Life Cycle Assessment of Sugar Production in Sudan: Green-House Gases Emissions and Energy Usage

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Abstract

A Life Cycle Assessment used to analyse the Sudanese sugar production environmental impact. The systems studied include sugarcane production, fertilizers, and herbicides manufacturing, sugarcane harvesting and transportation, and sugar milling. The study used SimaPro Software Version 9.0.0.49 and the methods of ReCiPe 2016 and Intergovernmental Panel for Climate Change (IPCC) 2007. Sugarcane production was the most consumer (39%) of fossil fuel (2166 MJ t\(^{-1}\) sugar), followed by sugar processing (26.6%), sugarcane cultivation (20.7%) and sugarcane harvesting with transportation (13.7%). The greenhouse gases emissions were 271.2 kg CO\(_2\)-equivalent t\(^{-1}\) sugar and 59% of this is from sugarcane production. However, 51% of the global warming potential was from sugar processing, sugarcane production. The principal contributor to ozone depletion was sugarcane production (44%). Sugar processing has contributed significantly to eutrophication, acidification, particulate matter, and ecotoxicity. The study has recommended enhancement on the sugar industry operations that would substantially improve environmental performance.

Introduction

The sugar production process consumes large quantities of resources, such as water and fossil energy (Nakhla 2014; Sahu 2018). The process generates a considerable amount of waste and pollutants in the form of gaseous and solid. Debris and contaminants harm the surrounding environment. For example, fossil fuel utilization releases harmful gasses that pollute the air and cause environmental problems such as global warming (Ramiro et al. 2019). Also, the combustion of bagasse for electricity to supply the system generates ash which could influence the human health (Cordiero et al. 2004; Mohamed and Samah 2011; Le Blond et al. 2017; Sahu 2018). Intensive sugarcane production requires chemicals such as fertilizers and herbicides to raise the yield and control diseases.

On the other hand, the residues of these chemicals could influence the soil and environment. Also, machinery is involved in almost all sugarcane agricultural stages and produces a large emission (Ramiro et al. 2019). From the environmental point of view, the gaseous emissions, effluents, and energy use of the sugar industry should be monitored to minimize the environmental impact. Therefore, it is necessary to identify the energy usage and assess the emissions and their effects on the environment's Sudanese sugar industry. Because the sugar production process could adversely create an impact in the environment, the life cycle assessment (LCA) method can be useful for calculating, analyzing, and interpreting these environmental impacts. The LCA became a familiar tool to undertake a systematic environmental assessment throughout the chain of sugar production. ISO 14040-44 standards design LCA, consisting of the scope, the inventory analysis, the evaluation of impact, and the interpretation of results (Livison et al. 2010; Astuti et al. 2018; Ramiro et al. 2019). Many studies have been conducted using this methodology in different countries around the world, such as Brazil, South Africa, Egypt, and Mauritius. Due to the lack of data in Sudan, the application of LCA has not been conducted for the sugar industry sector. This study aims to quantify the greenhouse gasses emissions into the air and the amount of energy used for sugar production in Sudan. The research applied the principles of life cycle
assessment to evaluate the environmental impact attributed to sugar production. Also, identify which stage of the product life cycle has the most significant environmental impact. The study identified opportunities to improve and develop the environmental performance, which would steer the decision-makers to achieve sustainable production and services of the sugar industry in the country.

Data Collection

Sugar is one of the strategic products produced in Sudan. However, the industry is considered a source of pollution due to its massive resources consumption and effluent discharge. The LCA methodology is applied to quantify the energy use and the environmental impact of Sudan’s six sugar industries. The case studied includes the country’s annual average of data on sugar production activities for the last ten years from 2007 to 2016. Data was collected from the relevant database of the selected sugar industries, such as field reports and annual records. Information related to the agricultural fields and sugar mills was obtained from personal contacts with engineers, managers, and administrators. A survey work (i.e., interview) was conducted with several agricultural engineers of the factories and farmers. Relevant sources such as dissertations, books, magazines, and manuals were also considered. Some of the information was obtained from the Ministry of Mining and Energy in Sudan. The collected data comprised several technical parameters related to sugarcane cultivation, sugarcane harvesting, sugarcane transportation, and sugar processing. Fossil energy consumption was calculated per Mega-Jules (MJ) per ton of produced sugar. The process was conducted by summing up the quantities of the consumed fuel during sugarcane farming, sugarcane burning, sugarcane harvesting, transportation, and sugar processing. Data related to the manufacture of fertilizers and herbicides was obtained from the relevant departments and laboratories. Assumptions were made for some of the calculations due to the lack of information about GHG relevant to the agricultural management in the stage of sugarcane production (i.e., the effect of irrigation water, vinasse, and filter cake). Table 1 contains the mean values of the parameters considered in sugarcane production for the last ten seasons from 2007 / 2008 to 2016 / 2017, while sugar processing parameters were presented in Table 2. The sugar production system for the selected stages was modeled to represent the current agricultural practices and manufacturing technologies used in Sudan (Fig. 1). The life cycle assessment (LCA) was applied based on the International Organization for Standardization (ISO) standard 14044. The LCA was divided into four phases: goal definition, inventory analysis, impact assessment, and interpretation by using SimaPro software version 9.0.0.49 (Livison et al. 2010). The functional unit used in this study was the average weight of sugarcane per ton that used to produce one ton of sugar by using the current technology of sugar processing Sudan.

