RENEWABLE ENERGY POTENTIAL OF SUGARCANE WASTE BIOMASS: A REVIEW

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ABSTRACT: *Traditionally a major percentage of sugarcane waste biomass (SCWB) has been used in various activities. Current practice in the burning of this waste biomass has identified as a poor thermal efficient process, a potential barrier to sugar industries for the achieving of economic sustainability, and indeed a threat to the environment. This study has conducted to reveal advanced technology that is used by sugar mills for the converting of SCWB into energy at a higher thermal efficiency. The data disclosed in this paper have collected from the published papers and reports. A total of sixty research papers and reports on SCWB have reviewed for the collecting of required information, which were mostly published in the years from 2000 to 2021. A major percentage of sugarcane bagasse and trash (SCBT) have been burned conventionally in the atmospheric air, and it becomes a potential source of carbon emission (CO_2eq). The range of calorific values of SCBT is from 8MJ/kg to 10MJ/k. Gasification with the combined heat and power (CHP) technology or Pyrolysis with CHP technology has been used for the gaining of higher calorific value (energy) of SCBT. The energy potential of SCBT is about 0.44 MWh/(ton SCBT). The report published by International Renewable Energy Agency (IRENA) demonstrated SCBT is an economically and environmentally feasible renewable solid fuel and a replacement of fossil fuel. IRENA also revealed; SCBT solid fuel is able to reduce 600 $kgCO_2eq/MWh$ carbon emission. The information documented in this paper on SCBT's energy potential, the technology used to produce energy, and benefits in carbon emission reduction would be a guideline for energy industries, policymakers, and government agencies for the implementing of economic scale renewable energy projects. This study concludes that the work publishes in this paper is novel, and a road map to produce energy from SCBT for the achieving of economic and energy sustainability for sugar industries.*

Keywords: Renewable Energy, Waste Biomass, Carbon Emission, Sugarcane Waste, Sustainable Development, Energy Optimization

1.0 INTRODUCTION

This article presents a review work made on research outcomes published in various scientific journals. The core issues of this review are to collect information on advanced technologies used by sugar mills for the converting of SCWB into energy at higher thermal efficiency. This review also aims to collect information on the optimization process of energy production from SCWB, its economic and environmental benefits. The review methodology has developed based on the guideline given by the United Nations (UN) [1], UNEP [2], IPCC [3], Eyerusalem et al.(2019) [4], and UNICA Brazil [5]. The Sustainable Development Goals (SDGs) and particular SDG-7 (clean energy), SGG-12 (sustainable production and consumption), and SDG-13 (climate actions) also influenced the methodology used for this study.

To achieve the study's goals, the required information collected from the relevant journals published mostly in the years from 2000 to 2021. The distribution of papers studied for this review is that 10% was published before 2005, 20% was published from 2006 to 2014, and 70% was published from 2015 to 2021.

2.0 SUGARCANE WASTE BIOMASS IN RENEWABLE ENERGY DOMAIN

Sugarcane is a high-yield energy crop grown in more than 100 countries. Starting from the sugarcane plantation to the sugar processing, the total waste biomass from this crop is about 30 percent; and sugarcane bagasse and trash (SCBT)are the main waste parts [4–6]. Gupta *et al.* [7]; Schumacher *et al.* [8]; and Shaikh and Shamim [9] reported that the sugar industry produces four major types of waste biomass, which are cane residue left in the field after harvesting (trash), bagasse, press mud, and bio effluent. All these wastes are lignin-enriched waste biomass and potential sources of energy.

Schumacher *et al.* [8]; Shaikh and Shamim [9]; and Mohammadi *et al.* [10] revealed; since ancient times, the SCBT has been used as a low-cost indigenous renewable energy source. The report published by Habibullah and Rahman [11] has also disclosed that most sugarcane industries of the world have been used SCBT to produce energy. According to the EIA [12], many nations such as Brazil, India, and China have been using SCBT as an alternative renewable energy source to replace fossil fuels. The EIA [12], and the IRENA [13] stated, advanced technologies are required for the exploiting of energy from SCBT.

Pantaleo *et al.* [14]; Siemers [15]; and Shahidul [17] reported that the carbon emission problems from SCBT can be solved by converting this waste biomass to heat and electricity. Siemers [15]; Shahidul *et al.* [18]; and Sing [19] have stated; when advanced technologies use for energy harvesting from SCBT, the carbon emission rate is only 26 kg CO_2eq/MWh. On the other hand, when fossil fuel oil use as an energy source, the emission rate is about 650 $kgCO_2eq/MWh$.

