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Life Cycle Assessment of Sweet Sorghum as Feedstock for Second-generation Biofuel Production

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Abstract

There exist few life cycle assessments (LCAs) in the literature that focus on the second-generation biofuel production from sweet sorghum, a non-food-source feedstock that offers several advantages in terms of farming requirements compared to corn or sugarcane. The objective of this LCA study was to evaluate biofuels produced from sweet sorghum to determine the potential environmental benefits of producing sweet sorghum biofuel compared to conventional fossil fuels. The biofuel production process used for this study differed from other LCAs in that, in parallel to stalk juice extraction and fermentation, residual bagasse and vinasse was pyrolyzed and upgraded to a diesel equivalent as opposed to being fermented or combusted for a source of heat or electricity production. The life cycle inventory included data available in the literature regarding mass and energy input requirements for farming, juice extraction, fermenting, pre-treatment, pyrolysis, and steam reforming steps. Experimental data for bio-oil upgrading was obtained from a pilot plant in Huntsville, AR, including hydrogen gas requirements for hydrotreatment and diesel, biochar, and non-condensable gas yields. The functional unit used for this study was the total kilometers driven by standard passenger vehicles using ethanol, gasoline and diesel produced from 1 ha of harvested sweet sorghum (76 wet tons). Total biofuel yields resulting from this basis were 5,122 L of bioethanol, 2,708 L of gasoline and 780 L of diesel. With these yields, distances of 58,500 km, 21,500 km, and 12,070 km were chosen as the functional unit for the combustion of E85, E10, and diesel, respectively based on vehicle fuel efficiencies from the GREET model. Compared to conventional gasoline, this production process resulted in nearly 50% reduction of GHGs and 46% reduction in fossil fuel depletion, in addition to reductions in eutrophication, ecotoxicity, and carcinogenics. However, fossil fuels were lower by 25%, 45%, and 12% in the categories of non-carcinogenics, respiratory effects, and smog, respectively. These lower impacts for fossil fuels are driven by heavy-metal uptake from corn production and the fact that less electricity is used in the supply chain compared to biofuel production. A Monte Carlo simulation showed the comparative impact assessment results were not sensitive to uncertainty in life cycle inventory. While the impact assessment showed benefits in producing sweet sorghum biofuel compared to fossil fuels, further research must be conducted on land use and water use. A detailed process simulation, coupled with continued experimental studies of the pyrolysis and upgrading processes, is recommended for further process optimization and heat integration, as well as composition analyses of the various co-products resulting from the process. Further studies will provide valuable information in choosing between feedstocks, specifically those which can be used to produce second-generation biofuels.

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1 Introduction

As the world's energy demands are expected to increase substantially in the next few decades, the use of conventional sources of energy, such as fossil fuels, are proliferating concerns regarding their sustainability and effects on the environment (Doman 2016). In order to combat these energy security concerns, research in renewable fuels has increased in recent decades, including efforts to increase the market share of these fuels and reduce dependence on fossil fuels. However, the production of first-generation biofuels has also sparked the food vs. fuel debate. Thus, there exist on-going efforts to produce second-generation biofuels from crop residues such as corn stover, switchgrass, etc. that are not primary sources of food (Daystar et al. 2014). Sweet sorghum, a type of grass that originates from Africa, is one potential feedstock that could be used for second-generation biofuel production since its bagasse is not a primary source of food (stalk juice can be used to produce syrup). When compared to sugarcane and corn ethanol, sweet sorghum provides several advantages, including: 1) high sugar content in its stem that is directly fermentable, 2) lower water and fertilizer requirements, 3) more drought and salt resistance and adaptability to tropical, subtropical, temperate climates, and 4) short harvesting period that lies in the intermittent sugar-harvesting period allowing for crop rotation (Ratnavathi et al. 2011; Eggleston et al. 2013). When compared to other feedstock crops for second generation biofuels such as corn stover, rice straw and wheat straw, sweet sorghum has competitive potential ethanol yields (0.27 L/kg dry biomass) and residue/crop ratios (1.3) (Capareda 2014).