System boundaries

The stages considered in the system boundaries are the sugarcane growing, sugarcane harvesting, sugarcane transportation and sugar processing, and co-generation of electricity from bagasse. It ended at the production of sugar at the factory gate (Fig. 1). The considered subsystems consist of four stages are as follows: (1) sugarcane cultivation four provinces White Nile, Gazeira, Sinnar, and Kassala. The
sugarcane is irrigating with the surface irrigation system (Obeid 2013; Suliman 2017). The application of fertilizers and herbicides to sugarcane varies from area to other depending on soil type and growth stage. Average fertilizer application rates were adopted for this study. (2) sugarcane transportation to the mill by using trucks with capacity ranging between 9 to 35 tons per vehicle and an average distance of 14 kilometers (Adam et al. 2015). (3) the energy used and the other impact of fertilizers and herbicides manufacture are included and (4) sugar milling, which was considered within an average sugarcane throughput at each mill of 308 t per hour or 1.27 mn t of sugarcane per annum. The rate is estimated for over five to six months of crushing sugarcane season, during which the mills operate continuously (Ibrahim and Workneh 2019). The study excluded some subsystems, such as the production and maintenance of buildings and machinery. The creation of machinery and harvesters are used in the establishment of the sugarcane plantations. It also excluded the distribution and transmission of generated electricity in the powerhouse. The road infrastructure for sugarcane transportation and the transportation of sugar to the storages and consumers were also exempted.

[Figure 1]

Life Cycle Inventory

The life cycle inventory for input data was obtained from databases of the Sudanese Sugar Company (SSC), which includes four sugar factories; the Guneid, the Halfa, the Assalaya and the Sinnar, Kenana Sugar Company (KSC) and the White Nile Sugar Project (WNSP). Some information related to sugarcane burning and emissions from soil was assumed due to the lack of data. In 2016/2017, the total cultivated sugarcane area was approximately 69 500 ha with an average of 88 t sugarcane per ha. About six mn tons of sugarcane was crushed by a rate of 42 266 t per day to produce around 720 000 t of sugar. The Kenana factory produces more than half (about 56%) of the sugarcane and sugar in the country. This sugar mill was taken as a reference due to the availability of information compared to other sugar industries considered in this study. At this sugar mill, approximately 14.5% of the cultivated sugarcane was harvested mechanically, and 85.5% was harvested manually. About 90% of the developed sugarcane areas were burned before commencing the harvesting operation. Table 1 shows the data and assumptions used for the life cycle inventory. In terms of fertilization, an average of about 26 kg, 16 kg and 0.5 kg of nitrogen (N), phosphorus (P₂O₅) and of potassium (K₂O), respectively, were applied to produce one ton of sugar. The average amounts of application of herbicides, pesticides, and flowering controllers and ripening were 2.09 kg, 0.5 litter, and 0.01 kg, respectively, for every one ton of sugar. Table 1 shows the average kilograms of diesel fuel used in sugarcane cultivation as input to produce fertilizers, herbicides, and pesticides. The average fuel oil consumption for sugar milling was about 87 tons per t sugar. Sugarcane transportation is carried out using trucks in private companies such as the Kenana factory and by wagons bulled by tractors in the publicly-owned factories. The capacity of vehicles varies from 35 tons to 70 tons of sugarcane per tuck. The trailer that pulled by tractor can carry up to 9 tons of sugarcane. The average distance of sugarcane transportation from the farm to the mill was about 16.8 km. The total diesel fuel consumed for sugarcane harvesting and transportation was
estimated to be about kg per ton of sugarcane. Table 2 illustrates the average values of resource input and output data and chemical materials used for sugar production. About 16 991 tons of bagasse is used to cogenerate electricity at the selected factories' power stations. Data were calculated according to the input and output values obtained at the stage of sugar processing. Table 3 shows the annual amounts (average values) of by-products and residues per one ton of raw sugar.