The IRENA [13, 20], and Samarjeet [21] reported on the economy of SCBT based power plants. The reports demonstrated, the range of Internal Rate of Return (IRR) is from 28.60% to 21.94%; the range of return on capital (ROC) is from 6% to 7.5%, and the range of payback period is from 15 to 20 years.

Based on the background started, SCBT is a potential renewable energy source. For the use of SCBT potentials, require to know its properties, calorific values, and technologies available in the market, benefits, and barriers in harvesting energy.

3.0 PROPERTIES OF SUGARCANE WASTE BIOMASS

Sugarcane is an excellent converter of solar energy into biomass-based green energy. The higher ratio of energy to biomass volume makes sugarcane an energy crop. Han *et al.* [22] reported that the SCWB contains low crude fat (2.0%) and a higher percentage of carbohydrates (55.4%). Hossain *et al.*[23] also reported, the high fiber content in

SCWB is another potential part of this biomass, it contains crude fiber about 30.4 g/100g, dietary fiber about 79.5 g/100g, and insoluble dietary fiber of about 75.7g/100g. Chauhan *et al*.[24]; Saad and Sayed [25] stated, the SCWB is a potential fiber source of cellulose (range from 40% to 50%), hemicellulose (range from 20% to 30%), lignin (range from 20% to 25%), and ash (range from 1.5% to 3%). Authors also revealed, the SCWB contains about 50% fiber with 50% moisture, which comprises 41.54% Carbon, 5.40% Hydrogen, 33.14% Oxygen, 1.83% Nitrogen, and less than one percent (<1%) Sulphur. The higher amount of fiber and significantly less amount of Sulphur make this waste biomass potential and feasible source of renewable energy.

4.0 ENERGY POTENTIAL OF SUGARCANE BIOMASS WASTE

The first part of this section presents the findings of the literature review on the energy potentials of SCBT. The second part of this section focuses on the models used to estimate caloric value. The third part of this section presents the technologies used to convert SCWB to energy.

4.1 Energy Potential of Bagasse and Trash

Alonsoamador and Cornacchia [6], Arshad and Ahmed [26], and Andreza *et al*.[27] demonstrated that higher fiber content, lower Sulphur value make SCWB a potential energy source. Based on the energy stock database (2018) [28], the total global SCBT potentials in a year is about 0.51 billion tons. The report published by Kumar *et al.* [28], and Pippo *et al*. [29] demonstrated, the calorific value of SCBT significantly depends on its moisture content. The energy potential of SCBT at different moisture content presents in Table 1.

Table1: Energy Potential of Sugarcane Waste Biomass

Sugarcane Biomass Waste	Moisture Contents	SCBT's Calorific value [6, 26, 27, 31]	
		LHV*	HHV
Sugarcane bagasse and trash (SCBT)	52%	7.5 MJ/Kg	12.5 MJ/Kg
	35%	12.5 MJ/Kg	17.5 MJ/Kg
	30%	13.2 MJ/Kg	18.35MJ/Kg

Low Heat Value (LHV), High Heat Value (HHV

Moisture content in SCBT is one of the main barriers for the utilizing of its energy potential. To address this issue; Gagliano *et al*. [32], and Mavukwana *et al*. [33] suggested drying SCBT prior to use this biomass for the combustion process. The energy recovery efficiency from SCBT significantly depends on the technology used for the thermal combustion of this biomass. The energy recovery efficiency of various technologies presents in Table 2.

Table 2: Energy Efficiency VS Thermal Process for SCBT

Energy Recovery Process	Thermal Efficiency	Energy Outputs
Traditional Combustion	≤30%	≈20KW(KG SCBT)$^{-1}$ [32], [33].
Gasification or Pyrolysis	≤50%	≈60KW(KG SCBT)$^{-1}$ [32], [33].
Gasification or Pyrolysis with CHP	≥80	≈100KW(KG SCBT)$^{-1}$ [26], [31], [34], [35]

According to the reports published by Gongora [36], Anena [37], and Sanchesz and Maury [38], a way of increasing energy yield from SCBT is optimizing air supply into the thermal process. Another way to reduce moisture contents is to dry SCBT by using waste heat of boiler and turbine.