The high potential for this crop to be utilized as a renewable fuel source has led to increased research in both the cultivation and harvesting aspects of the crop as well as the environmental performance of several biofuel production pathways from its grain, stalk juice, and/or bagasse. The majority of these studies have focused on the environmental impacts associated with ethanol production from sorghum juice, with residual bagasse used as either a heat source, animal feed, cellulosic feedstock for biofuel production, or simply returned to the field. For example, Wortmann et al focused on life cycle greenhouse gas emissions (GHG) per liter of ethanol produced from sweet sorghum stalk juice, with residual bagasse being returned to the field with no energy credits and negligible effects on soil organic carbon (2010). Wang et al conducted an LCA of sweet sorghum biofuel in which both stalk juice and bagasse was fermented and converted to bioethanol using continuous solid-state fermentation (2014). Other studies include multiple biofuel-pathway scenarios which produce ethanol from stalk juice and use residual bagasse either as a feedstock for a combined heat and power system or a cellulosic feedstock for additional ethanol production (Cai et al. 2013). Similar to these studies, Caffrey et al provides cradle-to-gate analyses of sweet sorghum biofuel in which the on-site product varies from complete ethanol production to biomass that is to be utilized as cellulosic feedstock (2014). While many of these studies focus on comprehensive LCAs for biofuel production from sweet sorghum and report favorable GHG emission reductions compared to conventional fuel (>50% reduction in GHG emissions which qualify sweet sorghum as an advanced biofuel, EPA 2012), there are no LCAs available in the literature that focus on a biofuel production process in which the bagasse is converted to gasoline and diesel using pyrolysis and hydrotreating technology (Cai et al. 2013; Wortmann, et al. 2010).

Pyrolysis is a thermal conversion process in which biomass is heated in the absence of oxygen; the heat applied to biomass breaks down complex macro-components in biomass and produces condensible liquid (bio-oil), non-condensible gases (syngas) and charcoal (biochar). The resulting bio-oil can be upgraded to transport fuels through catalytic hydrotreatment with hydrogen gas (Jones et al. 2013). These processes, while still currently under development, have shown to be successful in yielding bio-oil at temperatures above 400 °C with high heat transfer rates for sorghum biomass particles (amongst other types of biomass). This bio-oil can be upgraded to naphtha-range and diesel-range fuels (Ringer et al. 2006; Wright et al. 2010; Capareda 2014). Thus, the objective of this study was to conduct a life cycle assessment of sweet sorghum biofuel produced from both stalk juice fermentation and bagasse and vinasse pyrolysis and hydrotreatment using literature and experimental data for pyrolysis and hydrotreatment gathered from a pilot plant located in Huntsville, AR.

2 Methods

2.1 Goal and Scope

The goal of this study was to evaluate the environmental performance of a biofuel production from sweet sorghum. This process has potential to be a source of fuel due to its high energy content and sustainable production with low farming input requirements. This full process, while still currently in development, has environmental emissions that can be quantitatively estimated and compared to those of conventional gasoline in order to provide valuable information that will aid in making decisions regarding alternative sources of fuel.

The scope of this study includes a cradle-to-grave analysis of sweet sorghum biofuel production and consumption process built from the unit processes required to produce 1) bioethanol from sweet sorghum stalk juice, and 2) gasoline and diesel from the pyrolysis and hydrotreatment of bagasse and bio-oil, respectively. This analysis encompasses all unit processes involved in the production cycle, beginning with the cultivation and harvesting of sorghum and ending with the combustion of all biofuel products to propel a vehicle.