Table 1. Data for sugarcane production, burning, transportation and processing parameters

<table>
<thead>
<tr>
<th>Resources</th>
<th>Amount</th>
<th>Unit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1) Sugarcane production</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cultivated area</td>
<td>69492</td>
<td>ha</td>
<td>KSC 2016 and SSC 2016</td>
</tr>
<tr>
<td>Average sugarcane harvested</td>
<td>88</td>
<td>ton/ha</td>
<td>KSC 2016 and SSC 2016</td>
</tr>
<tr>
<td>Irrigation water requirement</td>
<td>24269</td>
<td>m³/ha</td>
<td>KSC 2016 and SSC 2016</td>
</tr>
<tr>
<td>Electricity consumption for irrigation</td>
<td>3600</td>
<td>kWh/ha</td>
<td>KSC 2016</td>
</tr>
<tr>
<td>Fertilizers application</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>261</td>
<td>kg/ha</td>
<td>KSC 2016 and SSC 2016</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>1465</td>
<td>kg/ha</td>
<td>KSC 2016 and SSC 2016</td>
</tr>
<tr>
<td>K₂O</td>
<td></td>
<td>kg/ha</td>
<td>KSC 2016 and SSC 2016</td>
</tr>
<tr>
<td>Herbicides use</td>
<td>19</td>
<td>kg/ha</td>
<td>KSC 2016 and SSC 2016</td>
</tr>
<tr>
<td>Pesticide use</td>
<td>5</td>
<td>L/ha</td>
<td>KSC 2016 and SSC 2016</td>
</tr>
<tr>
<td>Flowering control and ripening</td>
<td>0.9</td>
<td>kg/ha</td>
<td>KSC 2016 and SSC 2016</td>
</tr>
<tr>
<td><strong>2) Sugarcane cultivation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel input to produce herbicides and pesticides</td>
<td>9</td>
<td>litter/ha</td>
<td>WNSP 2012 and SSC 2016</td>
</tr>
<tr>
<td>Diesel input to produce fertilizers</td>
<td>4</td>
<td>litter/ha</td>
<td>WNSP 2012 and SSC 2016</td>
</tr>
<tr>
<td><strong>3) Sugarcane transportation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average distance</td>
<td>16.8</td>
<td>km</td>
<td>KSC 2016</td>
</tr>
<tr>
<td><strong>4) Sugar processing</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugar produced per hectare</td>
<td>8.5</td>
<td>t/ha</td>
<td>KSC 2016 and SSC 2016</td>
</tr>
<tr>
<td>Bagasse produced</td>
<td>40.2</td>
<td>% cane</td>
<td>KSC 2016 and SSC 2016</td>
</tr>
<tr>
<td>Molasses produced</td>
<td>3.6</td>
<td>% cane</td>
<td>KSC 2016 and SSC 2016</td>
</tr>
<tr>
<td>Filter cake produced</td>
<td>3.1</td>
<td>% cane</td>
<td>GSF 2016 and ASF 2016</td>
</tr>
<tr>
<td>Steam consumed</td>
<td>751</td>
<td>kg/t cane</td>
<td>KSC 2016</td>
</tr>
<tr>
<td>Electricity consumption</td>
<td>11</td>
<td>kWh/t cane</td>
<td>KSC 2016 and WNSP 2012</td>
</tr>
<tr>
<td>Water used for sugarcane and sugar processing</td>
<td>0.8</td>
<td>m³/t cane</td>
<td>KSC 2016</td>
</tr>
<tr>
<td>Diesel consumption</td>
<td>0.66</td>
<td>litter/t cane</td>
<td>KSC 2016 and WNSP 2012</td>
</tr>
</tbody>
</table>
Table 2
Average amount of resources input and output of sugar production

<table>
<thead>
<tr>
<th>Resources</th>
<th>Unit</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total sugarcane</td>
<td>t. year⁻¹</td>
<td>6962480</td>
</tr>
<tr>
<td>Sugarcane crushed</td>
<td>t.day⁻¹</td>
<td>42266.9</td>
</tr>
<tr>
<td>Extraction efficiency</td>
<td>%</td>
<td>79.1</td>
</tr>
<tr>
<td>Sucrose % cane</td>
<td>%</td>
<td>12.1</td>
</tr>
<tr>
<td>Sucrose loss % cane</td>
<td>%</td>
<td>2.5</td>
</tr>
<tr>
<td>Total sugar produced</td>
<td>t / day</td>
<td>4186</td>
</tr>
<tr>
<td>Industrial efficiency</td>
<td>%</td>
<td>77.3</td>
</tr>
<tr>
<td>Total sugar</td>
<td>t. year⁻¹</td>
<td>720027.3</td>
</tr>
<tr>
<td>Molasses produced</td>
<td>kg.t⁻¹ sugar</td>
<td>25921</td>
</tr>
<tr>
<td>Electricity surplus</td>
<td>kWh.t⁻¹ bagasse</td>
<td>89.7</td>
</tr>
<tr>
<td>Electricity consumption</td>
<td>kWh.t⁻¹ sugar</td>
<td>65.3</td>
</tr>
<tr>
<td>Bagasse burnt / total produced</td>
<td>%</td>
<td>92</td>
</tr>
<tr>
<td>Steam consumed</td>
<td>kg.t⁻¹ sugar</td>
<td>7286.3</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>t cane / t sugar</td>
<td>9.7</td>
</tr>
<tr>
<td>Water</td>
<td>m³ / t sugar</td>
<td>2669.7</td>
</tr>
<tr>
<td>Land</td>
<td>ha / t sugar</td>
<td>0.11</td>
</tr>
<tr>
<td>Fuel</td>
<td>Litter / t sugar</td>
<td>87</td>
</tr>
</tbody>
</table>