4.2 Model used to Estimate Energy Potential of Sugarcane Waste Biomass

SCBT's LHV can estimate by using Dulong's formula, which is presented by Eq (1) [24]:

$$LHV = \left[33800C + 144000\left(H - \frac{O}{8}\right) + 9270S - \left(\frac{9 \times 2442 \times H}{100}\right)\right]\left(\frac{kJ}{kG}\right) \qquad Eq.(1)$$

Here, H is the weight of hydrogen content available in SCBT. The HHV can be estimated by the models used by Kumar et al. [29]. The models presented by Eq (2) and Eq (3):

$$HVV = \left[19605 - 196.05\frac{m}{100} - 196.05\frac{A}{100} - 31.14\frac{A}{100}\right]\frac{kj}{kg} \qquad Eq.(2)$$

$$LHV = \left[18260 - 207.63\frac{m}{100} - 182.6\frac{A}{100} - 31.14\frac{A}{100}\right]\frac{kj}{kg} \qquad Eq.(3)$$

Here, m is the average moisture content in percent (%); A is Ash content in percent (%).

Alena [37], Sanchez and Maury [38], Chaturvedi *et al*. [39] and Carvalho *et al.* [40] revealed, the electric potential of SCBT at moisture content 32% is about 0.44MWh/1000kg. Arshad and Ahmed [26] also revealed the average electrical energy potential of SCBT is 0.46 MWh/ton. Pippo *et al.* [30] and Morasis *et al*. [41] found, about 3.6 tons of SCBT at 32% moisture is equivalent to 1.0 barrels of fossil fuel oil.

Table 3:Global Energy Harvesting from SCBT

Country	Capacity Million ton/Year)	Energy Potentials GWh/year	Aims and Government Policy Issue
India	40	19,000 GWh [42, 43]	SCBT use to replace fossil fuel [42,43,45] for the achieving of SDG-3,SDG-7 and SDG-13 [42, 46]
Cuba	6.5	2,850 GWh [47–49].	As of 2018, total electricity production from SCBT is about 532 MWh. The national policy is to increase energy production from SCBT to achieve energy and environmental sustainability [47–49].
Brazil	180	86,000 GWh [50–52].	Both ethanol and electricity production from SCBT to meet national energy demand and it will continue up to 2030 for the achieving of SDG-7 and SDG-13. [48, 50–52].
Pakistan	18.0	7,900 GWh [48, 53]	FY 2017-2018, bagasse-based electricity production was 894 GWh [43]. CHP has been used to optimize energy conversion efficiency. The national policy is to replace fossil fuels by SCBT [48, 53].
Thailand	34.5	15,500 GWh [43, 54], [55]	As of 2020, SCBT has been used to produce electricity for sugar mills. By the year 2030, expected electricity production from this sector would be about 755 MWh [43, 54, 55].
China	33	14,599 GWh [29, 54]	As of 2020, the CHP process has been used to achieve over 90% thermal efficiency. Fossil fuel has been replaced by SCBT to reduce carbon emission [29, 54].

The energy potentials and energy harvesting experience from SCBT of some countries are listed in Table 3Guido and William [44], Naqvi *et al*. [45] revealed, China and Thailand are the top East Asian countries involved in energy production from SCBT. Authors have also figured out sugarcane waste biomass stock of Asian countries including Bangladesh (2.17 million tons a year), Indonesia (8.5 million tons a year), Myanmar (3.3 million tons a year), Vietnam (5.9 million tons a year), and Philippines (0.9 million tons a year).

4.3 Technologies Used for Energy Harvesting from SCBT

Alena [37], Watanabe *et al*. [41], Chen *et al*. [42], Gongora and Villafranco [36] revealed, gasification and pyrolysis process with CHP are the feasible ways for optimizing of energy production from SCBT. Gasification technology has been used to produce gaseous forms of energy from SCBT. Aktawan *et al.*[46], reported, Hot air and steam have been used for thermal combustion of SCBT, and both updraft and downdraft gasification processes are suitable. The gasification process is able to produce biogas from SCBT. Vineet [47], stated that feedstock with high moisture (≈50%), upwards draft gasifier is efficient to produce biogas from SCBT. Samarjeet *et al*. [21]; and Shahidul and Malcolm [48] suggested using hot air (≥700^{o}C) and steam together for the combustion of SCBT in optimizing syngas and hydrogen production.

Pyrolysis mostly uses for the production of bio-oil from SCBT. Pyrolysis is a thermal combustion process. Bo-Jhih and Wei-Hsin [49], revealed, the range of pyrolysis temperature is from 300^{0}C to 950^{0}C. At the second stage of the Pyrolysis process, bio-oil converts into the gaseous energy at a temperature range from 430 ℃ to 950°C. The gas yield performance in pyrolysis has appeared to be optimum at a temperature of 950℃. Rotliwala and Behara [50] reported, at pyrolysis temperature 400 ^{o}C, bio-oil starts to produce from SCBT; and hydrogen and syngas start to produce at temperature 600℃ and continue to increase up to 950℃. Information published by Naqvi *et al*. [45] and Morais *et al.* [51] on pyrolysis demonstrated that hydrogen and syngas gas were produced from SCBT between the temperature of 600℃ to 950℃.

