Energy balance and greenhouse gas emissions from the production and sequestration of charcoal from agricultural residues

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Abstract

Agricultural residues (wheat/barley/oat straw) can be used to produce charcoal, which can then be either landfilled off-site or spread on the agricultural field as a means for sequestering carbon. One centralized and five portable charcoal production technologies were explored in this paper. The centralized system produced 747.95 kg-CO_2eq/tonne-straw and sequestered 0.204 t-C/t-straw. The portable systems sequestered carbon at 0.141 – 0.217 t-C/t-straw. The net energy ratio (NER) of the portable systems was higher than the centralized one at 10.29 – 16.26 compared to 6.04. For the centralized system, the carbon sequestration and the cumulative energy demand were most sensitive to the charcoal yield. Converting straw residues into charcoal can reduce GHG emissions by 80% after approximately 8.5 years relative to the baseline of in-field decomposition, showing these systems are effective carbon sequestration methods.

Keywords: Greenhouse gas emissions; charcoal production; net energy ratio; life cycle assessment; lignocellulosic biomass.

1. Introduction

Capturing energy from biomass that would otherwise decay is one of many options available to mitigate the impact of GHG emissions from fossil fuel use. There are various ways to use this biomass energy, such as conversion into heat, electricity, or other forms of energy, like liquid biofuels, biogas, or solid fuels (e.g., charcoal). One form of biomass processing is thermo-chemical conversion. In this process, heat is the dominant agent used to convert biomass into another chemical form. This analysis focuses on using charcoal produced through the thermo-chemical conversion of biomass.

Charcoal is different from other biomass-based solid fuels, with the main difference being that it is a very stable fuel with a high percentage of carbon. Charcoal can be deposited into the soil where it can be stored for a long time with minimal degradation. It can also be spread onto the soil; this has many environmental benefits. When the charcoal is produced from agricultural residues, a significant amount of the organic carbon found in the biomass can be returned to the same soil where the crops were grown. This practice increases soil fertility, (defined as an increase in bioavailable water, soil organic matter, and enhance nutrient recycling), and sequesters the carbon to mitigate climate change [1–4]. Charcoal, moreover, has a very long half-life compared to raw biomass or organic matter [5]. The stability of charcoal depends on the feedstock properties and the pyrolysis process [6]. Some studies on charcoal production systems discuss variations in charcoal yield from biomass in theoretical terms [6–8]. In reality, there are constraints on charcoal yields due to the design and capacity of the plants.

In 2012, the Canadian province of Alberta emitted approximately 249 million tonnes of CO_2eq GHGs [9], more than any province in the country. Although the energy sector had the largest contribution to these emissions, the agriculture sector contributed 17 million tonnes of CO_2eq GHGs [9]. One way to mitigate these emissions is to produce charcoal from agricultural residues, that is, straw left on the field to decompose, where it ultimately emits carbon dioxide to the atmosphere [10,11]. Agricultural residue charcoal has the potential to reduce N_2O emissions from soil by modifying the microbial activity, pH, aeration, and the concentrations of available nitrate and organic carbon [12–15]. There are not enough data to identify the net sequestration realized by spreading the charcoal back on the field; however, this practice can potentially mitgate GHGs. In addition, charcoal enhances plant growth, possibly by increasing the pH of the soil and its organic content, and hence increases the rate of absorption of CO_2 by biomass [13,15]. The possible increase in agricultural productivity was not considered in this study because there are few estimates available.

Various studies have estimated GHG emissions in agricultural activities such as harvesting, baling, and transportation [16,17], but none have evaluated the mitigation potential of converting harvest residues to charcoal. The aim of this research is to use a life-cycle assessment to assess the total carbon sequestration in the conversion of agricultural residues (e.g., wheat straw) to charcoal in Western Canada. Two types of production scenarios were evaluated, centralized and portable systems. In centralized production, charcoal is made in a plant that takes in biomass from several farms. The biomass is transported to the plant by truck and converted to charcoal by pyrolysis. The charcoal is then transported by truck to a landfill for sequestration. Portable charcoal production takes place in a mobile plant, which moves around an individual farm and produces charcoal, also by pyrolysis. The charcoal is then sequestered by spreading it on the same field where the straw was collected. The energy use, GHG emissions, carbon sequestration, and net energy ratio (NER) were calculated for various unit operations of charcoal production for both production scenarios. The CO_2 abatement estimate depended on the quantity of carbon in the sequestered charcoal, which for this study was assumed to be 80% carbon by mass [1,2,18,19]. The effect of charcoal sequestration on the agriculture fields was also assessed by analyzing the N_2O soil emission reduction for the portable systems. Finally, a sensitivity analysis determined which variables have the largest effect on the results.

2. Materials and Methods

The net carbon mitigation in the production of charcoal and its sequestration was estimated by taking into account the GHG emissions in various unit operations, which include the harvesting and collection of straw, transportation, pyrolysis, and the spreading of charcoal. The carbon emissions were calculated from the fuel consumption in each unit operation. Table 1 summarizes the energy use and emission factors used for the life-cycle calculations of charcoal production [20–25]. Figure 1 shows the system boundary and the unit operations involved in this life-cycle assessment (LCA) study.

2.1. *Input Data and Assumptions*

An LCA of the pathway for the production and spreading of charcoal would help assess the net impact of this process on the environment. This study is based on the LCA methodology documented in ISO 14040 and ISO 14044. The overall process followed four steps as defined by the standard methodology: goal and scope definition, inventory analysis, impact assessment, and interpretation. An LCA was used in this study to determine the net carbon sequestered in the soil through the conversion of agricultural biomass to charcoal. The GHGs emitted in each of the unit operations involved in this pathway were also considered in determining the net carbon sequestration. In this study, the functional unit was one dry tonne (t) of straw.

