increase the emission to soil and soil toxicity, which reduces crop production. The land utilized for biomass production and feedstock separation is related to the LU impact, WC is related to the WC impact, and diesel consumption is related to the FRS impact. Paddy cultivation requires a more significant amount of water; thus, the impact on the WC of rice husk is more important. A different trend is found in the impact category of ME and LU, where the impact by corncob is maximum while the impact due to RH surpasses SB. This is due to the higher land required for RH cultivation. Nonetheless, releasing nutrients, such as nitrogen and phosphorus, into aquatic ecosystems is typically the cause of MET, with disastrous effects on fisheries, drinking water sources, and recreational water bodies [30]. Overall, the impact on the environment due to the corncob is higher, followed by SB and rice husk. From Table 6, the lowest impact is found on SOD by the RH, SB, and CC. The CED and CExD for RH, SB, and CC are presented in Table 6. The CED of CC is higher, followed by SB and RH. Meanwhile, the trend of CExD is as follows: RH > CC > SB. CED is a metric that quantifies the total energy required throughout the lifecycle of a product or process. CED is crucial because it offers a comprehensive measure of an energy footprint, enabling the assessment of environmental impacts and the identification of energy efficiency opportunities. By understanding and minimizing CED, industries can reduce overall energy consumption, lower costs, and support sustainable development. While, CExD serves as an indicator for evaluating energy and resource demand. By considering both the quality of energy and the inclusion of non-energetic resources, CExD offers a more comprehensive measure.

3.1.2 *Endpoint analysis*

It is crucial to analyze impacts using the endpoint methodology to obtain a more thorough understanding of the environmental impact of all crop varieties.

The cultivation of maize and separation of corncob mainly affect the human health and resources impact categories, being less affected by the ecosystem impact category as presented in Table 7. Meanwhile, rice husk impacts the ecosystem more, while resources and human health are less affected by paddy cultivation and rice husk separation. As seen in Fig. 5, the CC crop has a



Method: ReCiPe 2016 Midpoint (H) V1.08/World (2010) H/Characterization
Comparing 3E3 kg 'Rice husk', 2.97E3 kg 'Sugarcane Bagasse' and 3.5E3 kg 'Corncob';

Figure 4. The graphical representation of midpoint impact categories of Phase 1.

considerably more significant impact on HH (100%) than SB (11%) and RH (7.26%). This can be linked to both the usage of fertilizers (N, P, K) and the emissions emitted during the production stage, which are engaged in the environmental consequences of HH. HH is associated with the human toxicity and the toxicity indicator of CC in midpoint category was higher. Thus, inhaling air contaminated by toxic material can cause short-term effects such as throat irritation, skin allergies, and eye swelling. In the long term, exposure may impact the skin, liver, and nervous system [15]. The rice husk has shown a maximum (100%) impact on the ecosystem impact category as compared to corncob (90.3%) and SB (16.8%). The higher effect of rice husks is due to air and water emission. A similar trend was observed in the resources impact category, which demonstrated higher impact due to corncob (100%) compared to SB (12.2%) and rice husk (8.35%). This may be due to the higher usage of resources like diesel in corncob production. Midpoint impact category like MRS and FRS is associated with resources endpoint impact category [31].

3.2 Environmental impacts associated with biochar production through pyrolysis system

This section evaluates the most ecologically friendly method of pyrolysis for producing biochar. The operation considered the pretreatment stage, including size reduction and drying. Nevertheless, because only renewable energy was consumed during the pretreatment phase, it was further ignored in the computation. During the pyrolysis process, a significant amount of electricity was utilized, and thus, it was considered.

3.2.1 *Midpoint analysis*

Table 8 displays the midpoint impact values obtained using the ReCiPe approach for biochar production. The impact magnitude order in this instance for RH 500 is as follows: HNCT, GW, TE, FRS, WC, HCT, MET, FET, IR, LU, TA, FPMF, OFTE, OFHH, FE, MRS, ME, SOD. While for SB 500: TE, HNCT, GW, FRS, HCT, MET, FET, IR, LU, WC, TA, FPMF, OFTE, OFHH, MRS, FE, ME, SOD and for CC 500: HNCT, GW, TE, FRS, HCT, MET, FET, IR, LU, WC, TA, FPMF, OFTE, OFHH, FE, MRS, ME, SOD.