Table 3
Annual means values of by-products and waste per t sugar

<table>
<thead>
<tr>
<th>By-product</th>
<th>Unit</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter cake</td>
<td>kg.t⁻¹ sugar</td>
<td>300</td>
</tr>
<tr>
<td>Boiler ashes</td>
<td>kg.t⁻¹ sugar</td>
<td>15.3</td>
</tr>
<tr>
<td>Wastewater</td>
<td>m³.t⁻¹ sugar</td>
<td>29.6</td>
</tr>
</tbody>
</table>

Calculations of fossil fuel energy consumption
The total energy required for sugarcane farming was calculated in mega-joule (MJ) per ton of produced sugar. The calculation included fossil fuel energy for fertilizers and herbicides manufacture that used during the stage of sugarcane cultivation. The calculation process was done by using the energy requirements to produce fertilizers and herbicides and their application rates used in Sudan. The fertilizers’ application rates per hectare were 261 kg, 146 kg and 5 kg for N, P₂O₅, and K₂O, respectively. The amount of land required to produce one ton of sugar was 0.11 ha (KSC 2016; SSC 2016). Fossil fuel energy for sugarcane transportation was calculated in MJ per one ton of sugar. The fuel consumption for one truck was determined in liter per t cane per km, and the energy content of the diesel fuel was taken as MJ per liter. Thus, energy consumption for the truck in Sudan was found per MJ.tkm⁻¹. The energy used during sugar manufacture (MJ.t⁻¹ sugar) was calculated by quantifying the amount of diesel consumed per kilograms to produce one ton of sugar. The net calorific value (NCV) of diesel per MJ.kg⁻¹ was determined (Livison et al. 2010).

Calculations of renewable energy consumption

Survey work to the power departments of the selected factories was made to collect the relevant data from the records sheets, and personal contacts with specialists were conducted. The parameters considered were; bagasse combusted per ton a day, the net calorific value (NCV) of bagasse which was assumed to be 7.8 MJ/kg (Rakesh et al. 2016; Livison et al. 2010), electricity in kW per day that generated to supply the system of sugar processing. Also, the renewable energy required to produce one ton of sugar, the total renewable energy consumption for the system in kWh per ton sugar, and the energy efficiency index calculated using Eq. 1 as follows:

\[ EI = \frac{(Et - Ed)}{S_j} \]

Where: \( EI = \) energy efficiency Index, \( ET = \) total energy, \( ED = \) Diffuser energy usage and \( SJ = \) volume of sugar in all final products (Hocking et al. 2015).

Calculations of green-house gasses emissions

Due to the lack of activity data, single Tier 1 methods in (Intergovernmental panel for climate change [IPCC] 2006) were used for calculations. The calculation methods were based on fuel used in the selected life cycle stages of sugar manufacturing in Sudan. Data on the consumed fuel was collected, and the emissions were estimated by using Eq. 2 (IPCC 2006). Emissions into the air were calculated by summing up the emissions at each stage of the life cycle for sugar production. Emissions represented in carbon dioxide equivalent per one ton of sugar produced were compiled for all the selected stages; sugarcane farming, fertilizers, and herbicides manufacture, sugarcane harvesting with transportation, and sugar manufacture. The CO₂-e emission from fossil fuel combustion during the sugarcane burning was excluded because of the lack of relevant empirical data in the Sudanese sugar industries. Therefore, it was assumed that the sugarcane releases the CO₂ absorbed during photosynthesis (Livison et al. 2010). The CO₂-e emission was calculated based on the diesel density of 0.845 kg per liter, the net calorific value
of 43 TJ per Gg, and the emission factor of 43.1 t CO₂-e per TJ. The three most important greenhouse gases (GHG) are calculated for the selected stages of the sugar life cycle. The gases are, namely, CO₂, CH₄, and N₂O. The global warming potentials (GWPs) are used to quantify the GHG, which is expressed as CO₂–equivalents. GWPs developed by the intergovernmental panel on climate change (IPCC) are quantified for a horizon of 100 years. Accordingly, equivalent factors for the three essential gases are defined as fellows; 1g CO₂ = 1 g CO₂-eq, 1 g CH₄ = 23 CO₂-eq and 1 g N₂O = 296 g CO₂-eq

\[ Emissions_{GHG, fuel} = Fuel\ Consumption_{fuel} \times Emission\ Factor_{GHG, fuel} \] ²

Where:

Emissions \(_{GHG, fuel}\) = emissions of a given GHG by type of fuel (kg GHG)

Fuel Consumption \(_{fuel}\) = amount of fuel combusted (TJ)

Emission Factor \(_{GHG, fuel}\) = default emission factor of a given GHG by type of fuel (kg gas/TJ).