2.1.1. *Unit Processes*

The charcoal production and sequestering pathway was divided into five major unit operations over the life cycle: straw processing (UP1), straw transport (UP2), plant operations and charcoal production (UP3), charcoal transport (UP4), and landfilling or spreading in the field (UP5). These major unit operations have several sub-unit operations. The system omits processes for the growth of biomass because it was assumed that the straw is a byproduct of production and all growth impacts would be burdened to the crop. Figure 2 shows the detailed unit operations involved in the production of charcoal from straw and the spreading of that charcoal.

2.1.2. *Impact Assessment*

2.1.2.1. Straw Harvesting, Collection, and Processing (UP1)

This study focused on the use of straw from wheat, barley, and oats for the production of charcoal. Under current practices in Western Canada, farmers remove grains and leave the straw in the field to decompose. Some of the straw is used for bedding and other applications but the level of use is very small compared to the total volume of straw produced. Harvesting straw involves raking, baling, tarping/stringing, and road-siding. The amount of straw harvested per year depends on the size of the charcoal production plant. In this study, the size is based on a detailed assessment of current technologies of charcoal production. Section 2.1.2.3.1 describes the technology and size of the centralized and portable charcoal production plants. The LCA assumes conventional equipment used for harvesting in Western Canada, and data were collected from earlier studies. Wherever possible, the largest size of the machinery was considered in order to get better processing efficiency.

This study assumed that a baler picks up the straw and makes rectangular bales (4′ x 4′ x 8′). After baling, the automatic bale collector collects the bales and puts them onto the side of the field. It was assumed that 10% of the biomass would be lost during baling, meaning it would remain on the field. Equipment capacities and fuel requirements were determined from earlier studies [16,17] and equipment specifications [17,26,27], which are summarized in Table 2.

Residues that remain on the field contain nutrients that can be used by crops after the residue decomposes. .Removing residues means that some nutrients need to be replaced. The fate of nutrients from fertilizers and residues is different in the soil [28], but their uptake efficiency is thought to be similar. It was assumed for this paper that the amount of nutrients lost in the residues would be comparable to the amount needed from fertilizers. The nutrient contents of wheat, barley, and oat straw were taken from Kumar et al. and Bailey-Stamler et al. [10,29]. The nitrogen, phosphorus, and potassium contents were averaged over the three residues and then multiplied by the biomass needed per tonne of charcoal, which gave the mass of N, P, and K to be replaced.

2.1.2.2. *Straw Transport (UP2)*

The transportation of biomass is a critical unit operation in the centralized system because the straw was transferred away from the farm. In this study, it was assumed straw is collected from a circular area. The transportation distance is the radius of a circular area, with the plant located at the center. The amount of straw required by the charcoal plant depended on its size. Hence the area and radius of the field were proportional to the size of the plant. For GHG emission calculations, the average yield of straw was considered, which for Western Canada was 0.754 t/ha [10]. This number is not the total amount of straw available, rather the amount that would prevent adverse effects from removal; it is assumed there will still be straw left on the field for soil conservation as well as some used for livestock feeding and bedding needs [30]. The lower value from Kumar et al.'s research [10] was used in this analysis. Based on this yield, an area of 196,774 ha and a radius of 21.19 km were estimated. Because the portable system does not involve straw transportation, that unit operation (biomass transport) is not considered for the portable system.

2.1.2.3. *Types of Charcoal Production Technologies and their Construction, Operation, and Commissioning (UP3)*

2.1.2.3.1. *Types of Charcoal Production Technologies*

In this paper, two types of charcoal production technologies were considered. The first is the production of charcoal in a centralized plant where the required biomass is transported to the facility by truck and is converted to charcoal through pyrolysis. The charcoal produced through this process is then transported to the landfill for sequestration. The pyrolysis system capacity assumed in this study was 5,500 kg/hr, with a lifetime of 10 years [31]. It was also assumed this system would operate 24 hours a day and an average yield of 20 – 35% [31]. This study assumed a 30% efficiency, which would produce 1,650 kg of charcoal/day. The fuel use and time required for various unit operations are summarized in Table 3.

The second scenario was the production of charcoal in a mobile plant. Charcoal is produced while it moves around and was then spread in the same field. There are three types of portable systems (the Big 22, the Big 1000, and the Adam), evaluated here in five different scenarios. The Big 22 system can process 1000 kg straw/hr and produce 200 kg charcoal/hr[31]. This study developed three scenarios in which this system operated for 12, 21, and 24 hours per day. The Big 1000 system capacity is 200 kg straw/hr, with a charcoal production of 40 kg/hr [31]. The manufacturer of the final system, Adam, provides processing information in terms of batches. The system can process five batches per week at 620 kg straw/batch, while producing 186 kg of charcoal per batch [32]. The lifetime of the Adam system is 3 years, while all other portable systems have a 10-year lifetime [31].

2.1.2.3.2. *Plant Construction, Operation, and Decommissioning*

GHG emissions and energy consumption in plant construction, operation, and decommissioning were not considered for the portable system. Nor were emissions and consumption for equipment set-up considered, as the portable equipment travels to the field for processing. So the sections that follow consider GHG emissions and energy consumption for the centralized system. It was assumed that during the first year, the plant would not operate at full capacity and it would take three years to get to the maximum operational capacity. The capacity during the first year would be 80%, 85% during the second, and 90% from the third year on [10,33].

Plant Construction

Energy use and plant construction materials were considered to determine the GHG emissions for plant construction. Primary energy inputs and GHG emissions during construction were difficult to determine and, moreover, were considered negligible compared to the construction materials' embodied impacts. Earlier studies on natural gas-combined power generation systems, hydrogen production via natural gas steam reforming [34], bio-hydrogen production [35,36], and power production from triticale [37] were used to approximate the plant size and material required. GHG emissions and energy requirements for plant construction are detailed in Table 4.