2.2 System Boundary

The system boundary (Figure 1) for this study includes required mass and energy inputs for: 1) cultivation and harvesting of sweet sorghum, 2) stalk juice extraction and fermentation, 3) pre-treatment and pyrolysis of bagasse, 4) hydrotreatment of bio-oil and fuel blending, 5) production of H_2 gas for hydrotreatment, and 6) production of corn ethanol for blending with gasoline produced (required process outlined in Section 2.5).

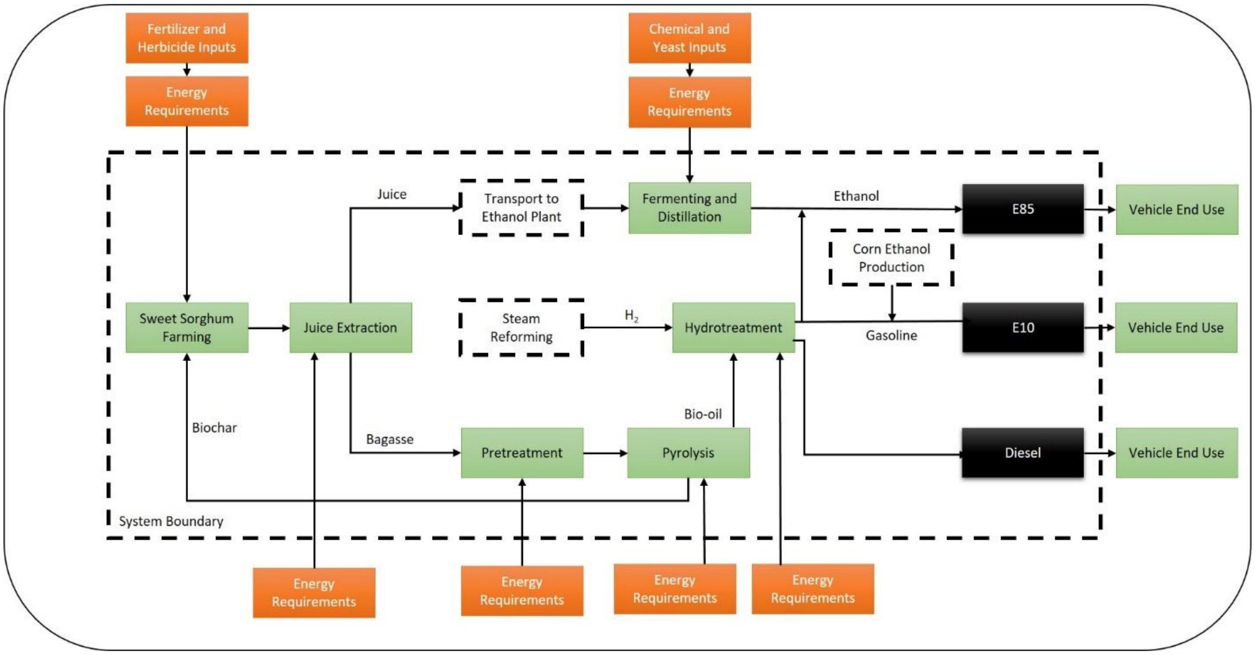

Figure 1. System Boundary of Life Cycle Assessment of Sweet Sorghum Biofuel Production

Each unit process of this production cycle is discussed in more detail in the following sections. These descriptions also include assumptions that were used in obtaining estimates for mass and energy inputs.

2.3 Functional Unit

The LCA studies mentioned previously for sweet sorghum biofuel production use a functional unit of liters (or other unit of volume) of ethanol produced to compare environmental impacts of the production process with those associated with a liter of conventional gasoline; however, the use of this functional unit does not account for the benefits of reduced end-use emissions from biofuel when compared to conventional fuels, specifically when comparing life cycle GHG emissions between fuels. Thus, the functional unit used for this analysis was total kilometers driven from the combustion of *all* biofuel produced from 1 ha of sweet sorghum cultivation (approximately 76 tons of fresh biomass).