Regarding the pyrolysis system of all biomass, the maximum impact values were found for the GWP, HNCT, TE, and FRS, and the values are presented in Table 8. These findings are primarily related to the consumption of critical utilities like electricity. GHG emissions from electricity usage are mainly responsible for GWP, which is closely connected to the GW impact category [32–34]. In another study by Shaheen et. al [35]., the GWP of date palm biochar was 1.53 kg CO_2 eq/kg. However, their date palm biochar GWP result was more significant than those found in a study where biochar was applied as a soil supplement or for carbon sequestration [36]. Carbon sequestration and soil amendment reduce CO_2 emissions, which may have decreased the GWP results. However, soil application of biochar was not conducted in this study as it is limited to biochar production only. Another factor

Table 6. The midpoint impact categories of Phase 1.

Sr. no.	Impact category	Unit	Rice husk	Sugarcane bagasse	Corncob
1	Global warming	kg CO_2 eq	190	347	3.05E3
2	Stratospheric ozone depletion	kg CFC_{11} eq	0.000123	0.000264	0.00238
3	Ionizing radiation	kBq Co-60 eq	3.73	7.37	65.8
4	Ozone formation, Human health	kg NO_x eq	0.424	0.787	6.99
5	Fine particulate matter formation	kg $PM_{2.5}$ eq	0.389	0.781	7.13
6	Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.438	0.806	7.15
7	Terrestrial acidification	kg SO_2 eq	0.623	1.18	10.9
8	Freshwater eutrophication	kg P eq	0.127	0.256	2.32
9	Marine eutrophication	kg N eq	0.0468	0.0199	0.218
10	Terrestrial ecotoxicity	kg 1,4-DCB	364	723	1.46E4
11	Freshwater ecotoxicity	kg 1,4-DCB	6.02	12.1	152
12	Marine ecotoxicity	kg 1,4-DCB	8.06	16.1	202
13	Human carcinogenic toxicity	kg 1,4-DCB	10.2	19.9	179
14	Human non-carcinogenic toxicity	kg 1,4-DCB	183	402	4.31E3
15	Land use	m^2a crop eq	20.8	7.28	75.8
16	Mineral resource scarcity	kg Cu eq	0.248	1.65	12.8
17	Fossil resource scarcity	kg oil eq	57	99.9	864
18	Water consumption	m^3	2.8E3	227	224
19	Cumulative Energy Demand (CED)	MWh	0.828	1.36	11.8
20	Cumulative Exergy Demand (CExD)	MWh	39.8	4.56	15.3

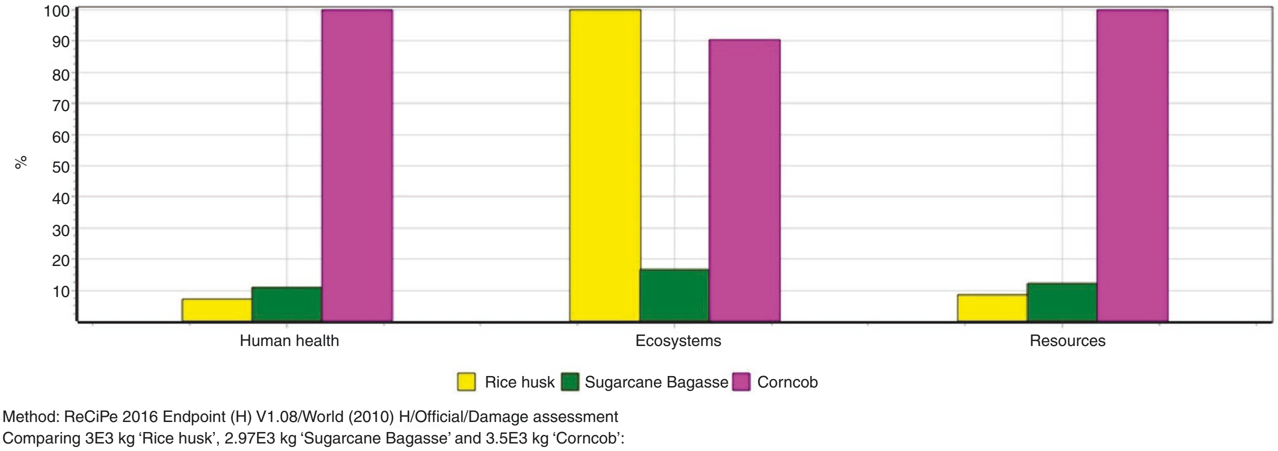
Table 7. The endpoint impact categories of Phase 1.