Plant Operation

Energy input and GHG emissions involved during plant maintenance were assumed to be from 2.5 to 5% of plant construction energy and GHG emissions [21]. For this study, it is assumed that the GHG emissions are 3% of the plant construction.

Conversion – Pyrolysis

It was assumed that CO_2 emitted during the biomass conversion step is balanced by the CO_2 absorbed during the growth phases [19,38]. Hence, GHG emissions during the energy conversion stage of straw (pyrolysis) are assumed to be zero. No additional fossil fuel or electricity is needed to operate a pyrolysis plant as the plant is self-sufficient in terms of energy [39].

Biomass Feeding Mechanism

A chain conveyer is used to transfer biomass to the pyrolysis equipment. The conveyer considered had a capacity of 50 dry t/hour and a fuel consumption of 8.29 L/hour [40].

Plant Decommissioning

For all plants, the decommissioning impact is assumed to be 3% of the construction impact [37,41]. After decommissioning, non-recyclable materials were transported by truck for 50 km to a landfill site. It was assumed that 25% of the steel (the remaining 75% recycled) and 100% of all the other non- recyclable materials (concrete and aluminum) are landfilled [34,35,41,23]. The GHG emissions of recycling the steel after decommissioning were not included in this analysis. It was assumed that energy required for recycling the material into a usable product would be burdened to the recycled steel itself and is outside the boundary of this analysis.

2.1.2.4 Transportation (UP4) and Sequestering of Charcoal (UP5)

In the centralized system scenario, charcoal is sent to a landfill and in the portable system, it is spread directly back onto the field along with fertilizers. The landfilling operation requires two machines, an excavator and a truck to transport the charcoal. GHG emissions were calculated based on the amount of fuel used by these vehicles, and this depends on how long the machines operate. In the case of trucks, GHG emissions are calculated for hauling as well as for the waiting time while loading or unloading of the charcoal. Table 2 gives details on charcoal transportation and landfilling.

In the portable system, which produces considerably less charcoal than in the centralized system, charcoal is spread on the field with existing farming equipment; there is a minimal increase in energy use as the charcoal is spread with fertilizers and therefore extra energy and CO_2 emissions are considered to be negligible. It was assumed that any CO_2 released due to the application of charcoal with fertilizers would be attributed to the fertilizers. As the equipment used in the portable system travels to the field and charcoal is spread in the field along with fertilizer, no additional transporting equipment is required.

2.2 Overall Biomass Requirement and Charcoal Production

The biomass requirement is found from the pyrolysis system capacity, the plant operation efficiency, and the lifetime of the plant. To find this value, first the amount of biomass needed was estimated. For the centralized system, the annual biomass requirement was found by multiplying the pyrolysis system capacity of 5,500 kg/hr by the total number of hours in a year. It was assumed the biomass would be stored for three months due to the difficulty in transporting the biomass from the field during spring in Western Canada. The mass of biomass stored was found by dividing the annual biomass requirement by four (the number of times biomass would be put into storage for a three-month storage time). The gross biomass required was found by dividing the mass of biomass stored by the percentage of overall biomass that is collected during baling (assumed to be 90%). Performing these calculations gave an overall biomass requirement of 49,459 t-biomass/year. When accounting for the operational capacity of the plant, the final biomass requirement increased from 39,567 t-biomass/year in year one, 42,040 t-biomass/year in year two, to 44,513 t-biomass/year for years 3 – 10. The total biomass produced was estimated based on the production in different years and the lifetime of the plant. This gave an overall biomass requirement of 43,771 t-biomass/year. The charcoal production was found by multiplying the biomass requirement by the charcoal production efficiency.

2.3 Energy Use and GHG Emission Calculations

The calculations of energy use were based on the hours required by the equipment to complete the process for the selected size of production. Tables 3 and 4 give the details of energy requirement and GHG emissions for all unit processes in the centralized system. To find the GHG emissions, energy and material use were aggregated over the lifetime of the plant (see section 2.1.2.3.2). These values were then multiplied by the emission factors from Table 1.

3. **Results and Discussion**

3.1. *Energy and Emissions for the Centralized Production System*

The above steps comprised the net fuel consumption for each unit operation in the production of biomass-based charcoal. The GHG emissions and energy consumptions for each unit process are summarized in Figures 3 and 4 and Tables 3-5. Biomass collection comprises 51% of GHG emissions followed by biomass transport at 43%. The other unit processes contribute only 6% of the GHG emissions. Fertilizer replacement is the largest contributor to biomass collection, followed by baling, then shredding. Biomass truck transport is the largest contributor to biomass transport and consitutes almost 97% of the transport GHG emissions. The largest contribution of consumed energy is from biomass transport (57%), followed by biomass collection at 36%. As with the GHG emissions, the other processes contribute only 7% to the energy consumption. The largest consumer of fuel to biomass processing comes from the baler, followed by shredding, then the tractor used for the baler. The largest consumer of fuel to biomass transport is the biomass truck transport, which contributed almost 97% to this process.

The total average fuel consumption per year to transport and process straw is 26.1 L-diesel/t-straw, which amounts to GHG emissions of 107.1 kg-CO_2/t-straw. When the GHG emissions for plant construction and fertilizer replacement are included, the emissions increase to 143.58 kg-CO_2/t-straw. Biomass-based charcoal consists of 80% carbon [1,2,18,19]; thus, using the molecular weight of carbon dioxide, the net carbon sequestered was estimated to be 0.204 t-C/t-straw .