The amount of fuel of a particular kind combusted per one ton of sugar expressed in tera joule (TJ) can be estimated by using Eq. 3.

\[ Fuel_{a, f} = litters_{fuel a, f} \times Density_{fuel a} \times NCV_{fuel} \div 10^6 \] ³

Where:

Fuel \(_{a, t}\) = Amount of fuel type a consumed in TJ

Litters \(_{Fuel a, t}\) = Quantity of fuel of type a consumed (litre)

Density \(_{Fuel a}\) = Density of fuel type (kg/litre)

NCV \(_{Fuel a}\) = Net calorific value of fuel type (TJ/Gg)

Calculation of the total emissions by gas from the Eq. 1 were made by summed up the overall fuels by using Eq. 4 (IPCC 2006).

\[ Emissions_{GHG} = \sum_{fuels} Emissions_{GHG, fuel} \] ⁴

The approach used for this methodology is summarized in five steps as follows:

- Determined the amount of fuel consumed at all the sugar factories, measured in terms of mass or volume.

- Convert the amount of fuel consumed into energy flow by using the heating value of the fuel type.
- Determine the emission factor of a given GHG by the type of fuel expressed as kg gas / TJ. For CO₂, it includes the carbon oxidation factor, assumed to be 1.

- GHG emitted calculation expressed as kg CO₂ equivalent.

- Sum-up the total GHG emission according to fuel type.

Then, the global warming potential of fossil energy estimated by quantifying the total GHG emissions along the selected sugar production stages. Hence, they multiply the GHG emissions by their respective equivalence factors and sum up the results (Francesco 2010). The GHG emissions calculated below are related to the defined functional unit, one ton of sugar.

Life cycle assessment

The LCA was carried out by using SimaPro 9.0.0.49 Software. The results were described according to ReCiPe 2016 v1.1 endpoint methodology. The interpretation was carried out to identify which stage of the sugar life cycle has the most significant impacts. The method of IPCC 2007 GWP 100a v1.01 was used for the global warming category. The identified impacts were global warming "in terms of greenhouse gas emissions (CO₂-equivalent) based on 100-year global warming potential (GWP)," fossil fuel use, ozone depletion, acidification, and ecotoxicity.

Results And Discussion

There is a necessity to effectively analyze the environmental impacts generated by a production system such as sugar by using efficient tools. Due to the lack of ecological data in Sudan, there is no LCA study conducted on the sugar supply chain. However, there is the fact that the environmental damage caused by the sugar industry in the country is enormous. This study is the first LCA developed for the Sudanese sugar industry, where six sugar factories in the whole country. This work studied four stages of the life cycle of sugar production supply chain: sugarcane farming, sugarcane cultivation, sugarcane harvest, and transportation and sugar processing. The study showed some similarities with other studies conducted for the sugar industry, especially in the life cycle inventory phase (LCI).

Fossil Energy Consumption

Energy consumption was accumulated for the selected stages of the sugar production life cycle; sugarcane farming, sugarcane transportation, fertilizers, herbicides, and sugar processing per one ton of produced sugar. The consumption of fossil fuel for the whole process of sugar production is a summation of the different quantities of the fuels consumed during the selected stages. The results show that 9.7 t of sugarcane is the average weight required to produce one ton of sugar. Hence, the total fossil energy required for sugarcane farming was 2166 MJ per ton of sugar. This amount of energy indicated that the stage of sugarcane farming is the greatest (39%) consumer to the fossil resources in the life cycle of sugar production. The sugar processing stage considered the second contributor to fossil energy
consumption, with 26.6%. The sugarcane cultivation and sugarcane harvesting with transportation significantly contribute to the fossil resources used, which were 20.7% and 13.7%, respectively. Figure 2 shows the fossil resources use for the selected stages of the sugar production life cycle. A comparison of the results was made with other studies conducted in Mexico, South Africa, and Mauritius. This study showed that about 39% of the fossil energy consumed in the stage of sugarcane farming, compared to 60.3%, 34%, and 75% in sugarcane farming in Mexico, South Africa, and Mauritius, respectively. The total fossil energy consumed to produce one ton of Sudanese sugar was about 3651 MJ. The amount indicated in this study is lower compared to Ramiro et al. (2019), who found consumption of about 8,572 MJ and Livison et al. (2010), who estimated 5350 MJ consumption.

Nevertheless, the amount of consumption is higher than the estimation done by Ramjeawon (2008), which was 1995 MJ for South Mauritius. However, Ramiro et al. (2019) calculated 60.3% for both stages of sugarcane farming and sugarcane harvesting. This result indicates the high dependence and usage of diesel fuel in the phase of sugarcane farming. The reason is that the stage of sugarcane farming includes different agricultural activities such as soil preparation and sugarcane plantation, which heavily consume diesel fuel. In Sudan, the required land to produce one ton of sugar is 0.11 ha, compared to 0.15 ha for South Africa and 0.12 ha in Mauritius. This seems to indicate that Sudan has the highest sugarcane productivity per smaller unit area than others. However, the land size of the sugarcane of Sudan and Mauritius is relatively the same and smaller than that in South Africa. The reason is mainly due to the fully irrigated sugarcane farms of both countries, while 80% of the South African sugarcane is rainfed. Generally, the rainfall's uncertainty is severely impeding the agricultural productivity in rainfed (Tilahun et al. 2011). Liu et al. (2016) found that the sugarcane yield under rainfed condition influences by variation of available water. Hence, this illustrates the higher sugarcane productivity per unit area in the fully irrigated farms compared to the lower the rainfed plantations.

