Life Cycle Assessment of a Sugarcane Biorefinery Complex in Pakistan

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Abstract

Pakistan is the seventh largest sugar producer of the world, of which Punjab province contributes to more than fifty five percent of the total sugar production. In this study, an environmental life cycle assessment was conducted of a sugarcane biorefinery complex, with the aim to examine the environmental performance of such a complex in the context of Pakistan. The assessment was made from cradle to gate involving the agricultural, transportation, and industrial stages. The agricultural stage included the plantation, maintenance, and harvesting of the crop, while the transportation stage involved the movement of sugarcane to the sugar mill. The industrial stage, i.e., biorefinery complex, consisted of sugar milling plant, heat and power generation, ethanol plant, biogas production, and fertilizer plant. The functional unit of this study has been taken as one tonne of sugarcane processed in the biorefinery complex. Moreover, data collection was done by visiting the sugarcane farms and the biorefinery complex while the missing parameters were obtained from the literature and inventory databases. Calculations were then performed for the five most relevant impact categories including global warming, terrestrial acidification, freshwater eutrophication, human toxicity (carcinogenic), and fossil resource scarcity. The results revealed that prevention of cane trash burning in the fields, optimized use of groundwater, fertilizers, and pesticides at the agricultural stage, and fuel for transportation with an enhanced use of cane trash for the production of surplus electricity, and wastes from industrial plant for the production of compost fertilizers may result in a significant reduction in the environmental burdens along with savings of useful natural resources. As no other study on this topic in Pakistan exists to the knowledge of the authors, this particular study serves as a first step to further enhance the environmental sustainability of the sugarcane sector in the country.

Keywords : Life Cycle Assessment / Biorefinery / Sugarcane Industry / Pakistan

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การประเมินวัฏจักรชีวิตของระบบไบโอรีไฟน์เนอรี่จากอ้อยในบริบทของประเทศปากีสถาน

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ศูนย์ความเป็นเลิศด้านเทคโนโลยีพลังงานและสิ่งแวดล้อม สำนักพัฒนาบัณฑิตศึกษาและวิจัยด้านวิทยาศาสตร์และเทคโนโลยี กรุงเทพฯ 10140