2.4 Life Cycle Inventory

2.4.1. Cultivation and Harvesting of Sweet Sorghum

A system process for the cultivation and harvesting of sweet sorghum was available in SimaPro and used as a basis for this step of the process (sorghum, at farm/US Mass). This system process, based on a typical sorghum farm in the U.S., includes fertilizer, pesticide and diesel use required for sorghum farming on 1 ha of land and includes all emissions to air, water and soil. This process was modified for various inputs, including offsets in fertilizer requirements arising from application of biochar (Section 2.4.3).

2.4.2 Stalk Juice Extraction and Conversion to Ethanol

An industrial-scale roller mill was chosen for stalk juice extraction from harvested sweet sorghum biomass. Based on manufacturer information for a specific roller mill (Demuth Standard Roller Mill Model 720), the energy required per kg of mass processed through the mill was estimated to be 10.85 kJ/kg of fresh sorghum stalk (2013). For this step, it was assumed that approximately 87 % of soluble sugars in the sorghum stem were retained in the sorghum juice from juice extraction (Almodares & Hadi 2009; Eggleston et al. 2013). Some water (~10% of sorghum stem feed) was also added in this step to aid in the sugar extraction process. Leftover bagasse (22.7 tons) is then prepared for pyrolysis, and leftover grain (1.8 tons) recycled back into the farming step as seed for the subsequent planting season.

For stalk juice fermentation, sugar content for stalk juice was assumed to be 14 wt % based on literature values (Gnansounou et al. 2005). A conversion factor of 90% of fermentable sugars was used in calculating ethanol yields. Similar to the farming unit process, a combined fermentation and distillation system process for sorghum stalk was available in SimaPro, which was modified to use stalk juice created in this process (ethanol, 95% in H_2O, from sweet sorghum, at distillery/kg/CN).

2.4.3 Pre-treatment and Pyrolysis of Bagasse

According to technical reports provided by the NREL, fast pyrolysis of biomass requires small, dry particles, approximately 2-5 cm in diameter depending on the equipment used. Additionally, water is generated during the pyrolysis process (resulting bio-oil may contain 12-15 wt % water). The latent heat of the water can act as a heat sink for energy that would otherwise be utilized for conversion of biomass to pyrolysis products (Ringer et al. 2006). Thus, pretreatment of bagasse must include particle comminution (size reduction) and a drying step to minimize the amount of water in the pyrolyzer. Energy requirements for a dryer were estimated using the moisture content of wet bagasse (73 wt % after stalk juice extraction) and the latent heat of water, assuming 75% efficiency of the dryer (Almodares & Hadi 2009). Energy requirements for particle size reduction were estimated based on a knife mill with a ¼ inch screen size. Based on particle size requirements, energy inputs were found to be approximately 28 kWh/tonne of dry bagasse for a mean particle size of 1.68 mm (Bridgwater & Boocock 1997).

Bio-oil, biochar, and syngas yields for pyrolysis of dry sorghum bagasse particles was assumed to be consistent with theoretical NREL values of 75 wt % bio-oil, 12 wt % biochar, and 13 wt % syngas (2006). Energy requirements for this process were also estimated based on NREL values of 1000 kJ/kg of biomass. Syngas resulting from the process was used as a source of heat via combustion and was used in the ethanol distillation step of the process. Biochar produced was recycled to the farming step where it was assumed to offset fertilizer requirements by 0.91 kg ammonium nitrate per 100 kg of applied biochar (Capareda 2014).

2.4.4 Hydrotreatment of Bio-oil and Steam Reforming

Yields of gasoline, diesel, and non-condensable gases were based on experimental data provided by Process Dynamics, Inc. Hydrogen gas requirements were also based on experimental requirements, amounting to 30 g of hydrogen gas per kg of bio-oil. Steam was a co-product generated in this process, which as utilized as a source of heat for the bagasse drying step. Additionally, the non-condensable gases resulting from this process were also used as a source of heat via combustion for ethanol distillation.