The total amount of energy consumed for fertilizers and herbicides production was 472 MJ per ton of produced sugar. The energy consumption in sugarcane harvesting and transportation was calculated after considering the distance between the factories and the farms. The average length of the roads for sugarcane transportation is 16.7 km by using trucks (Ibrahim and Workneh 2019). The total fossil energy consumption for sugarcane transportation required to produce one ton of sugar was 770 MJ.

Fuel oil and diesel are the fossil fuels energy used during the sugar manufacture to start up boilers and to supplement bagasse supply during the off-season. The amount of fuel oil and diesel consumed were multiplied by their net calorific values (TJ/Gg). Sugar industry data showed that approximately 0.18 and 6.65 of fuel oil and diesel were required to produce one ton of sugar. The net calorific value of fuel oil and diesel are 43 and 42.3 TJ/Gg, respectively (IPCC 2006). The total energy from both fuel oil and diesel used for sugar processing was 249 MJ per one ton of sugar.

The total fossil fuel energy used for the whole stages is 3978 MJ per ton of sugar.

Renewable energy consumption
The renewable energy used in the whole process was calculated using the net calorific values (NCV) of bagasse, which is assumed to be 7.8 MJ/kg (Rakesh et al. 2016 and Livison et al. 2010). The result showed that 33,969 MJ of renewable energy from bagasse are required to produce one ton of sugar. The total energy consumption for the system from renewable and fossil sources is about 37,947 MJ per one ton of produced sugar.

Global warming potential

Global warming is referred to as climate change through trapping heat in the atmosphere (Zahedi et al. 2018). Global warming potential is given for GHG emissions to the atmosphere and expressed as kg CO$_2$-eq (Chandra et al. 2018). The results showed that the total fossil emissions over the selected stages of the sugar production life cycle in Sudan were estimated to be about 271.2 kg CO$_2$-equivalent per one-ton of sugar. The emissions from sugar processing, sugarcane farming, sugarcane cultivation, and sugarcane harvesting with transportation stages were 18.5 kg, 160.5, 35 kg, and 57.2 kg CO$_2$-eq per ton sugar, respectively. The contributions of global warming potential based on 100-year were 51%, 27%, 12%, and 10% for sugar processing, sugarcane production, sugarcane cultivation, and sugarcane harvesting and transportation, respectively. The sugar processing stage is the greatest (51%) contributor to gasses emissions. The contribution to the global warming of sugarcane production, sugarcane cultivation, and sugarcane harvesting and transportation was 49%. This indicator was lower than Ramjeawon (2008), who estimated 80% and Livison et al. (2010), who estimated 74% for the same stages. In those cases, the stage of sugarcane transportation has the most significant (50.6%) contribution to global warming. In comparison, both phases of sugarcane growing and harvesting contribute by 90.1% of the CO2-equivalent of the LCA. Chandra et al. (2018) found that the majority of the global warming potential of sugarcane production is due to direct and indirect usage of fossil fuel, such as during the production of fertilizers. In this study, the low value was due to the moderate use of chemicals such as pesticides and herbicides. The sugarcane transporting from the field to the sugar mill represents a small load of emissions. The main reasons are the trucks' modern models and the short distance of sugarcane transportation, which is about 16.5 km on average.

Consequently, the relatively low fuel consumption in these stages has lessened their contribution to global warming. This finding concurs with Ramiro et al. (2019), who found that the sugarcane growing and harvesting stages contribute 39.5% to global warming (climate change endpoint category). Figure 2 shows the contributions of the sugar life cycle's selected stages to global warming potential based on 100-year.

[Figure 2]

Ozone depletion and acidification

The principal contributor to ozone depletion was the sugarcane production (44%) followed by sugar processing, sugarcane cultivation, and sugarcane harvesting with a record of 22%, 18%, and 15.5%,
respectively. This result was because the stage has massive emissions due to fossil fuel consumption in essential operations such as land preparation and sugarcane plantation. During the sugar processing, the power cogeneration represents the second contributor to the ozone depletion because of the bagasse combustion in the factories. These findings agree with Ramiro et al. (2019), who found that sugarcane farming has the most severe impact on the environment in Mexico. Sugar processing contributed significantly to eutrophication, acidification, particulate matter, and ecotoxicity. The factors attributed to this stage were the use of chemicals such as lime for sugar refinery, the use of fuel oil, and the bagasse burning for electricity generation. Consequently, these processes release an enormous quantity of greenhouse gases, which adversely reflected on the environment. Figure 3 shows the damage assessment of sugar life cycle stages in the environment.