บทคัดย่อ

ปากีสถานเป็นประเทศผู้ผลิตน้ำตาลอันดับที่เจ็ดของโลก ซึ่งมากกว่าร้อยละ 55 ของการผลิตน้ำตาลทั้งหมดในประเทศผลิตที่จังหวัด Punjab การศึกษานี้ทำการประเมินวัฏจักรชีวิตของระบบไบโอรีไฟน์เนอรี่ (Biorefinery complex) ซึ่งตั้งอยู่ในจังหวัด Punjab โดยมีวัตถุประสงค์เพื่อประเมินประสิทธิภาพด้านสิ่งแวดล้อมของโรงงานไบโอรีไฟน์เนอรี่จากอ้อยในบริบทของประเทศปากีสถาน ในการประเมินวัฏจักรชีวิตนั้นจะพิจารณาตั้งแต่ขั้นตอนการได้มาซึ่งวัตถุดิบจากการเพาะปลูก การขนส่ง และขั้นตอนของโรงงาน ซึ่งในขั้นตอนการเพาะปลูกอ้อยนั้นครอบคลุมตั้งแต่การเตรียมดิน การบำรุงรักษาและการเก็บเกี่ยวผลผลิต ตามด้วยขั้นตอนการขนส่งอ้อยไปยังโรงงาน เพื่อผ่านกระบวนการหีบอ้อย ซึ่งในระบบไบโอรีไฟน์เนอรี่นั้นประกอบด้วย ขั้นตอนการหีบอ้อย การผลิตไฟฟ้าและความร้อน โรงผลิตเอทานอล รวมไปถึงโรงผลิตแก๊สชีวภาพและปุ๋ย หน่วยการทำงานของการศึกษานี้คือ หนึ่งตันของอ้อยที่ผ่านเข้าสู่ระบบไบโอรีไฟน์เนอรี่ ข้อมูลที่ใช้ในการศึกษาเป็นข้อมูลปฐมภูมิที่ได้จาการสำรวจภาคสนามกับเกษตรกรและโรงงานไบโอรีไฟน์เนอรี่ในพื้นที่ ประกอบกับข้อมูลที่ได้จากการทบทวนวรรณกรรม การประเมินมุ่งพิจารณากลุ่มของผลกระทบที่เกี่ยวข้องเพียง 5 ประเภทเท่านั้น ได้แก่ ศักยภาพในการทำให้เกิดภาวะโลกร้อน ผลกระทบความเป็นกรดทางภาคพื้นการเกิดยูโทรฟิเคชันในแหล่งน้ำจืด การขาดแคลนเชื้อเพลิงฟอสซิล และความเป็นพิษต่อมนุษย์ (สารก่อมะเร็ง) ซึ่งผลการศึกษาพบว่า การป้องกันการเผาอ้อยในไร่ การใช้น้ำใต้ดินอย่างเหมาะสม การลดการใช้ปุ๋ยเคมีและสารกำจัดศัตรูพืชในขั้นตอนการเพาะปลูกรวมไปถึงการลดการใช้เชื้อเพลิงในการขนส่งโดยอาศัยการส่งเสริมให้ใช้ใบอ้อยเพื่อผลิตเป็นไฟฟ้าส่วนเกิน และการนำของเสียจากโรงงานอุตสาหกรรมมาผลิตเป็นปุ๋ยหมัก จะช่วยให้ลดผลกระทบด้านสิ่งแวดล้อมดังกล่าวข้างต้น ควบคู่ไปกับการลดการใช้ทรัพยากร ได้อย่างมีนัยสำคัญ เนื่องจากไม่มีการศึกษาวิจัยในหัวข้อดังกล่าวนี้มาก่อนในประเทศปากีสถาน ดังนั้นการศึกษาในครั้งนี้จึงถือเป็นก้าวแรกในการเพิ่มความยั่งยืนทางด้านสิ่งแวดล้อมของอุตสาหกรรมอ้อยในประเทศปากีสถานต่อไป

คำสำคัญ : การประเมินวัฏจักรชีวิต / ไบโอรีไฟน์เนอรี่ / อุตสาหกรรมอ้อย / ปากีสถาน

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1. Introduction

Agriculture plays a vital role in the economy of Pakistan; it has a share of about 20% in the GDP of the country while providing employment to over 42% of the total labor force of the country. Sugarcane being a high value cash crop accounted for 3.2% in the agriculture value addition and contributed 0.6% in the overall GDP of the country in the economic survey of 2015-16 [1]. At present, there are more than eight million farms in the country with one million cultivating sugarcane, most of them are smallholders having less integration with the industry [2, 3]. The crop is cultivated at around 1.13 million hectares area of the country out of a total global cultivation area of 19.6 million hectares [4, 5]. Cultivation is performed in two seasons, namely autumn and spring [6]. Sugar industries purchase the sugarcane either from their own farms or the other individual farmers. Every year minimum support prices of the sugarcane are set up by the provincial governments in consultation with the representatives from the industry and farmers [3, 4].

The sugarcane industry is the second largest agrobased industry after textile and there are around 89 sugar mills in the country [7, 8]. The country is the seventh largest sugar producer as well as eighth largest sugar consumer of the world. In the season of 2015-16, 5.08 million tonnes of the sugar was produced with an average recovery rate of obtaining sugar from the sugarcane as 10.16%. Moreover, a considerable amount of molasses and alcohol are also produced and a large amount of them is exported; in the 2015-16 season around 396 million liters of Ethyl Alcohol and 73 thousand tonnes of the molasses were exported [8]. However, it is to be noted that Punjab province having the highest share in the agricultural sector of the country with more than five million agricultural farms, produces more than 55% of the total sugar production in the country while having 44 sugar plant in the province [3, 4].