A steam reforming unit process was created in SimaPro for producing the hydrogen gas required for hydrotreatment/upgrading bio-oil to transportation fuels. The inputs were stoichiometric amounts of natural gas and water (steam) that generated hydrogen gas and residual steam. This residual steam was utilized as heat for drying.

2.5 Vehicle End Use for Fuel Blends and Diesel

As the functional unit for this study was total distance (km) driven, the three main fuel products that were analyzed for vehicle end-use were 1) ethanol produced from stalk juice and 2) gasoline and diesel produced from pyrolysis and upgrading of bagasse. In order to determine the distance driven from these products, fuel blending was required to make four common blends that are used in either standard passenger vehicles (spark ignition direct injection, SIDI) or diesel cars (compression ignition direct Injection, CIDI). These blends are 10 vol % ethanol/90 vol % gasoline for E10, and 85 vol % ethanol/15 vol % gasoline for E85. To produce E85 blend, all ethanol produced from stalk juice fermentation was assumed to be used in conjunction with gasoline (approximately 810 kg of gasoline) produced from bio-oil upgrading. The excess gasoline (1,137 kg of gasoline) was then blended with conventionally produced corn ethanol to produce an E10 blend. This blend was chosen because, although it required corn ethanol, it is more common than pure gasoline. Diesel produced was assumed to have the same energy content as renewable diesel. The energy content of these blends as well as the energy requirements of the vehicles that would utilize these fuels were taken from the GREET model (Table 1).

Table 1. Vehicle and Fuel Data Obtained from GREET (2016)

Fuel	**Energy Required (kJ/km)**	**Energy Content (MJ/m^3)**	**Density (kg/m^3)**	**Fuel Economy (kg/km)**
Spark Ignition Direct Injection				
E10	2,452.5	31,270	749	0.0587
E85		23,125	781	0.0829
Compression Ignition Direct Injection				
Low Sulfur Diesel	2,350	35,800	832	0.0546
Renewable Diesel		34,000	778	0.0538

In order to compare the environmental emissions from producing and combusting sweet sorghum biofuels with the emissions associated with conventional fuels, the same functional unit was used for both processes. A process for total kilometers driven using E10, E85, and diesel fuels was created in SimaPro in which fuels where produced from conventional petroleum processes.

2.5 Allocations and Recycle Streams

In unit processes that generated co-products, mass allocations were used to distribute environmental burdens. As discussed in each unit process description, recycle streams and process heat integration were utilized in this analysis. Figure 3 summarizes the recycle of streams including sweet sorghum grain, biochar, and vinasse. Heat integration for excess steam and non-condensable gases is also shown.

3 Results

3.1 Mass Balance and Biofuel Yields

Based on the inputs for each unit process, yields, and energy requirements outlined in methods, total yields of ethanol, gasoline and diesel were found for the basis of sweet sorghum harvested from 1 ha of land. These results are shown in Table 2.

Table 2. Biofuel Yields from 1 ha of Sweet Sorghum

Sweet Sorghum Component	**Type of Biofuel**	**Amount of Fuel (L)**
Stalk Juice	Ethanol	5,122
Bagasse	Gasoline	2,705
	Diesel	780

As mentioned previously, E10 and E85 blends were chosen as end-use products for combustion in a standard passenger vehicle. Based on the ratio requirements for each blend, amounts of E10 and E85 blends were 1686 L and 6,211 L, respectively (Figure 2). The excess gasoline produced from the process required corn ethanol for blending. All of the diesel produced from 1 ha of sweet sorghum farming was assumed to be utilized as diesel fuel for a vehicle equipped with a CIDI engine.