Human toxicity

One of the definitions of human toxicity is the effect of poison materials on the social environment. It is expressed as disability-adjusted life years (DALY) as one of the quantitative severity-based indicators yield measures. The DALY approach attempts to account for the years of life lost. The total human carcinogenic toxicity for the whole process of sugar production was $15.5 \times 10^{-3}$ DALY. Sugarcane production has a higher $6.6 \times 10^{-3}$ (43%) contribution to the human toxicity compared with the other stages of sugar production life cycle. The human toxicity for sugar processing, sugarcane harvesting, transportation, and sugarcane cultivation was $4.2 \times 10^{-3}$, $2.4 \times 10^{-3}$, and $2.3 \times 10^{-3}$ DALY, respectively. Human toxicity comprises not limited to processes of supply capital goods, emissions from machinery and production, and use of agrochemicals. Human health is affected as consequential of these processes, which produced heavy metals. The comparable impact in Fig. 3 shows that the human toxicity from the stage of sugarcane production is the highest. This result is in agreement with the findings of Chandra et al. (2018) and Silalertruksa et al. (2017).

Terrestrial eco-toxicity

The terrestrial eco-toxicity and marine eco-toxicity effect are both represented the eco-toxicity. The unit for the impact of eco-toxicity is expressed as species per year (species.yr) - time-integrated loss of species (Baldowska-Witos et al. 2020). The term of terrestrial eco-toxicity is mainly for emissions into the atmosphere, water, and soil. These emissions are representing the release of heavy metals in the form of dissolution. However, the eco-toxicity impact is useful in the soil only by interaction with the aqueous stage. The aquatic eco-toxicity is for heavy metals that applicable to being released into dissolved minerals. The terrestrial eco-toxicity for sugarcane production, sugar processing, sugarcane cultivation, and sugarcane transportation and harvesting was $1.49 \times 10^{-8}$, $1.16 \times 10^{-8}$, $1.14 \times 10^{-8}$ and $5.28 \times 10^{-9}$ species.yr, respectively.

On the other hand, the marine eco-toxicity was $1.15 \times 10^{-5}$, $1.01 \times 10^{-5}$, $9.47 \times 10^{-6}$ and $4.07 \times 10^{-6}$ species.yr for the sugarcane production, sugar processing, sugarcane cultivation, and sugarcane harvesting and transportation, respectively. As shown in Fig. 3, marine eco-toxicity has a relatively higher
impact, while terrestrial eco-toxicity has a lower effect on the stage of sugarcane production. However, both the terrestrial and marine eco-toxic have the highest impact during sugarcane production compared to the other studied life cycle stages of sugar production. This result goes in line with the findings of Chandra et al. (2018), who concluded the higher impact of terrestrial eco-toxicity during the sugarcane production. While Prasara and Gheewala (2016), found that the sugarcane cultivation caused the highest effect on marine eco-toxicity.

Eutrophication potential

Eutrophication is known as the over-enrichment of the aquatic environment with nutrients (Carpenter 2005). This condition leads to a depletion of oxygen in the water, which causes algal blooms and anoxic events (Carpenter 2005; Chandra et al. 2018). The term of eutrophication is a determined circumstance of surface waters and a widespread environmental problem. It divided into two impact categories; marine eutrophication and freshwater eutrophication. The marine eutrophication includes the nitrogen enrichment of seawater and freshwater.

On the other hand, the freshwater eutrophication considers only phosphor enrichment of freshwater (Morao and de Bie 2019). The main factors influencing the eutrophication include emissions from agricultural operations such as fertilizer run-offs, leaching, denitrification of nitrogen oxide, and ammonium. There are other factors with fewer contributions to eutrophication, such as transportation and machinery operation. The freshwater eutrophication potential was $1.1\times10^{-7}$, $7.5\times10^{-8}$, $4.5\times10^{-8}$ and $2.6\times10^{-8}$ species.yr for sugar processing, sugarcane production, sugarcane cultivation, and sugarcane harvesting and transportation, respectively. The marine eutrophication was $2.02\times10^{-9}$, $1.45\times10^{-11}$, $7.2\times10^{-12}$ and $5.15\times10^{-12}$ for sugar processing, sugarcane production, sugarcane cultivation, and sugarcane harvesting and transport, respectively. Figure 3 shows the contribution of sugar manufacture life cycle stages to the marine eutrophication and freshwater eutrophication. As noted in Fig. 3, the freshwater eutrophication potential has a relatively higher effect on the environment compared to marine eutrophication. However, sugar processing accounts for 98% of the impact on marine eutrophication and 41.5% on freshwater eutrophication. This result is mainly due to NOx emissions to air, which generally results from combustion processes. The processes include power generation and production of chemicals used in a sugar refinery, such as lime.