In this study, an environmental life cycle assessment was conducted of a sugarcane biorefinery complex located in the Punjab province of Pakistan. A biorefinery concept is an approach to obtain multiple products of biochemical and bioenergy by the refining of biobased materials [9,10]. A typical biorefinery complex in the context of a sugar mill consists of sugarcane farming, sugar milling plant, heat and power generation, ethanol production plant, and fertilizer plant [11]. Today, countries are adopting the strategy to enhance the use of their neglected renewable resources. These resources are helping to reduce dependence on nonrenewable fossil fuels as well as to minimize the global warming potential as the production and combustion of fossil fuels have been proved to be a crucial source of greenhouse gas emissions [9, 12, 13]. The intention behind this concept is to get an enhanced efficiency in terms of economics, energy, and resource use [14]. Hence, sugarcane biorefinery complex could play a vital role in maximizing the environmental as well as economic sustainability which will be attained in terms of enhanced use of byproducts in the production of useful products including energy products like bioethanol, biogas, and surplus electricity as well as other products like compost fertilizer, etc. This enhanced use of byproducts will also result in diminished waste as well as prevention of the use of virgin resources to produce these products.

Despite the fact that numerous studies have already been done on different stages of sugarcane biorefinery all over the world including sugarcane harvesting, milling, and ethanol production, etc.; no particular life cycle assessment study of sugarcane industry in Pakistan exists in the knowledge of authors. This study is aimed at evaluating the environmental performance of a sugarcane biorefinery complex in the context of Pakistan using a life cycle perspective. Hence, this study does not only fulfill this research gap but it will also serve as a first step to further enhance the environmental sustainability of sugarcane sector in the country.

2. Methodology

In general, this study follows the methodology of life cycle assessment according to the principles outlined in ISO14040:2006 [15] and ISO14044:2006 [16]. The goal of this study is to carry out an environmental life cycle assessment of a sugarcane biorefinery complex located in the Punjab province of Pakistan. The study is intended to quantify the environmental impacts from a sugarcane biorefinery complex in the country and provide suggestions for improving the environmental performance with enhanced sustainability. The functional unit of this study is defined as one tonne of the sugarcane processed in the biorefinery complex to produce sugar and its allied byproducts.

The study was performed from cradle to gate with system boundaries including the agricultural stage, transportation stage, and the industrial stage. Agricultural stage involved the sugarcane farming; transportation stage included the transportation of cane to the mill; the industrial stage was comprised off sugar milling plant, ethanol plant, heat and power generation plant, and compost fertilizer plant. System boundaries of the study are shown in Figure 1.