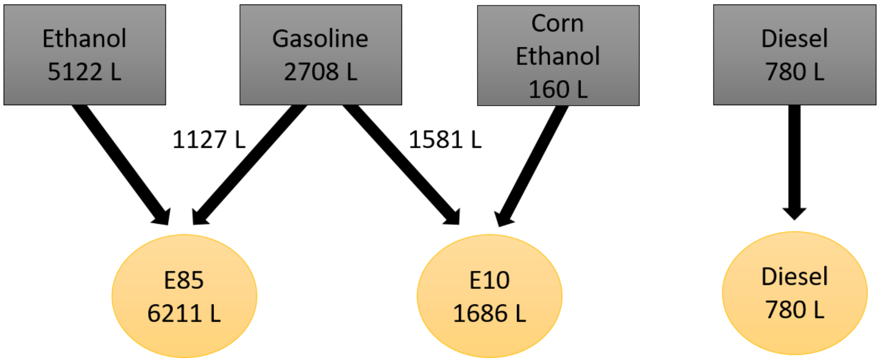

Figure 2. Fuel Blending with Sweet Sorghum Biofuels

Based on energy content values and vehicle energy requirements, distances of 58,500 km, 21,500 km, and 12,070 km were found for E85, E10, and diesel, respectively. Thus, the functional unit used to find environmental emissions was chosen as these distances achieved by the combustion of these blends, originating from either conventional sources or sweet sorghum stalk juice and bagasse.

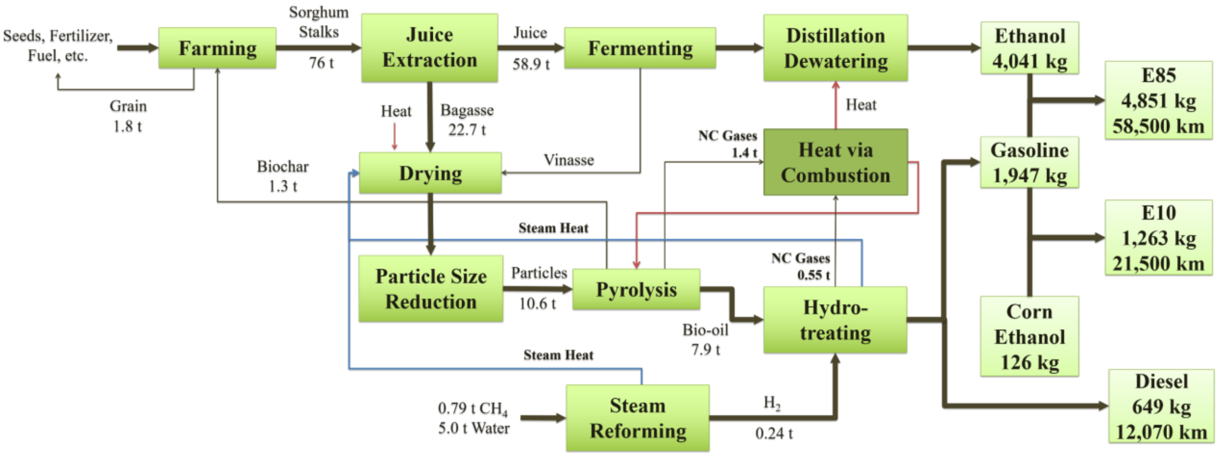

Figure 3. Mass Balance of Sweet Sorghum Biofuel Production

Figure 3 shows a detailed overview of the production process used for this study, including an overall mass balance and process heat integration. As shown in the diagram, steam was a by-product in the hydrotreating process and steam reforming process. This steam is used as a source of heat for the drying step of the process. Supplemental heat is also required for the drying step in the form of natural gas. Non-condensable gases produced from pyrolysis and hydrotreating are combusted to provide heat to the ethanol distillation process.