Damage category	Unit	Rice husk	Corncob	Sugarcane bagasse
Human health	DALY	0.000649	0.00894	0.000987
Ecosystems	species. yr	1.74E−5	1.57E−5	2.91E−6
Resources	USD2013	12	144	17.7

that can impact the GWP results is the type of furnace used for this investigation. A different study claims that the GWP outcome is influenced by various pyrolysis systems [37]. GWP of biochar produced from forest residues using the Air Curtain Burner, Oregon Kiln, and portable biochar system integrated by Biochar Solutions were 0.16, 0.11, and 0.25-0.31-tons CO_2 eq/tons, respectively. The minimum or lowest value of impact categories for RH 500, CC 500, and SB 500 biochar production is SOD (0.00141, 0.00276, and 0.00332 kgCFC11 eq, respectively). The biochar production from SB impacted more on following categories: GW, SOD, IR, OFHH, FPMF, OFTE, TA, FE, ME, TE, FET, MET, HCT, HNCT, LU, MRS, and FRS. The higher impact may be due to electricity consumption during pyrolysis (Table 5).

The biochar production of SB impacted more FET and MET (100, 100%, respectively) followed by CC (71.6, 71.2%, respectively) and RH (42.6, 42.6%, respectively). This fact can be related to the usage and removal of water from the pyrolysis system (see Fig. 6). The impact of RH is more on WC (100%), followed by SB (11.9%) and CC (9.19%). This result is linked to the higher water use in the Phase 1 process. Furthermore, Table 8 shows that the effect values for FPMF are related to the use of electrical power. I and FE have comparatively low impact values for RH, CC, and SB, such as (5.11, 7.63, 12 kg P eq, and 0.334, 0.504, and 0.748 kg N eq, respectively) (Table 8). These impact categories pertain to the “hidden” emissions that result from using electricity [38], as well as the use and removal of water from the pyrolysis step [22]. Lowering the electricity required to run the pyrolysis system is crucial in improving environmental performance [38].

This study used solar instead of traditional energy to complete the drying process. Nonetheless, solar energy is a significant factor in SOD and global warming. A conventional dryer would have much more significant environmental effects.



Method: ReCiPe 2016 Endpoint (H) V1.08/World (2010) H/Official/Damage assessment
Comparing 3E3 kg ‘Rice husk’, 2.97E3 kg ‘Sugarcane Bagasse’ and 3.5E3 kg ‘Corncob’:

Figure 5. The graphical representation of endpoint impact categories of Phase 1.

Table 8. Environmental impacts of biochar production from various biomass Phase 2.

Sr. no.	Impact category	Unit	Biochar (RH 500)	Biochar (CC500)	Biochar (SB 500)
1	Global warming	kg CO_2 eq	5.82E3	8.84E3	1.37E4
2	Stratospheric ozone depletion	kg CFC_{11} eq	0.00141	0.00276	0.00332
3	Ionizing radiation	kBq Co-60 eq	127	192	298
4	Ozone formation, Human health	kg NO_x eq	12.9	19.6	30.2
5	Fine particulate matter formation	kg $PM_{2.5}$ eq	14.4	21.7	33.8
6	Ozone formation, Terrestrial ecosystems	kg NO_x eq	13	19.9	30.5
7	Terrestrial acidification	kg SO_2 eq	18.4	28.4	43.1
8	Freshwater eutrophication	kg P eq	5.11	7.63	12
9	Marine eutrophication	kg N eq	0.334	0.504	0.748
10	Terrestrial ecotoxicity	kg 1,4-DCB	4.82E3	1.21E4	1.13E4
11	Freshwater ecotoxicity	kg 1,4-DCB	162	272	380
12	Marine ecotoxicity	kg 1,4-DCB	221	370	520
13	Human carcinogenic toxicity	kg 1,4-DCB	337	513	792
14	Human non-carcinogenic toxicity	kg 1,4-DCB	6.79E3	1.06E4	1.6E4
15	Land use	m^2a crop eq	86.6	133	186
16	Mineral resource scarcity	kg Cu eq	2.12	7.82	5.5
17	Fossil resource scarcity	kg oil eq	1.49E3	2.29E3	3.49E3
18	Water consumption	m^3	1.24E3	114	148
19	Cumulative Energy Demand (CED)	MWh	20.2	31.1	47.3
20	Cumulative Exergy Demand (CExD)	MWh	38.2	33.7	51