The combined heat and power (CHP) technology has been used in many sugar industries for increasing energy efficiency and to reduce carbon emission (CO_2eq) rate per unit of energy. Traditionally, CHP has been used with either gasification or pyrolysis processes. Birru et al. (2019) [52] and Sampaio and Cardoso 53] reported, the CHP is a highly thermal efficient technology compared with the traditional energy reclamation process.

Gasification and pyrolysis have been used to produce syngas from SCBT; this gas is utilized through a turbine to produce electricity. Costa and Pinheiro [54] and Junqueira [55] revealed, the waste heat of the turbine is utilized through the CHP cycle in reducing moisture of SCBT; heating up boiler feedwater, and increasing air temperature used for gasification and pyrolysis. Thus, CHP contributes to increasing the thermal efficiency of the energy reclamation process. It was also demonstrated; CHP integration with pyrolysis or in gasification, the energy recovery efficiency can increase up to 95 percent. In this process, the greenhouse gas emission (CO_2eq) rate is about 30% less compared with the traditional SCBT combustion processes.

5.0 ENERGY EXTRACTION FROM SCBT AND BENEFIT

Converting SCBT to energy has a strong link with social benefits including economy, environment, and health. The economic benefits can measure by the Internal Rate of Return (IRR) on capital and Return on Investment (ROI). The social benefits can measure by reduction of pollution and carbon emission. The health benefits can measure by evaluating the impact on health quality improvement for the reducing of pollution and carbon emission (CO_2eq) due to converting SCBT into resources.

The IRENA [13, 20] pointed out, economic and environmental benefits depend on the size of the power plant for the production of renewable energy from SCBT. A power plant size of about 50MWh has appeared to be economically feasible. It also reported that though small-sized power plant is not economically feasible but is able to contribute to reducing carbon emission and pollution.

Grande *et al*. [56], Pantaleo *et al.* [14], EIA [12], IRENA (2018) [57], and IRENA (2020) [58] revealed; for the gaining of higher benefits in the economic, environmental, and health, advanced technologies shall use to convert SCBT to energy and resources.

6.0 SCENARIO ANALYSIS OF FINDINGS AND CONCLUSION

Bagasse and trash are the main waste biomass of Sugarcane crop. As of the 2020 estimate, the global SCBT stock was about 0.5 billion tons. SCBT is a lignin enriched waste biomass and a potential source of energy. The calorific value of SCBT depends on moisture contents. The gaseous product produces in pyrolysis and gasification are (volumetric percentage) 39.71% CO, 16.48% CO_2, 36.26% H_2, and 7.55% CH_4. The calorific value of SCBT is 10MJ/Kg at moisture contents of 32%; and 7.0 MJ/Kg at a moisture content of 55%. The high moisture contents are a key disadvantage for the use of SCBT as an alternative fuel to fossil fuel. With this constraint, UNEP [59] suggested using SCBT as a replacement of fossil fuel to reduce emissions.

The gasification with CHP or pyrolysis with CHP process can use to increase LHV of SCBT from 10 MJ/kg to 14.4 MJ/kg. Thus, the CHP can contribute to an increase of about 40% higher thermal efficiency compared with the traditional combustion system.

Economic analysis on energy production from SCBT showed the cost of energy production from small-scale plants (<10 MWh) is higher compared with the larger scale one (>50MWh). For economic feasibility, a power plant size of more than 50MWh would be better. Nevertheless, in the aspect of social, health, and environmental benefits, Cardoso *et al*. [60] also suggested implementing the small-scale power plant with SCBT.

The identified challenges in implementing SCBT based renewable energy projects are many including inadequate investment for setting up the plant, lack of human resources with required skills, availability of affordable technology, maintaining an effective supply chain of SCBT, and favorable government policies. In regards to these challenges, Sampaio *et al*.[61] and Mohammadi *et al*. [62] suggested forming a government and private partnership for the implementation of SCBT based power plants to make the projects successful.

Based on the findings stated, this study concludes, sugarcane waste biomass is a feasible substitute for fossil fuel. SCBT conversion to energy would contribute to reducing carbon emission (CO_2eq); and as well as can be a source of renewable fuel for the achieving of SDG-7 (clean energy) and SDG-13(climate actions).

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