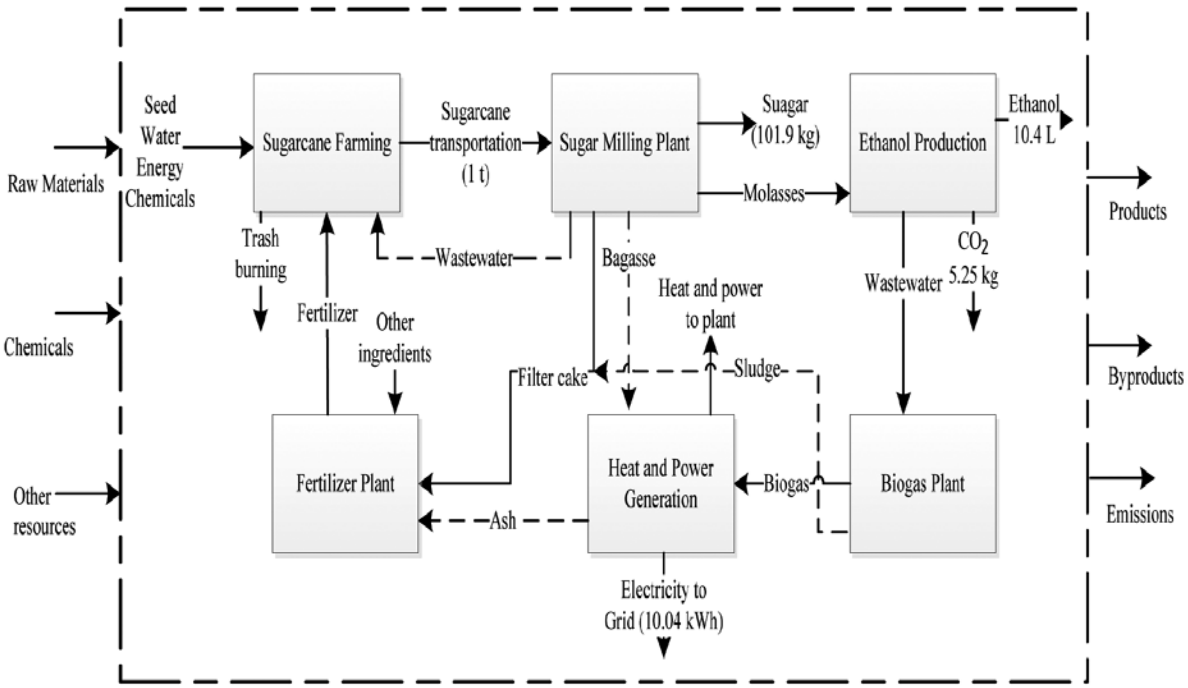

Figure 1 Sugarcane biorefinery complex along with its system boundaries

For sugarcane cultivation, most of the agricultural work is performed manually. A highly fertile soil is required for this purpose [17], land preparation is done by using the tractors with diesel as fuel. Seeds are applied evenly while seed rate was considered as around 52.5 kg per tonne of cane. The maintenance of the crop included the fertilization with urea, DAP (di ammonium phosphate), SOP (sulfate of potash), and compost fertilizer; for each crop three times on average (4.9 kg, 2.46 kg, 2.15 kg, and 7.36 kg per tonne of cane, respectively). In fact, 7.36 kg of compost fertilizer also has a potential to replace around 1.64 kg of urea, 0.41 kg of SOP, and 2.45 kg of SSP (single super phosphate). Transportation distance of compost fertilizer from the plant to the agricultural farm was considered at 5 km on average, by using the tractor trolleys (around 0.012 L of diesel per tonne of cane). Additionally, pesticide and weed control chemicals consisting of chlorpyrifos, carbofuran, halosulfuron-methyl, and ametryn plus atrazine, are also applied (0.04 L, 0.86 kg, 0.001 kg, and 0.05 kg per tonne of cane, respectively). Irrigation is performed 18 times on average, either using the surface water or ground-water considered at 70:30 [18]. Harvesting is carried out manually having no pre-harvest burning, while cane trash is mostly burned. Nevertheless, after the first plantation, ratoon crop is retained for 2 times on average. Total fuel used in different operations of the agricultural stage (including land preparation, plantation, irrigation, crop maintenance, and ratoon management, etc.) was taken as 1.56 L of diesel and 1.81 kWh of electricity per tonne of cane. The yield of the crop was considered at around 67 tonnes per hectare. Then, the cane is transported to the complex by using the tractor trolleys while distance to the mill was considered at 25 km on average (around 0.67 L of diesel per tonne of cane).

For the industrial stage, inside the sugar factory washing of the cane is not a practice. After sugar milling, the juice is processed in the house to obtain the sugar as a product with an average recovery of obtaining sugar from the sugarcane as 10.19%. In addition to sugar, filter cake (30 kg), bagasse (300 kg), and molasses (45 kg) are obtained here as byproducts. Bagasse is sent to the boiler house via conveyors to produce steam at a rate of around 2 kg of steam per kg of bagasse, with operating parameters of steam as 24 bar and 350°C. This steam is then used to run the turbine for electricity generation while the exhausted steam is used back in the industrial process. However, it satisfies the energy needs of the plant only in terms of both electricity and steam requirements. Wastewater from the sugar mill (0.26 m^3/ tonne of cane crushed) is sent back to the agricultural stage after treatment, to serve as ferti-irrigation. Moreover, filter cake, part of ash from power plant, and sludge from ethanol plant are used at the fertilizer plant for the production of compost fertilizer with the addition of additional ingredients. Compost fertilizer is considered to partly replace conventional NPK fertilizers back in the agricultural stage.