The net energy ratio (NER) of the system is defined as the energy produced in the form of charcoal divided by the life cycle of fossil fuel energy consumption [36,41,43]. This value gives the efficiency of fossil fuel consumption and can be used as a benchmark to compare other GHG mitigation pathways. Life-cycle efficiency, on the other hand, is a measure of overall system efficiency. It is the relationship of total output energy in the form of charcoal to total fossil fuel input energy. The calorific value of charcoal was assumed to be 28 MJ/kg. The total energy consumed during production was 1,355.1 MJ/t-straw while the total energy produced in the form of charcoal was 8,187.1 MJ/t-straw. Hence, the net energy ratio for the centralized system is 6.04.

3.2. *Energy and GHG Emission Results for the Portable Production System*

The results for energy and emission calculations for both the centralized and portable systems are given in Table 5. The centralized system produces more charcoal per unit of straw (0.292 t-C/t-straw) than all of the portable systems (0.141 t-C/t-straw) except the Adam system (0.217 t-C/t-straw). However, the centralized system has a lower net emission reduction than the portable systems. This is because GHGs are emitted in transporting biomass to undergo pyrolysis, while the portable systems process the residues on site. The centralized system also has a lower NER (6.04) than the portable systems, whose NERs range from 10.29 – 16.26. The NER results show a higher efficiency for the portable system. The carbon sequestration for the Adam portable system was the highest at 0.217 t-C/t-straw, followed by the centralized system at 0.204 t-C/t-straw, then the other portable systems at 0.141 t-C/t-straw. Of the portable systems, Adam has both the highest NER and the most carbon sequestered. For the centralized system, most (94%) of the GHGs are emitted in straw processing (UP1) and straw transport (UP2) (Table 6). For the Big 22 portable system, almost all (99%) of the emissions come from straw processing (UP1). Portable systems seem advantageous when considering these parameters, but there are drawbacks, the biggest of which is the amount of biomass each can process per year. The Adam system can only process 170 dry-t biomass/year, while the Big 22 (operating for 24 hours per day) can process 9,200 dry-t biomass/year. In contrast, the centralized system can process 437,713 dry-t biomass/year. The portable systems would be advantageous on small farms. One of the other key factors that should be considered before making decision on the type of system is the economics of charcoal production and its sequestration.

3.3. *Benefits of Charcoal Production*

Two benefits of producing charcoal from agricultural residues include carbon sequestration and GHG emission reduction over standard practice. For carbon sequestration to be beneficial, it should release less carbon into the atmosphere than that released through the decomposition of the residues left on the field. When the residues decompose, some carbon goes into the soil and the rest degasses into the atmosphere. After 5 – 10 years, only 10 – 20% of the carbon from the residues remains in the soil [44]. The carbon content of wheat straw is estimated to be 45.6% by weight [45], meaning the straw contains approximately 0.456 t-C/t-straw. Assuming an average of 15% remains in the soil after 10 years, 1.42 t-CO_2/t-straw would be released to the atmosphere.

The centralized production process releases 0.143 t-CO_2/t-charcoal. The charcoal is in a stable form in the soil [44], but approximately 6% could be converted to CO_2 after 8.5 years [46]. Assuming that 6% of the charcoal is converted to CO_2, 0.176 t-CO_2/t-charcoal will be released after 8.5 years. This means an estimated 0.319 t-CO_2/t-charcoal is released, 20% less than the amount released (after approximately 8.5 years) through decomposition in the field.

Another benefit of charcoal production is the mitigation of N_2O emissions from fertilizer use in crop growth [14]. In Alberta soils, most of these emissions are released after the soil thaws in spring [47]. With the portable systems, charcoal was put back into the same field the straw was taken from, potentially mitigating emissions from the soil. To estimate this mitigation potential, a field study done near Ellerslie, Alberta showed a nitrous oxide emission of 3.5 kg-N_2O-N/ha [47] and a study based on 14 different agricultural soils from the United States, Spain, and Brazil showed that biochar can mitigate 10 – 90% of the N_2O emissions were used [14]. No information was found on biochar N_2O emissions specifically for Alberta, so using the estimates from [14] with the N_2O releases from the Alberta field study [47], it was found that 0.35 – 3.15 kg-N_2O-N/ha could be mitigated. Using the GWP of N_2O (298 for the 100-year time horizon) and the straw yield of 0.754 t/ha for Western Canada, the N_2O mitigation potential was found to be 138.3 – 1,245.0 kg-CO_2eq/t-straw. Compared to the net emission reduction of the portable systems from Table 5, charcoal can mitigate the GHG emissions from 16 – 151% depending on the system type. The largest potential net emission reduction would be 2,108.16 kg-CO_2eq/t-straw from the Adam system with a 90% N_2O emissions reduction from charcoal. Experimental studies should be carried out to determine the maximum nitrous oxide mitigation in Alberta soils used for crop production.

3.4. *Sensitivity Analysis*

A sensitivity analysis was performed for the centralized system to evaluate the impact of four input parameters. The original values were varied by ±25% to show what effect these parameters have on carbon sequestration and cumulative energy demand (CED). The baseline values for carbon sequestration and CED were 0.204 t-C/t-straw and 1,355.2 MJ/t-straw.

Charcoal yield: Charcoal yield is a critical characteristic of the charcoal production equipment. It has a significant impact on the energy produced in the form of charcoal. Based on current equipment specifications and biomass quality, the energy produced for the base case was found to be 30%. Increasing and lowering the charcoal yield by 25% changes the yield range to 22.5 – 38.3%.

Straw-to-grain ratio: The straw-to-grain ratio impacts the biomass yield. A higher ratio results in a higher yield of straw per unit area of biomass harvested, and the transportation distance for the straw is shorter for higher yields. A shorter distance means lower GHG emissions than for the base case. The base case yield was 0.754 t/ha. The yields found in the sensitivity analysis ranged from 0.566 – 0.943 t/ha.