3.2.2 *Endpoint analysis*

Figure 7 displays the pyrolysis system's endpoints using the ReCiPe approach for the pyrolysis scenario. Thus, the higher impact value in human health is caused by SB (100%), followed by CC (64.7%) and RH (42.7%) (see Table 9). A similar order was observed in the ecosystem and resources impact category. The biomass pyrolysis system significantly influences HH damage because of the increased utility demand and byproduct generation [39]. At the same time, the biochar production from SB impacted the resource's endpoint impact category more, followed by CC (73.3%) and RH (43.1%). Water, air, and electricity can significantly impact the RA damage category. Conversely, the primary causes of the ecosystem damage are the water evacuation and energy use.

3.2.3 *Sensitivity analysis*

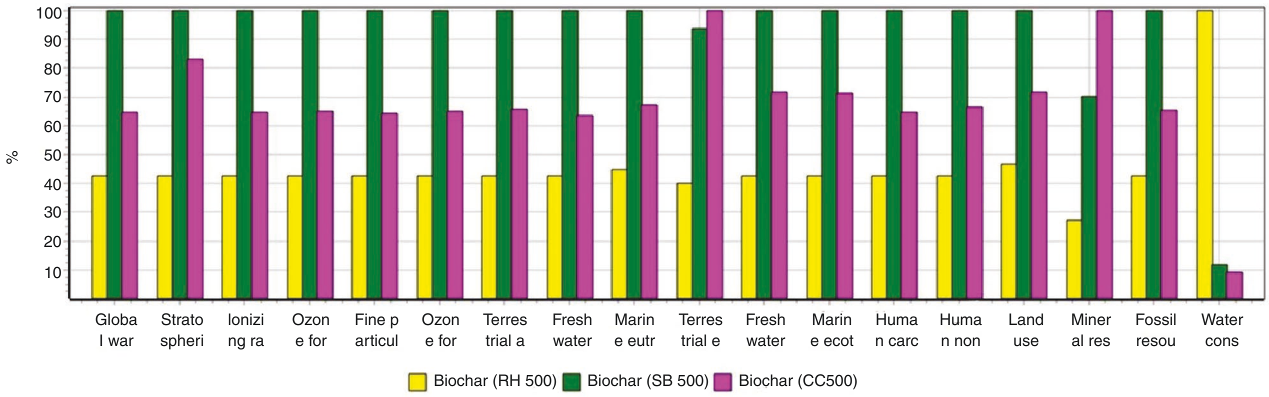
A sensitivity analysis was performed for Phases 1 and 2 to ascertain the environmental effects of reducing transportation distance and switching to solar energy sources. The transportation and electricity consumption inventory data were reduced by 20% to check the GWP environmental impact category changes. The comparative results of the CC, SB, and rice husk after changes in their data were presented in Fig. 8. Figure 9 represents how electricity consumption affects the environmental impact on biochar production.

It was observed from Fig. 8 that reduced distance lowered the GWP for corncob from 100 to 91%. At the same time, a slight difference was observed in SB from 11.4 to 11.3%. In the case of rice husk, reduced distance did not affect the GWP. Meanwhile, the changes in electricity (conventional) to nonconventional produce a significant difference in the GWP of all biomass feedstock compared to transportation. Almost 22.96% of the GWP impact on corncobs can be minimized by reducing consumption by 20%. At the same time, the impact of GWP was reduced by 1.75% and 0.83% in SB and RH, respectively. The CED was reduced for CC, SB, and RH from 11.8 to 9.32, 1.36 to 1.18, and 0.828 to 0.741 MWh, respectively.

The sensitivity analysis mainly affects the CC inventory, followed by SB and RH.