Molasses from the sugar mill is transported in pipes to the attached distillery unit, where it is processed to obtain 99.5% pure alcohol, which is also considered as an avoided product for gasoline; substitution ratio between ethanol and gasoline was taken as 0.8 [19, 20]. CO_2 produced during fermentation is captured and then liquefied to be sold to the beverage industry as an avoided product to the CO_2 from conventional resources. Wastewater (0.135 m^3) from ethanol plant is treated by using the anaerobic digestion in the biogas plant where biogas is produced at a rate of around 40 m^3 of biogas per m^3 of wastewater. This biogas, after the cleaning of H_2S

and drying of the humidified gas is sent to the generators, to generate the surplus electricity which is then sold to the national grid. Moreover, exhaust gases from the generator which have a temperature of 500-550°C are burned in specially designed boilers to produce additional 7.5 kg of steam to be used back in the industrial process [21]. The wastewater coming out from the biogas plant will be used for ferti-irrigation.

Inventory analysis (data collection) was performed by visiting the different sugarcane farms in the area and then biorefinery complex using questionnaires while obtaining the missing parameters and validating the data from the literature. Experts were also interviewed for this purpose, especially in making the assumptions where data were not available. Furthermore, most of the emission factors were either taken from available online inventories (i.e. for materials, chemicals, fuels production, and fuel combustion, etc.) or from the literature (i.e. for cane trash burning, fertilizer as well as pesticides application, bagasse burning, and biogas burning, etc.). Detailed information on the type of data, list of required data, and the data sources are given in Table 1.

Table 1 List of required data along with their sources for the inventory analysis

Type of data	List of data	Source
Primary data	**Agricultural stage** ➢ Land preparation and plantation ➢ Crop maintenance (irrigation, fertilization, weed/ pest control, etc.) ➢ Harvesting of the crop **Transportation stage** ➢ Transportation of cane from field to the complex **Industrial stage** ➢ Sugar milling ➢ Molasses to ethanol production ➢ Heat and power generation including bagasse power plant and biogas power plant ➢ Compost fertilizer production	Questionnaires and interviews
Secondary data	**Emissions from different processes** ➢ Cane trash burning [22, 23], fertilizer application [24, 25] ➢ Bagasse burning [26, 27] ➢ Biogas burning [27, 28] ➢ Wastewater treatment [29] ➢ Other emissions including materials and fuels production as well as fuel burning, etc. from the databases available in SimaPro software	Literature review and databases available in SimaPro software

The impact assessment was carried out with the help of SimaPro 8.4 software [30] using ReCiPe 2016 midpoint Hierarchist [31] as the life cycle impact assessment method. Calculations were performed for the five most relevant impact categories including global warming, terrestrial acidification, freshwater eutrophication, human toxicity (carcinogenic) and fossil resource scarcity. Since multiple byproducts are being obtained along with the products, therefore, to avoid the allocation of the environmental burdens, system expansion was performed.

3. Results and discussion

The results of this study for the five impact categories are shown in Table 2. The most environmental intensive materials and processes for the respective impact categories are discussed in the following. It was found that global warming potential was mainly being caused by the nitrogen based fertilizers application (especially direct and indirect N_2O emissions) as well as production, biomass burning (CH_4 and N_2O emissions), use of diesel fuel (production and burning), and the treatment of wastewater (CH_4 emissions), respectively. For terrestrial acidification, fertilizer application (NH_3 and NO_X emissions), burning of biomass fuel in terms of cane trash and bagasse (SO_2 and NO_X emissions), and then the use of diesel fuel were found to be the respective major sources. Furthermore, emission of phosphorus due to runoff from the fertilizer was the main source of freshwater eutrophication. For the impact category of human carcinogenic toxicity, production of chemicals and use of fuel (diesel and electricity), were found to be the main contributors, respectively. As far as the impact category of fossil resource scarcity was concerned, the production of fossil based fertilizer followed by the fossil based energy resources and pest/weed control chemicals were found as the most significant contributor, respectively.