Biomass transportation distance: As described before, the study assumed a circular field and a plant that draws biomass from the area around it. The radius of the circular area is the biomass transportation distance. Biomass transport (UP2) constitutes over 50% of energy consumption and emissions involved in charcoal production. The distances evaluated ranged from 15 – 25.5 km.

Charcoal transportation distance: The location of landfill sites for charcoal can vary. The base case assumes a distance of 20 km. The impact of charcoal transport was studied by varying the transportation distance from 15 – 25.5 km.

The net impact of the above parameters on carbon sequestration is shown in Figure 5. The largest effect comes from charcoal yield. Decreasing the yield by 25% reduced the carbon sequestration from 204 t-C /t-straw to 0.195 t-C /t-straw. The straw-to-grain ratio has a smaller, but still noticeable, effect. The biomass and charcoal transportation distance has a minor effect, but this is due to small increases in the range of transportation distances evaluated. If the biomass transportation distance is increased to 200 km, the carbon sequestration falls to 0.195 t-C/t-straw. There is a similar effect seen with the charcoal transportation distance, with a 200 km transportation distance resulting in a carbon sequestration of 0.202 t-C/t-straw.

For the sensitivity analysis of the CED, shown in Figure 6, the charcoal yield has the largest effect, with a 25% decrease resulting in an increase of the CED to 1,789.1 MJ/t-straw. The effect is the same for the straw-to-grain ratio, with a 25% decrease resulting in an increase of the CED to 1,462.0 MJ/t-straw. There is once again only a minor effect when the biomass and charcoal transportation distances change. Increasing distances to 200 km results in CED values of 1,767.0 and 1,462.2 MJ/t-straw for the biomass and charcoal transportation distances, respectively.

4. Conclusion

The GHG emissions, cumulative energy demand, and net energy ratio for biomass conversion to charcoal and its sequestration in either a landfill or spreading onto the growth field were assessed. For both the centralized and portable systems, biomass collection was the largest contributor to GHG emissions and energy demand. Carbon sequestration and NER were higher in the portable systems than the centralized, but the amount of biomass they can process is substantially smaller. Both the carbon sequestration and the cumulative energy demand were most sensitive to the charcoal yield. Fixing the carbon of straw residues as charcoal can reduce the amount of carbon released to the atmosphere compared to allowing the residues to decompose on the field.

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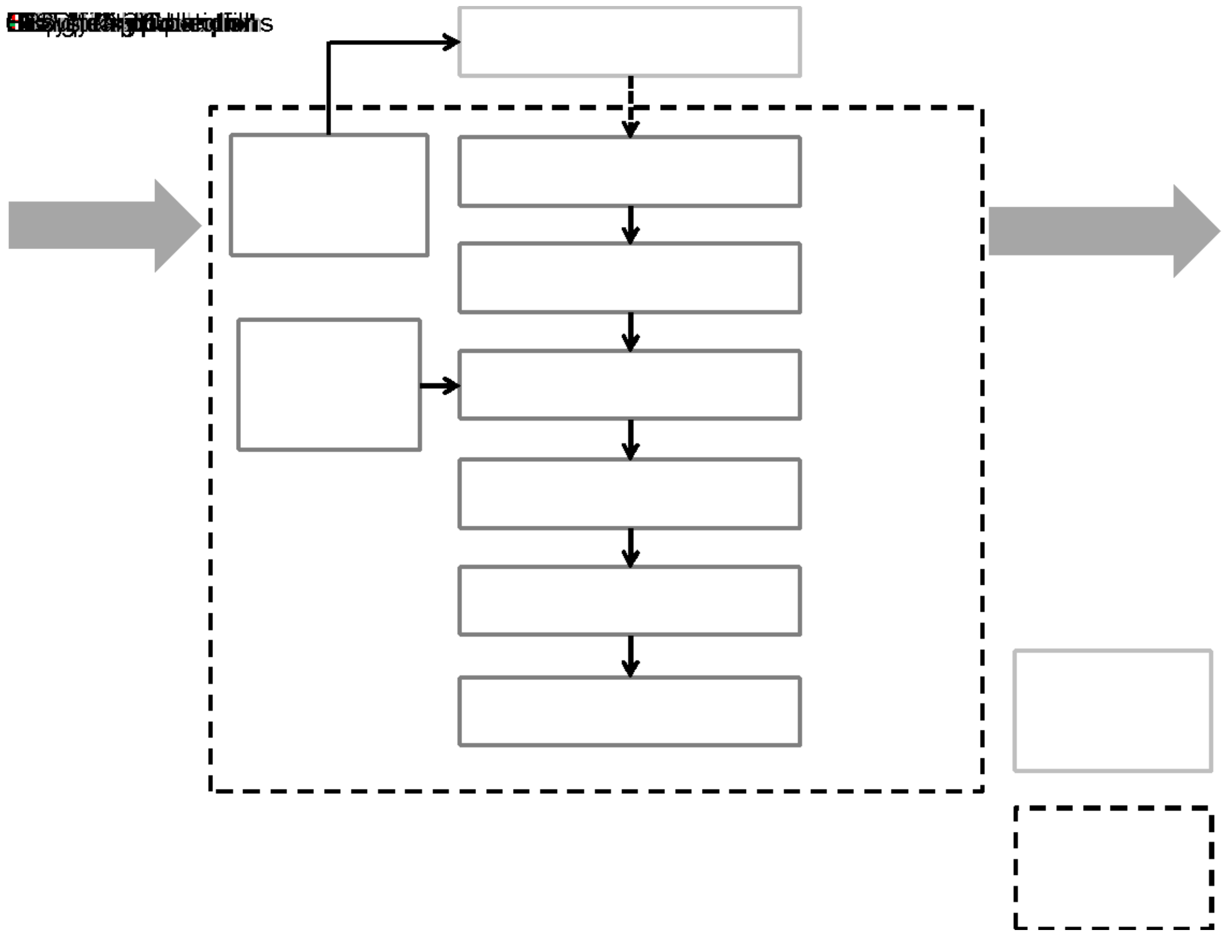

Figure 1: Life cycle assessment and energy methodology for the centralized system.