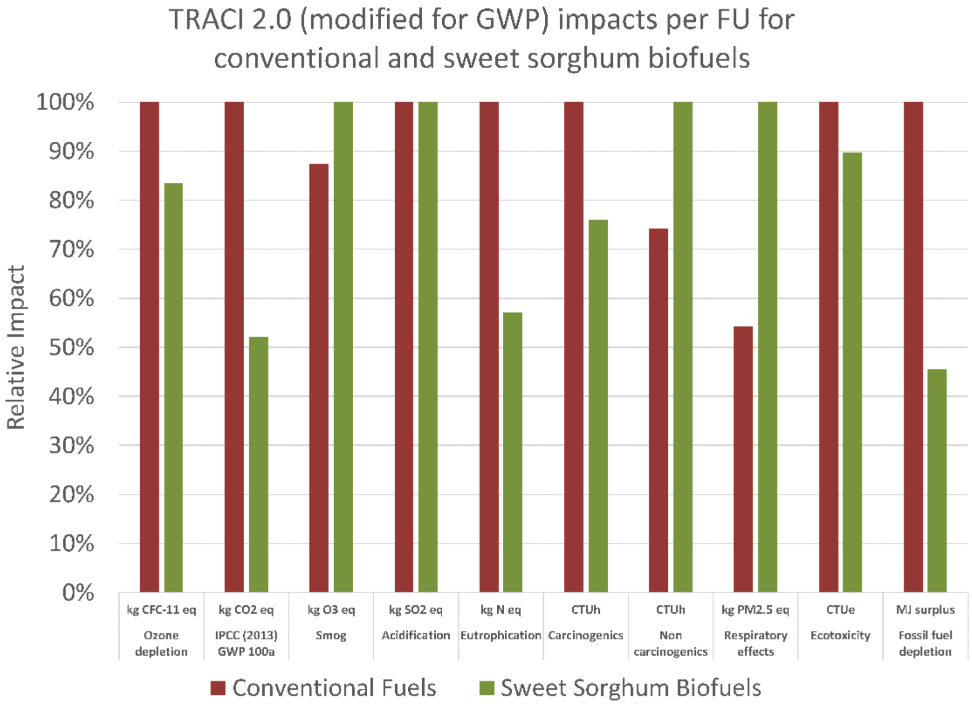

Figure 4. Environmental Impacts of Sweet Sorghum Biofuels Compared to Conventional Fuels

Compared to conventional fuels for the functional unit of total kilometers driven, the production and combustion of sweet sorghum biofuels shows a reduction of almost 50% in the global warming potential category (kg CO_2 equivalent). Additionally, reductions are also seen in the categories of fossil fuel depletion (54%) eutrophication (62%), carcinogenics (34%), and ecotoxicity (11%). There are also categories that show equal or increased values of emissions when compared to conventional fuels including smog, acidification, non-carcinogenics, and respiratory effects. Both sorghum fuels and conventional fuels had equal relative impacts in the acidification category. For the categories of smog, non-carcinogenics, and respiratory effects, conventional fuels had lower emissions of 12%, 25%, and 45%, respectively, in comparison to sorghum fuels.