Table 2 Results of the environmental impacts from the biorefinery complex per functional unit

Impact category	Unit	Value
Global warming (GW)	kg CO_2 eq.	6.54E+01
Terrestrial acidification (AC)	kg SO_2 eq.	1.21E+00
Freshwater eutrophication (EU)	kg P eq.	3.44E-03
Human carcinogenic toxicity (HT)	kg 1,4-DCB eq.	-6.99E-03
Fossil resource scarcity (FS)	kg oil eq.	-3.13E+00

However, a substantial reduction of the impacts was also obtained for all the impact categories (GW, AC, EU, HT, and FS) due to the environmental benefits obtained with the use of byproducts from the biorefinery complex as the avoided products (i.e. which can replace the production of the concerned products from the virgin resources). This resulted even in the negative impacts values (HT and FS) due to these environmental credits obtained with the use of byproducts. For example, use of the wastewater as ferti-irrigation caused a reduction from the overall impactsof approximately - 0.6%, - 0.1%, - 0.1%, - 1%, and - 4%, respectively due to the replacement of fossil based NPK fertilizer. The compost fertilizer (which can replace NPK fertilizer) from the filtercake, ash, and sludge made a reduction from the overall impact of about -1%, - 0.1%, - 6%, and -14%, for GW, AC, HT, and FS while slightly higher values compared to the agrochemicals was observed for EU. Actually, reduced environmental benefits were obtained from the compost fertilizer due to the mixing of fossil based chemical ingredients with high impacts to adjust its NPK contents. On the other hand, ethanol also caused a notable reduction from the total impacts of around - 4%, - 3%, - 73%, and - 84%, for GW, AC, HT, and FS, due to the prevention of production of an equivalent amount of gasoline while its other environmental benefits could only be assessed by taking into consideration the burning of the respective fuels. Besides, CO_2 production from ethanol plant provided a benefit (reduction) of around - 5%, - 0.5%, - 3%, - 13%, and - 7%, for GW, AC, EU, HT, and FS, respectively from the total impacts. Similarly, surplus electricity in the industrial stage (i.e. which can replace fossil-based national grid electricity) from biogas plant caused a change of impacts of around - 9%, - 3%, - 9%, - 41%, and - 27%, for the respective impact categories. A graphical representation of overall impacts from the biorefinery complex to show the environmental benefits due to the benefits obtained with the use of byproducts as the avoided products is shown in Figure 2.

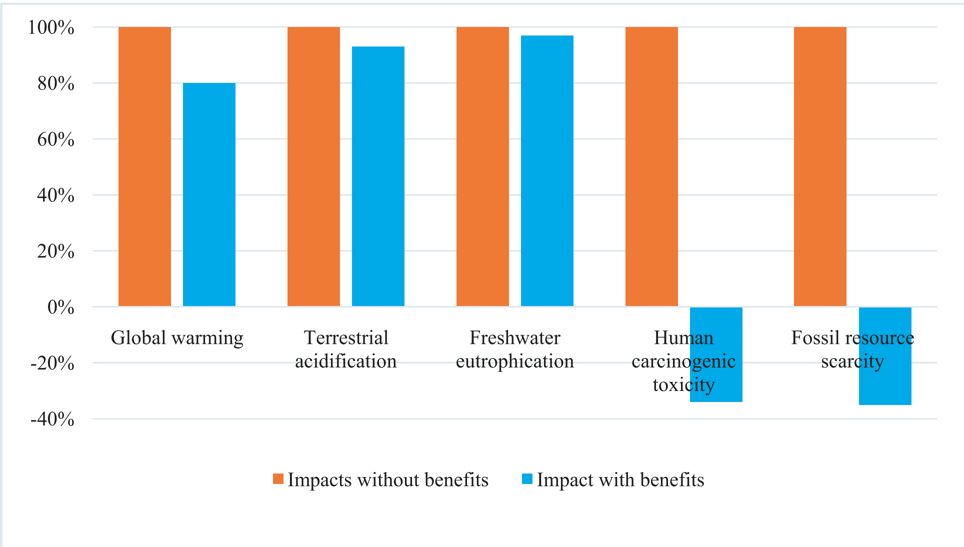

Figure 2 A graphical representation of overall impacts from the biorefinery complex to show the environmental benefits obtained with the use of byproducts