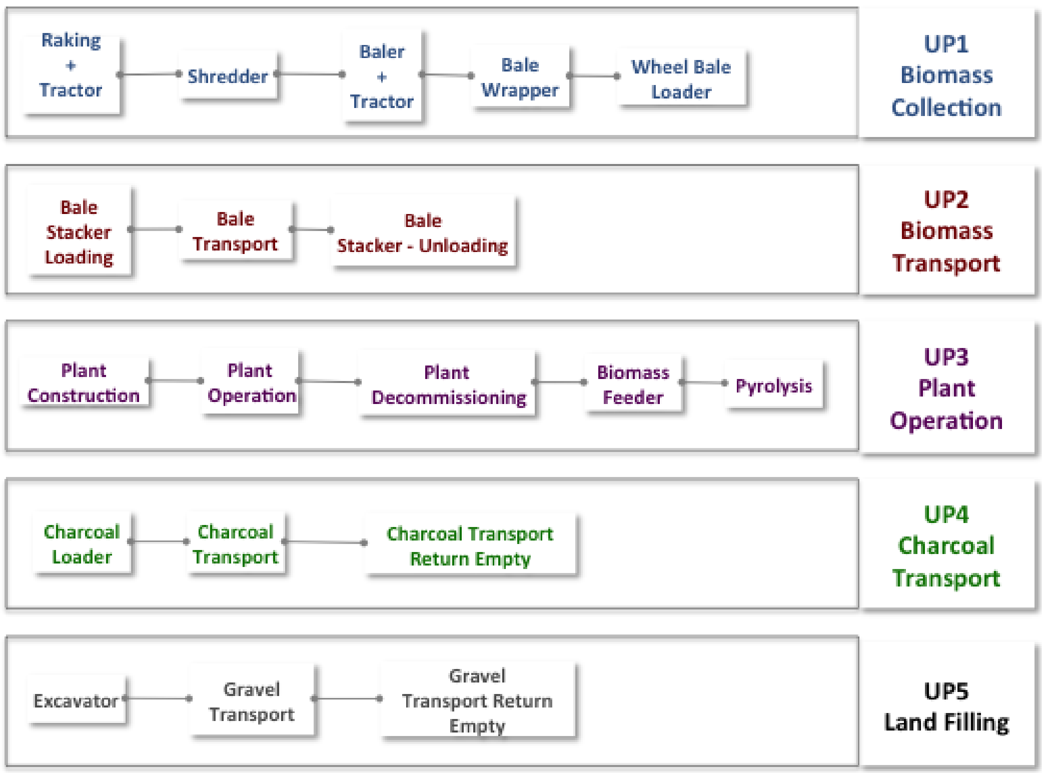

Figure 2: Unit operations involved in charcoal production from agricultural biomass.

Figure 3: GHG emissions for charcoal production in the centralized system.

Figure 4: Cumulative energy demand (CED) for charcoal production in the centralized system.

