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S.I. : DIVERSIFICATION OF SUGAR CROPS FOR VALUE ADDITION

Valorization of Sugar Industry's By-products: A Perspective

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Abstract The worldwide expansion in energy and resource use has resulted in a number of unsustainable innovations, necessitating the development of resource sustainability and a reduction in energy usage. Valorization of industrial waste is centred on reducing the amount of pollutants in the environment as well as increasing the revenue generated by industries. Sugarcane processing generates large amount of by-products, namely cane trash, bagasse, molasses and press mud which can be valorized into various value-added products. In this paper, the authors reviewed the variety of applications of sugar industry by-products that has been physically and chemically transformed. It also observed that the technology for producing power from the by-products has advanced, while the manufacture of value-added chemicals has not. The key technological challenges in this area are downstream separation and purification. The difficulties in putting these waste valorization methods in place are also discussed. The amount of investigation and implementation of various solutions varies a lot. In order to translate research findings into commercial products, both business participation and government encouragement are essential. Economic and technological constraints must be recognized for effective commercialization. Some interesting areas were also highlighted which can become the basis for further investigations and could act as guidance for further research in this domain.

Keywords Environmental pollution · Industrial waste · Ecotoxicity · Valorization · Sugarcane

Introduction

All living creatures require sugar as a source of energy (Iwuozor et al. 2022a). Sugar cane and sugar beet are the primary sources of crystalline sugar for humans (Afiomah and Iwuozor 2020). Every year, roughly 125–130 million tonnes of sugar are produced worldwide, with two-thirds coming from sugarcane and one-third from sugar beet (Casu et al. 2012; Chauhan and Rai 2012). Sugarcane (*Saccharum spp.*) is a massive, thick perennial grass belonging to the *Poaceae* family (Iwuozor et al. 2021a; Williams et al. 2016). Sugarcane is a major crop in countries like Brazil, India, Thailand, China and Australia that are tropical or subtropical. Sugarcane, among other crops, has a high sucrose content, a high biomass content and a high production efficiency (Adeniyi et al. 2019). The plant's abundance is undeniable, as Brazil being the largest producer of sugarcane in the world produced about 647 million metric tons of sugarcane in the 2019/20 sugarcane crushing season, the majority of which was used in the ethanol and/or sugar industries (Barros 2020; Bezerra and Ragauskas 2016).

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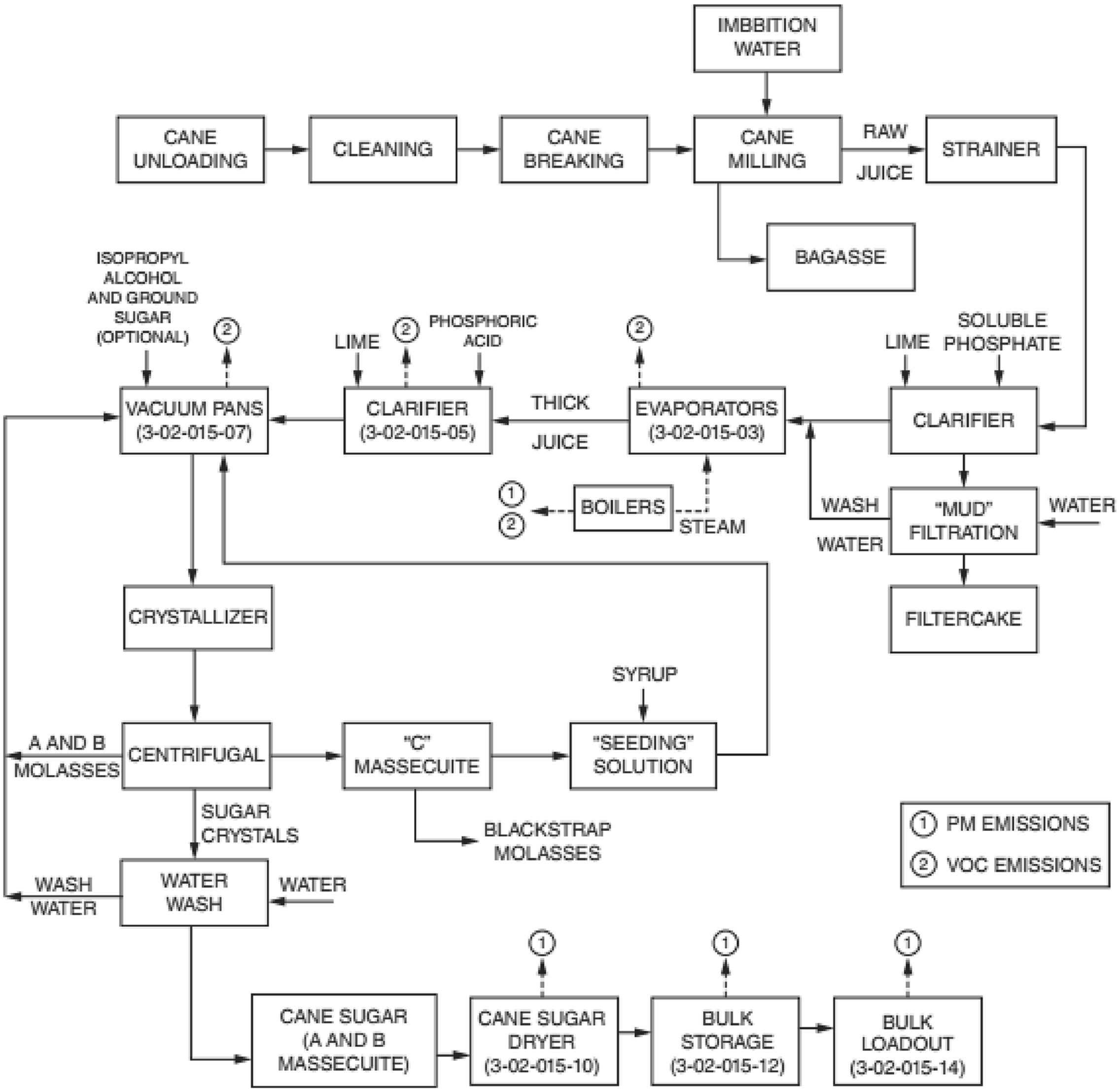