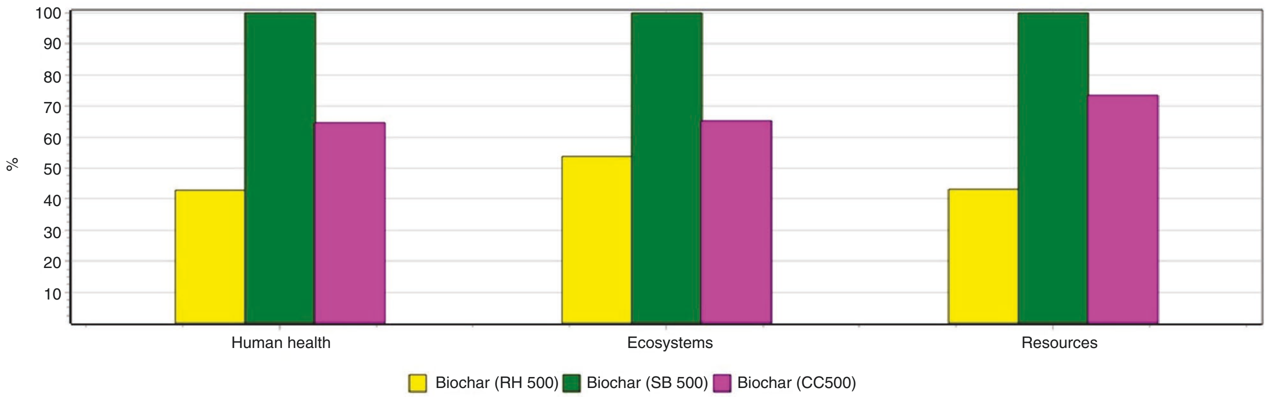
As observed in Fig. 9, switching from traditional to renewable sources can save the environment significantly. The significant gap observed in SB indicates the reduction of GWP from 100 to 75.2, thus reducing GWP by 24.8%. Similarly, the CED was decreased from 47.3 to 36.2 MWh in SB. The comparatively lower GWP reduction was observed in CC biochar (16%) and RH biochar (10.5%). The analysis revealed that using solar energy as an energy source lowered CED from 31.1 to 23.9 MWh for CC biochar production and 20.2 to 15.5 MWh for RH biochar production.

Improvements for both phases were noted in both sensitivity analysis scenarios. As a result, it can be concluded that changing



Method: ReCiPe 2016 Midpoint (H) V1.08/World (2010) H/Characterization
Comparing 1E3 kg 'Biochar (RH 500)', 1E3 kg 'Biochar (SB 500)' and 1E3 kg 'Biochar (CC500)';

Figure 6. Environmental impacts of biochar production from various biomass.



Method: ReCiPe 2016 Endpoint (H) V1.08/World (2010) H/Official/Damage assessment
Comparing 1E3 kg 'Biochar (RH 500)', 1E3 kg 'Biochar (SB 500)' and 1E3 kg 'Biochar (CC500)';

Figure 7. Environmental endpoints impact of biochar production from various biomass (Phase 2).

Table 9. Environmental impacts of biochar production from various biomass Phase 2.

Damage category	Unit	Biochar (RH 500)	Biochar (SB 500)	Biochar (CC500)
Human health	DALY	0.0172	0.0403	0.026
Ecosystems	species. yr	3.35E–5	6.24E–5	4.07E–5
Resources	USD2013	136	315	231

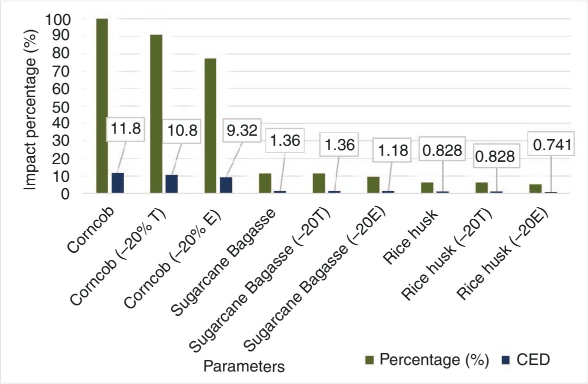


Figure 8. Sensitivity analysis of Phase 1.

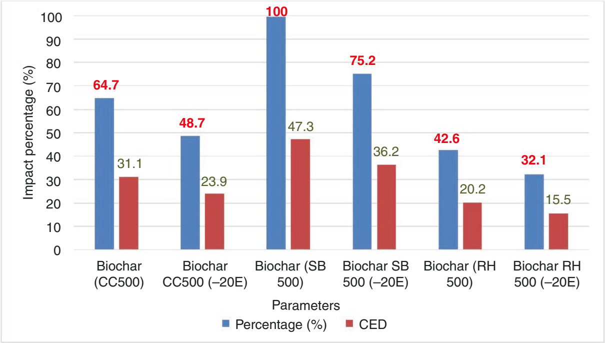


Figure 9. Sensitivity analysis of Phase 2.

the source of energy used during the process of growing biomass and creating biochar will significantly impact the environment. To reduce the environmental impact, it is strongly advised that production be done using cleaner energy sources. Conversely, a decrease in transportation did not yield an essential change in terms of GWP and CED. The sentences agree with the literature published by [35].