Furthermore, an efficient management of water could save up to 40% of irrigation water along with an increased productivity of soil and enhanced yield of the crop [18]. This could result in an overall improved environmental performance due to the reduced needs of fuel for groundwater irrigation as well as other ingredients per tonne of cane. Additionally, by considering the cane trash as 140 kg per tonne of cane, 50% of it retained in the field to complete the needs of soil with the remaining to recover for the electricity could also provide an additional 14.7 kWh of electricity [32]. This electricity from cane trash then could provide additional benefits in the replacement of national grid mix electricity along with prevention of trash burning burdens at around - 30%, - 10%, - 60%, and - 35% for GW, AC, HT, and FS, respectively. However, slightly higher values will be obtained for EU mainly due to the diesel fuel which will be used in the recovery of cane trash.

Nevertheless, if we compare the results of this study with other studies on biorefinery complex e.g. the study conducted by Silalertruksa et al. [31] on a biorefinery complex in Thailand; a comparison and discussion of results for different impact categories is given as in the following. For this purpose, the results from the study of Silalertruksa et al. were normalized per tonne of cane and system expansion was also carried out on their study for making a valid comparison. The impact values from the current study and the study conducted by Silalertruksa et al. in Thailand for GW, AC, EU, and FS were found to be as follows; 65.4 kg CO_2 eq. vs 38.6 kg CO_2 eq., 1.21 kg SO_2 vs 0.22 kg SO_2 eq., 3.44E-3 kg P eq. vs 6.62E-3 kg P eq., and - 3.13 kg oil eq. vs - 1.44 kg oil eq., for the respective impact categories. For GW, considerably high impact values were found in Pakistan mainly due to the higher use of nitrogen based fertilizers. For AC, again high values were obtained due to the higher use of nitrogen fertilizers resulting in more NH_3 and NO_X emissions. However for EU, the results for this study were found to be slightly lesser than the results of biorefinery complex in Thailand. Similarly, for the impact category of FS the values of this study were found lower as compared to the FS values of the study conducted by Silalertruksa et al., which happened due to an increased use of by products in this study. The negative impact values were obtained due to the credits being acquired from the byproducts.

4. Conclusions and recommendations

The paper shows the environmental impacts of a sugarcane biorefinery complex in Pakistan using a life cycle perspective. Environmental intensive stages and materials are shown along with environmental benefits obtained with use of different byproducts. From the above mentioned results, it could be concluded that prevention of cane trash burning in the fields, optimized use of fuels, irrigation water, fertilizers as well as pesticides at the agricultural stage and fuel for transportation may cause a significant reduction in environmental burdens. Likewise, an enhanced use of cane trash for the production of surplus electricity and wastes from the industrial plant for the production of compost fertilizers at the industrial stage may cause a significant reduction in the environmental burdens along with saving of virgin resources. The prevention of cane trash burning along with asignificant reduction in the environmental burdens will also provide additional electricity to the national grid when the country is facing a severe energy crisis. A maximized use of byproducts would result in additional products which will result in diminished waste as well as reduced impacts on the environment along with economic benefits. Importantly, a diversified range of the product would also help the plant to maintain its economic flow. Nevertheless, a further brief economic as well as environmental analysis of cane trash electricity, and use of ethanol in the replacement of gasoline is recommended.

This study would help the biorefinery complex to address the environmental intensive stages and materials whereas for the other plants to adopt the good practices being used in this complex for reducing the environmental impacts. Moreover, the hotspots revealed in the study could help the designers and policymakers in making the sugarcane sector in the country environmentally more sustainable. The authors also would like to recommend further investigation of other available practices, sugarcane plantations, sugar plants, and ethanol plants in the country.

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