Acidification potential

Acidification is defined as the comparative effects of SO$_2$ acidifying. It is mainly affected by emissions of air by ammonia NH$_3$, nitrogen oxide NO$_2$, and sulfur oxides SO$_x$. The substances change the soil acidity when deposited into it, which leading to acidification. The acidification potential was $1.3\times10^{-6}$, $3.9\times10^{-7}$, $2.6\times10^{-7}$ and $1.4\times10^{-7}$ species.yr for sugar processing sugarcane production, sugarcane cultivation and sugarcane harvesting and transportation respectively. As noted in Fig. 3, that terrestrial acidification impacts sugar processing relatively high compared to the other life cycle stages. The acidification potentials reflect the depletion of fossil fuel, which resulted from the usage of fossil fuels. Other factors
influence the acidification potential, such as emissions from the usage of fertilizers. However, the impact of acidification seems to be not extensive in sugarcane production. This result is in agreement with the findings of previous studies (Renouf et al. 2010; Prasara and Gheewala 2016; Chandra et al. 2018), that concluded the insignificant of terrestrial acidification in the stage of sugarcane production.

Particulate matter

The environmental impact category of particulate matter formulation is a measure of suspending particles that harm human health. The particulate matter potential was $8.4 \times 10^{-4}$, $6.3 \times 10^{-4}$, $2.9 \times 10^{-4}$ and $2.2 \times 10^{-4}$ for sugar processing, sugarcane production, sugarcane cultivation, and sugarcane harvesting and transportation, respectively. Figure 3 shows that sugar processing was the highest contributor to the emissions that formulate particulate matter. This result is due to emissions from various processes in the mill, such as bagasse combustion during power generation and transport.

![Figure 3](image)

Conclusion

This study revealed that the indiscriminate use of resources such as fossil fuels, chemicals, water, electric power, and land use had caused a severe environmental impact on human health, ecosystem quality, and climate change. The results showed that sugarcane farming is the most significant consumer to fossil resources in the life cycle of sugar production. Sugar processing is the second contributor to fossil energy consumption, with 26.6%. However, sugar processing is the most significant contributor to global warming due to high gasses emissions. Sugarcane production is the principal contributor to ozone depletion (44%), followed by sugar processing. The stage of sugar processing has a significant impact on eutrophication, acidification, particulate matter, ozone depletion, and eco-toxicity. This is because of the use of chemicals (i.e., lime and phosphate) for sugar refinery and fuel oil and bagasse burning for electricity generation. This study recommends improvements in the sugar industry operations that would significantly improve its environmental performance.

Recommendations

The use of fertilizers and herbicides represent a pollution load to the environment due to contained chemical materials and the fossil fuel used for the application. The life cycle inventory showed that the amount of nitrogen used was 261 kg/ha, phosphate 146 kg/ha, and potassium 5 kg/ha. In some cases, it wasn't easy to apply these recommended dosages of fertilizers. On the other hand, the agricultural practices must be improved to increase the sugarcane yields per unit area to decrease the land occupation. Therefore, accurate measures such as a decision support system based on artificial intelligence can be used to effectively monitor fertilisation. The organic matter that resulted from sugar processing, such as filter-cake, might be used as alternative fertilizers. This approach would positively lessen the application rates of fertilizers and herbicides per hectare.
The sugarcane in Sudan is fully irrigated from the River Nile mostly by using the traditional irrigation methods. The surface irrigation technique, such as the hydro-flume system, is implemented in most sugarcane farms. However, the improved management of irrigation water could increase the application efficiency. The adoption of modern irrigation systems such as center-pivot would positively improve water application efficiency.

About 16% of the Sudanese sugarcane is harvested mechanically and transported to the mills by trucks and trailers pulled by tractors. This percent implied a high consumption rate of diesel fuels, which reflected on the damage the environment in different ways such as climate change and health risks. A cleaner technology such as new models of harvesters with less fuel consumption should be implemented to minimize the emission generated by mechanization. Another alternative may be the sugarcane being harvested manually instead of using the machine.

Sugarcane transportation is the integral stage of harvesting operation in the sugar industry supply chain. Any stoppage of the sugarcane transport system from the field to mill during the crushing season could influence the production process. Therefore, it is imperative to keep this process efficient while ensuring its minimum impact on the environment. The inefficient routes of sugarcane transportation are one of the principal causes of the effect on the environment. The average distance of the road from the fields to the mills is reasonable for most of the sugar industries. However, improvement of the sugarcane transportation routes is one of the alternatives that could mitigate the emissions. Also, renewing the fleet of trucks to improve the efficiency of fuel consumption per trip would positively benefit the environment.

The co-generation process has produced electricity from bagasse burning in the sugar industry. The efficiency of generation is higher in private companies such as the Kenana and White-Nile, which reach up to 150 kWh per t cane. The publicly-owned sugar factories have lower efficiency than the private sugar industries. However, such technology of power generation in the private sectors must be adopted by the government-owned sugar factories. This adoption would increase generating efficiency and reduce the energy use for sugar processing. Thus, it could lead to reduce fossil fuel consumption and minimize emissions.

Declarations

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References


**Figures**
Figure 1

System boundary
Figure 2

Green-houses gases emissions based on 100-year GWP

Figure 3

Results of characterization and damage assessment