3.2.4 *Improvement of the environmental performance and result of similar studies*

Alternative methods are available to reduce the environmental impacts and improve environmental performance. The assessed stages are often interrelated, and each stage affects the outcome. Therefore, it is necessary to find ways to enhance every aspect of the scenario that has been examined. As a result, agricultural operations can be improved by optimizing fertilizer usage. Thus, it is best to utilize fertilizers that are favorable to the environment. Fertilizers from the literature and eco-invent database were used in this investigation. Further research on this topic is warranted because the simulation of fertilizer production can alter the outcomes. The use of water and electricity also needs to be more efficient. However, to limit the effects on the environment, emissions and waste output must be decreased. Additionally, environmental effects can be significantly reduced if energy is utilized more wisely and under control. One of the most important ways to lessen the impact on the environment and lower CO_2 emissions is through energy efficiency. Eliminating the moisture from the biomass is another method to alleviate the environmental effects. The efficient utilization of byproducts can reduce environmental impacts. The detailed LCA at different pyrolysis temperatures and residence times can be suggested for future work. However, environmental impacts will increase with the rise in pyrolysis temperature and residence time due to higher energy consumption. Additionally, the physicochemical properties of biomass can be correlated with the result of LCA.

Multiple LCA studies have been conducted to examine the environmental impact of biochar production. In their research, Hamedani et al. (2019) utilized two distinct feedstocks, namely willow and pig dung, to produce biochar. They found that biochar obtained from willow exhibited superior LCA outcomes compared to pig manure [40]. The research found that the temperature, kind of pyrolysis, and feedstock all affect the LCA of biochar formation. These investigations demonstrated how variations in feedstock, methods, and pyrolysis temperature impact LCA outcomes. Using LCA, biochar's impact on climate change has been assessed for various feedstocks, including rice straw and coarse wood chips [38, 41, 42] and pyrolysis systems [43]. According to an analysis of biochar LCAs, biochar systems are typically projected to reduce emissions by 0.4 to 1.2 t CO_2-eq t-1 (dry) feedstock [44]. The mitigation of greenhouse gas (GHG) emissions of biochar production for several pyrolysis processes was compared by Hammond et al. (2011) [45]. Sparrevik et al. (2013) investigated the particulate matter emissions and human toxicity of creating biochar from maize cobs using several pyrolysis processes using LCA [46].

3.2.5 *Economic assessment*

Economic indicators like payback period, NPW, B/C ratio, and IRR were used to check the economic feasibility of biochar production from different biomasses using vaccum pyrolysis unit. The economics results are tabulated in Table 10. The result of Table 10 indicated that, the production of biochar from CC, SB, and RH are profitable and it was observed by positive value of B/C ratio. The lowest payback period was observed for SB (2.62) compared to CC (2.74 year) and RH (2.66).

4. Conclusions

This research used standard pyrolysis techniques to assess the environmental and economic impact of producing biochar from different agricultural residues. The assessment followed a life cycle approach, specifically cradle-to-gate research, with a functional unit of 1-ton biochar production. The LCA model was created using the SimaPro platform and fulfilled the requirements of ISO14044. The findings indicated that the choice of biomass significantly influences the environmental and economic impacts of biochar production. Therefore, it is crucial to carefully select biomass for biochar production to maximize environmental

Table 10. Economic assessment of biochar production from CC, SB, and RH using vaccum pyrolyzer.