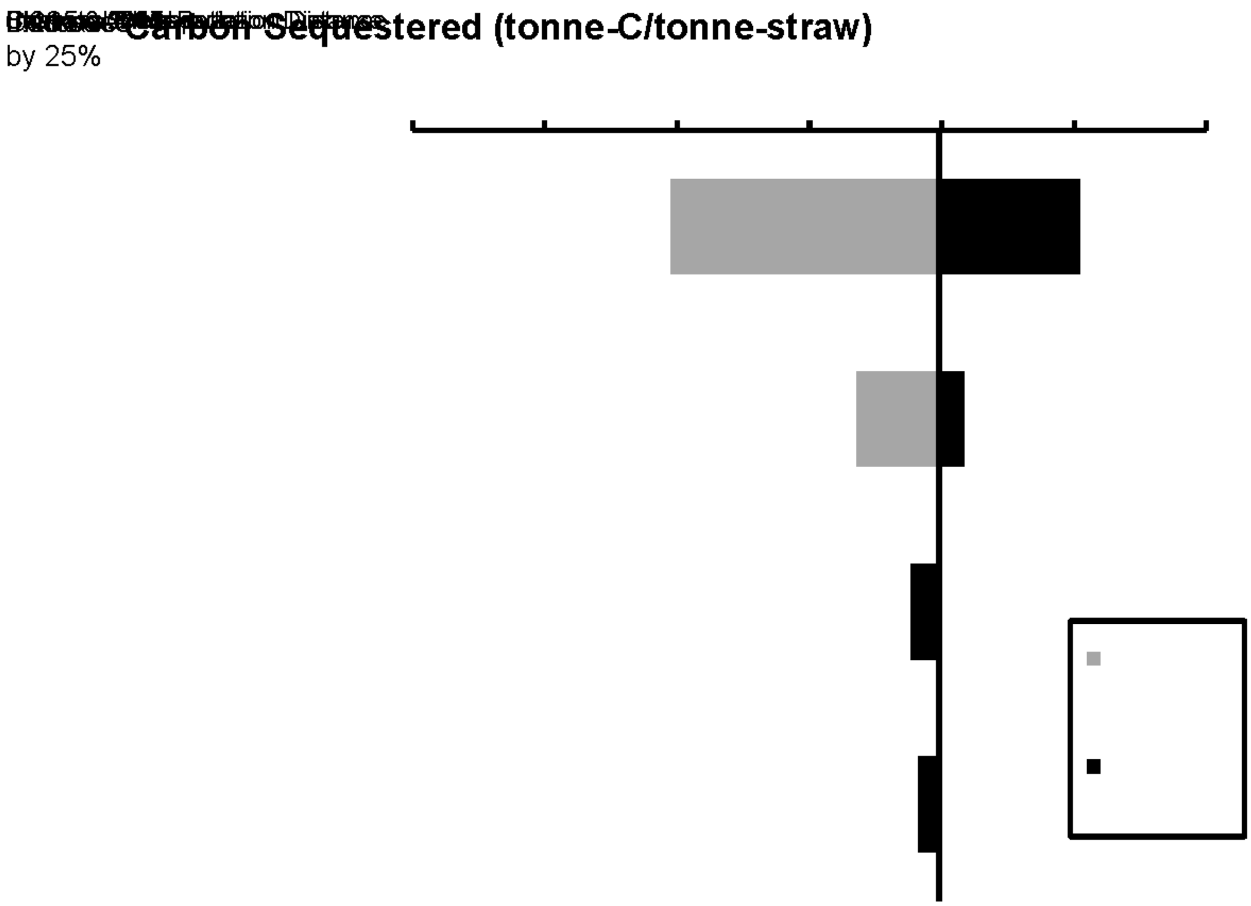

Figure 5: Sensitivity analysis of the net carbon sequestered for the centralized production system.

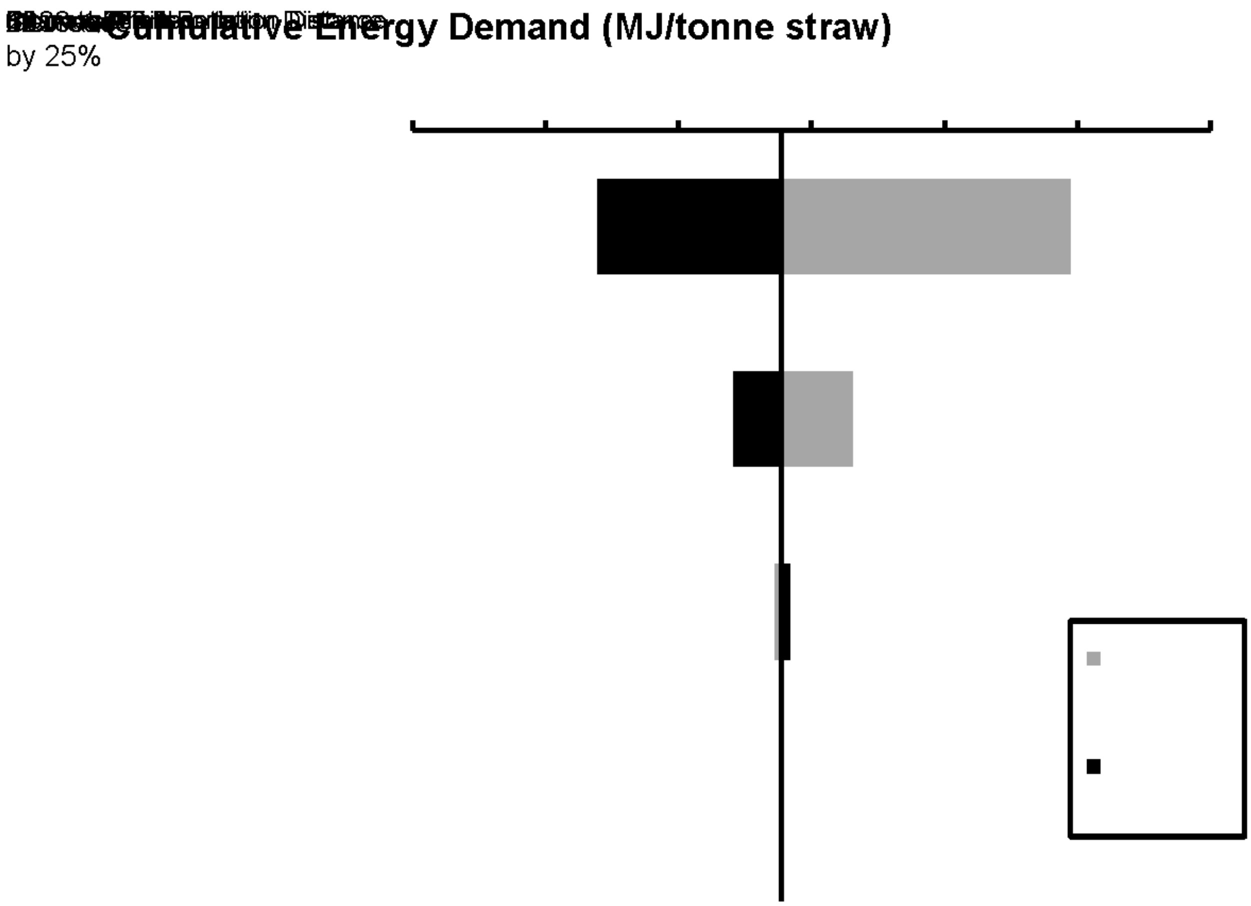

Figure 6: Sensitivity analysis of the cumulative energy demand for the centralized production system.

Table 1: Emissions and energy factors

Items	Energy required (GJ/t)[1]	GHG emissions involved (kg -CO_2 eq./t)[2]	% To be land-filled[3]	Source / Comments
Steel (used 30%)	25.5	2500	25%	For material acquisition, manufacturing, and transportation [23]
Recycled steel (used70%)	9.7	1820		
Aluminum	120.3	3470	100%	
Landfilling	0.08	7.45		Based on transportation of charcoal to a distance of 200 km for landfilling [23]
Concrete	0.87	120	100%	Includes procurement, processing, and transportation of concrete [22,24]
Diesel	51.5	4.1		Values for IL of diesel combustion [20,21,23]
Nitrogen (as N)		3,518		Production of nitrogen fertilizers [25]
Phosphorus (as P_2O_5)		675		Production of phosphorus fertilizers [25]
Potassium (as K_2O)		654		Production of potassium fertilizers [25]

Energy required in GJ per tonne of raw material consumption due to its manufacturing, transportation, acquisition, and other related operations.