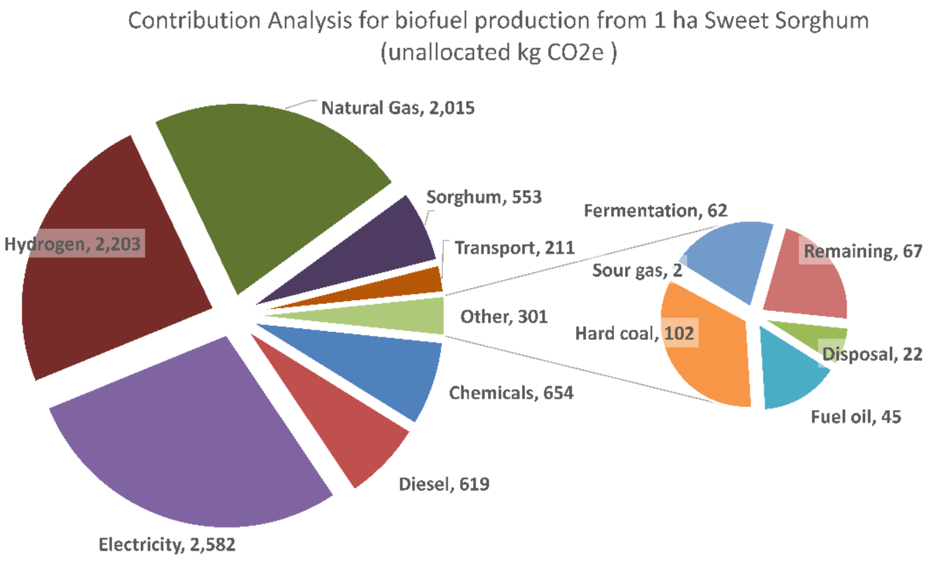

Figure 5. CO_2 Equivalent Contribution Analysis for Sweet Sorghum Biofuel (1 ha)

Figure 5 shows a contribution analysis of global warming potential (GWP), where unallocated kg CO_2 equivalent refers to the fact that there are not separate calculations for the different fuels, but reports contributions for the functional unit. As shown in the figure, hydrogen, electricity, and natural gas were the largest contributors to global warming potential (GWP). Approximately one third of the natural gas was required for the drying step of the process and the remainder was used for hydrogen gas production for hydrotreating.

4 Discussion

Based on literature and experimental data available for the use of sweet sorghum as a feedstock for biofuel production, a process for converting sugars in stalk juice to ethanol and bagasse into fuel was constructed. The functional unit for this process was the total distance that could be driven by combusting these fuels produced. Yields for ethanol, gasoline, and diesel were 5,122 L, 2,708 L, and 780 L, respectively. Based on these yields, E10 and E85 blends were made by using all ethanol produced from 1 ha for an E85 blend. Gasoline produced was split between use in E85 blend and making E10 blend. The E10 blend was composed of sorghum gasoline and corn ethanol, as this blend would most likely be used in a standard passenger vehicle. The diesel was assumed to be used directly as produced by a diesel vehicle. These blends, when combusted, were found to propel a vehicle distances of 58,500 km, 21,500 km, and 12,070 km, respectively, totaling approximately 92,070 km driven from sweet sorghum biofuels (based on fuel efficiencies from the GREET model). This functional unit was used in analyzing the impact assessment between sorghum fuels and fossil fuels.

When compared to fossil fuels, the production and combustion of sweet sorghum biofuels for the same distance travelled shows lower emissions in the categories of fossil fuel depletion, global warming potential, ozone depletion, eutrophication, carcinogenics, and ecotoxicity. GWP in particular showed almost a 50% reduction for sweet sorghum biofuels, which shows that both the production and combustion of these fuels significantly reduces kg of CO_2 equivalent compared to fossil fuels. Large contributors to GWP for sweet sorghum biofuels were in the production of hydrogen gas and the use of natural gas and electricity for a number of unit processes.

While there are no similar studies on this particular process to compare impact assessment results, Cai et al determined the well-to-wheels (WTW) greenhouse gas emissions associated with the production of ethanol from sweet sorghum sugars in the stalk and some bagasse used as cellulosic feedstock and the rest used for combined heat and power (2013). The impact assessment from this study showed that the production of sweet sorghum fuel showed greenhouse gas reductions of 70-72% compared to gasoline. This reduction is higher than the value found for this study. Differences in these reductions could be due to the amounts of natural gas required for hydrotreating/upgrading of bio-oil in this process in comparison to using bagasse for combined heat and power.

5 Conclusions/Recommendations

While research continues to expand in discovering feedstocks that can be utilized to produce second-generation biofuels, more efforts are needed to determine whether processes utilizing these feedstocks provide reduced greenhouse gas emissions and fossil fuel depletion, as well as other desired environmental benefits in comparison to conventional fuels. Additionally, comparing environmental burdens between various cellulosic feedstocks can provide valuable insight into the multiple options for alternative fuels that need to be evaluated when deciding if and how these fuels should be utilized.

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