S. No	Economic parameters			Output
1	Capital cost of vaccum pyrolyzer			$4782
2	Number of days of operation in a year			300 days
	Number of batch per day			4 batch/day
3	Life of vaccum pyrolyzer			10 years
4	Repair and maintenance cost: 5% of capital cost			$239
5	Cost of biomass required per year * Cost of biomass including transportation and labor cost: $59.77/ton for CC and SB, and $95.63/ton for RH. * 20 kg of biomass per day is required, therefore, around 6 ton of biomass can be processed per year. * Total cost of biomass per year:			CC = $359 SB = $359 RH = $574
	CC	**SB**	**RH**	
	6 * 59.77 = $359	6 * 59.77 = $359	6 * 95.63 = $574	
6	Electricty cost per year * Power required for whole system: 2 kWh * Electricty unit consumed per day: 24 units * Commercial rate of electricity: 0.12 $/kWh * Cost of electricty required per day: $2.87 * Total electricty cost per year: 300*2.87 = $861			**$861**
7	Labor cost required per year * Considering 2 labor hour for loading and unloading per day * Labor cost 0.6 $/hour labor * Total labor cost per year: 0.6*2 *300 = $359			**$359**
A	**Total production cost of biochar (4 + 5 + 6 + 7)**			**CC = $1817** **SB = $1817** **RH = $2032**
8	Market price of biochar per kg			$0.84
9	Market price of liquid oil per kg			$0.38
10	Market price of gas yield per kg			$0.62
11	Biochar production per year:			CC = **1812.6 kg** SB = **2075.4 kg** RH = **2149.2 kg**
	CC	**SB**	**RH**	
	6.04 kg of biochar was produced per day (30.21% solid yield)	6.92 kg of biochar was produced per day (34.59% solid yield)	7.16 kg of biochar was produced per day (35.82% solid yield)	
	Production per year: 300 * 6.04 = 1812.6 kg	Production per year: 300 * 6.92 = 2075.4 kg	Production per year: 300 * 7.16 = 2149.2 kg	
12	Liquid oil production per year			CC = **2322 kg** SB = **2245 kg** RH = **1527 kg**
	CC	**SB**	**RH**	
	7.74 kg of oil was produced per day (38.71% oil yield)	7.48 kg of oil was produced per day (37.42% oil yield)	5.09 kg of oil was produced per day (25.45% oil yield)	
	Production per year: 300 * 7.74 = 2322 **kg**	Production per year: 300 * 7.48 = 2245 **kg**	Production per year: 300 * 5.09 = 1527 **kg**	
13	Gas production per year			
	CC	**SB**	**RH**	CC = **1866 kg** SB = **1679 kg** RH = **2324 kg**
	6.22 kg of gas was produced per day (31.10% oil yield)	5.59 kg of oil was produced per day (27.98% oil yield)	7.74 kg of oil was produced per day (38.73% oil yield)	
	Production per year: 300 * 6.22 = 1866 kg	Production per year: 300 * 5.59 = 1679 kg	Production per year: 300 * 7.74 = 2324 kg	
B	**Money recovered by selling biochar, oil and gas**			
	CC	**SB**	**RH**	
	$3565	**$3639**	**$3827**	
12	Net profit per year (B-A)			
	CC	**SB**	**RH**	
	$1748	**$1822**	**$1795**	
13	Payback period: (Capital cost/Net profit)			
	CC	**SB**	**RH**	

Table 10. Continued

S. No	Economic parameters			Output
	2.74 year	2.62 year	2.66 year	
14	Net present worth (NPW)			
	CC	**SB**	**RH**	
	$5958.7	$6413.4	$6247.5	
15	Benefit/Cost ratio			
	1.37	1.4	1.36	
16	Internal rate of return (IRR)			
	22%	24%	23%	

Note: Table 10 present all economic parameters in USD. 1 USD = 83.65 Indian rupee (as on 19 July 2024).

and economic benefits, especially when considering the local and regional context, agroecosystem, climate change, and sustainability. Biochar is an effective tool for carbon-smart management of agricultural residues. Corncob has the highest impact on most biomass cultivation categories, while rice husk has a more significant impact on WC. Using diesel, electricity, and fertilizers mainly affects GWP. SB has the most negligible impact on all three indicators. Biochar reduces GWP and can be used for carbon sequestration and soil improvement. The sensitivity analysis revealed that changing the energy source used during the process significantly affects environmental factors. Economic parameters reveled the profitability to the biochar production with highest Benefit cost ratio for CC (1.37) biomass followed by SB (1.4) and RH (1.36).

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Author contributions

Nakum Divyangkumar (Conceptualization [equal], Writing—original draft [equal]), Narayan Lal Panwar (Investigation [equal], Project administration [equal], Supervision [equal], Writing—review & editing [equal]), Chitranjan Agrawal (Data curation [equal], Software [equal]), Trilok Gupta (Supervision [equal], Validation [equal], Visualization [equal]), Girdhari Meena (Writing—review & editing [equal]), and Manjeet Singh (Supervision [equal])

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Conflict of interest statement

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

Data availability

Data can be available on reasonable request.

Ethical approval

This work does not contain any studies with human participants or animals. All authors provided informed consent to participate in this study.

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