[2]GHG emissions involved per tonne of raw material consumption (manufacturing, transportation, acquisition, and other related operations).

[3]This column indicates the % of material that is assumed to be landfilled after the plant is decommissioned.

Table 2: Equipment specifications used for the production of charcoal (derived from [17,26,27]).

	Horsepower Requirement	Work Rate	Unit	Operational Efficiency[1]	Fuel Economy (g/hr)
Shredder	225	25	t/hr	0.8	9.86
Raker		30	t/hr	0.7	3.72
Baler	275	20	t/hr	0.65	15.33
Telescopic Stacker				0.65	3.5
Bales/Load		2			
Weight/Bale		0.55	tonne		
Load Time		0.25	minutes/load		
Unload Time		0.2	minutes/unload		
Speed		30	kmph		
Farm Wheel Loader	120	2	bales/load	0.65	14.81
Load Time		0.25	minutes/load		
Unload Time		0.2	minutes/unload		
Truck Transport 40' Bale BC 4075	550	26	bales/load	0.75	24.09
Average Travel Speed		24	kmph		
Load/Unload Time		2.6	minutes/bale		
Inspection Time		1.3	minutes/bale		
Tractor 45-P	275	160	horsepower	1	5.26
Excavator	138			1	25.15
Charcoal Loader					20
Charcoal Transport					16

[1] Assumed to be one unless literature provided a value

Table 3: Energy and emissions for various unit operations in a centralized production system

UP*		Operation	Time Required (hrs/t-straw)	Fuel Economy (L/ hr)[1]	Energy Required (MJ/t-straw)[2]	Emissions (kg- CO_2eq/t-straw)
UP1						
	1	Shredding	0.050	37.32	96.2	7.7
	2	Tractor for shredder	0.050	5.26	51.3	4.1
	3	Rake	0.047	14.08	34.6	2.7
	4	Baler	0.076	58.03	230.0	18.3
	5	Tractor for bailer	0.076	19.91	78.9	6.3
	6	Fertilizer Replacement				34.4
	Total	Straw collection and processing	0.301		490.9	73.5
UP2						
	1	Loader field	0.006	56.06	16.8	1.3
	2	Biomass loading	0.006	13.25	4.0	0.3
	3	Biomass truck transport	0.158	91.19	747.8	59.5
	4	Unloaded	0.006	13.25	3.2	0.3
	Total	straw transport	0.175		771.8	61.4
UP4						
	1	Charcoal loader	0.001	75.71	4.0	0.3
	2	Truck transportation	0.006	60.57	18.3	1.5
	Total	Charcoal transportation	0.006		22.3	1.8
UP5						
	1	Excavator	0.003	95.20	7.5	0.6
	2	Dump gravel (loading + travel + unloading)	0.015	60.57	48.9	3.9
	Total	Landfilling	0.018		56.4	4.5

*UP: Unit operations.
1Fuel economy is obtained from [17,26,27].
2Energy and emissions calculations are based on factors taken from Table 1.

Table 4: Energy and GHG emissions for plant operations (UP3) in a centralized production system

Material required in plant construction		Amount of material required (kg/t-straw)	Energy required (MJ/t-straw)[1]	GHG emissions (kg-CO_2eq/t-straw)
Plant Construction[2]				
	Concrete	2.222	1.92	0.27
	Steel	0.702	10.14	1.42
	Aluminum	0.006	0.56	0.01
	Total		12.62	1.70
Plant Operation				
	3% of Construction		0.38	0.05
Plant Decommissioning				
	Landfilling concrete	100%	0.18	0.27
	Landfilling steel	25%	0.01	0.001
	Landfilling aluminum	100%	0.0003	0.00003
	Decommissioning process 3% of construction		0.51	0.07
Conveyer				
			0.0003	0.03

[1]Energy and emissions calculations are based on parameters from Table 1.
[2]Materials required for the construction of the size of the charcoal production plant considered in this study were estimated based on data from earlier studies and adjusted using a scale factor of 0.76 [6,34,35,41].

Table 5: Cumulative energy demand (CED), net energy ratio (NER), and GHG emissions for all charcoal production systems.

Equipment	Biomass Processed (dry-t/yr)	Charcoal Production (t-charcoal/t-straw)	Net Emission Reduction (kg CO_2eq/t-straw)	Net Carbon Sequestered (t-C/t-straw)	CED (MJ/t-straw
CENTRALIZED SYSTEM					
	437,713	0.292	747.95	0.204	1,354.4
PORTABLE SYSTEM					
Big 22 12 Hrs	4,600	0.285	835.04	0.141	517.00
Big 22 21 Hrs	8,050	0.285	835.04	0.141	517.00
Big 22 24 Hrs	9,200	0.285	834.76	0.141	517.00
Adam	170	0.282	863.16	0.217	490.68
Big 1000	1,840	0.285	825.63	0.141	506.74

Table 6: Summary of results for cumulative energy demand (CED) and GHG emissions for the centralized system and the Big 22 portable systems.

Unit Processes	Emissions Produced		CED	
	$kgCO_2eq$/t-straw		MJ/t-straw	
	Central	*Portable*	*Central*	*Portable*
UP1: Straw processing	73.5	74.7	490.9	517.1
UP2: Straw Transport	61.4	0	771.9	0[a]
UP3: Charcoal Production	2.1	0.8	13.7	14.2
UP4: Charcoal Transport	1.8	0	22.2	0[a]
UP5: Charcoal Landfilling	4.5	0	56.4	0

[a] These would be a very small amount as the transportation is in the farm itself.