Fig. 1 Sugar production flowchart (Akbar and Ali 2017). *Reproduced with data from* Akbar and Ali (2017) *with permission from Wiley*

Sugar processing is a lengthy process as shown in Fig. 1 that involves multiple phases in order to produce the final product (crystal sugar) (Akbar and Ali 2017). The sugar industry is regarded as one of the most significant sources of pollution in the environment. The industrial processing of sugar involves a number of physical and chemical techniques. Calcium hydroxide (milk of lime, $Ca(OH)_2$), carbon dioxide (CO_2), phosphoric acid (H_3PO_4), sulphur dioxide (SO_2), polyelectrolytes, polyacrylamide flocculent, caustic soda (NaOH), soda ash (Na_2CO_3), lead sub-acetate and hydrochloric acid are among the most commonly used compounds in the industry. The presence of all of these complicated contents in sugar industrial waste causes environmental pollution, but on the other hand, it provides opportunities for valuable by-products isolation and re-use of polluting elements (Akbar 2006; Iwuozor 2019a; Iwuozor and Gold 2018; Zhul-quarnain et al. 2018).

Environmental awareness and ecological concerns are driving the development of novel eco-friendly materials (Adeniyi et al. 2020a, b; Iwuozor et al. 2021d). Waste and by-products created during the sugar production process are a rich source of high-value chemicals that could be employed as food/chemical additives and/or nutraceuticals as shown in Fig. 2 (Esparza et al. 2020; Gharib-Bibalan 2018). The principal by-products of the sugar industry are bagasse, cane trash, press mud and molasses. Molasses can contain up to 48% sugar. It is widely utilized in livestock feeds and other industrial processes. In the case of untreated effluent discharge, it can also be a major source of contamination in water bodies (Casu et al. 2012). Molasses is a common substrate used in the fermentation

Fig. 2 Summary of value-added products obtainable from the sugar industry

industry as a feedstock for the manufacture of ethanol and baker's yeast. It is more appealing for industrial fermentation and other related uses due to its abundance, high sugar content and cheap cost availability (Cueva-Orjuela et al. 2017; Fatoye and Onigbinde 2020).

The worldwide expansion in energy and resource use has resulted in a number of unsustainable developments, necessitating the development of resource sustainability and a reduction in energy usage (Adeniyi et al. 2021; Umenweke et al. 2021). Sugarcane is one of the most widely cultivated crops in the world with great demand. As a result, it would be beneficial to examine and discuss the various valorization strategies, as well as the factors impacting the valorization of its by-products. Lots of studies have reviewed the valorization of these wastes, but none of the works in published literature has comprehensively studied current progresses that has been made in this field irrespective of region with a view to providing a stepping stone for future researches. This study is aimed at reviewing the use of various valorization techniques aimed at reducing hazards and recovering value-added products from sugarcane in order to provide an overview and key insights into current progress in the disposal and valorization of this abundant waste generated in the sugar industry. Some interesting areas were observed by this review which can become the basis for further investigations in the future.

By-products of the Sugar Industry

From the cane and beet harvesting stage, all through to the milling stage and down to the sugar refining stage (which includes numerous separation processes), the sugar industry generates vast amount of waste materials and by-products which are rich in chemicals and have great potential for use in numerous other processes. By-products of sugar industry include cane trash, sugarcane bagasse, press mud, molasses, wastewater, etc.

Generally, for every tone of sugarcane harvested, approximately 270 kg of cane trash is generated. Also, for every tone of sugarcane crushed 0.3 tonne of bagasse is produced. Similarly, for every tone of sugar refined, 0.03 tonne of press-mud and 0.041 tonne of molasses are generated (Meghana and Shastri 2020). This review will focus on the applications of cane trash, sugarcane bagasse, press mud and molasses (shown in Fig. 3).

Cane Trash

Cane trash consists of the leaves and other extraneous matter which are found together with the sugarcane stalk during harvesting of the cane. Per ton of sugarcane harvested, 0.09–0.11 ton of trash is generated (Balakrishnan and Batra 2011; Singh et al. 2008). Traditionally, waste is disposed of by burning in fields. It is left in the field after cane harvesting because the presence of large amount of cane trash with the stalk during the processing of the cane to produce sugar can lead to the following: increased wear of machinery cane knives, mill rollers, etc., extend load on juice clarification and crystallization adversely affecting sugar quality and recovery, higher loss in milling due to unwanted fibrous material, lower juice purity resulting in lower sugar recovery and more molasses formation (Mohan 2021). The cane trash which consists of 12–23% of the total cane harvested is a substantial by-product of the sugarcane industry (Romero et al. 2007). Cane trash has been utilized in various application fields, as shown in Table 1.

Besides being availed as cattle feed (Mahala et al. 2013) and cane field blanketing purposes, studies focusing on utilization of cane trash along with bagasse for heat and electricity required to make sugar mill energy self-sufficient along with surplus electricity generation have been reported (Khatiwada et al. 2016). Cane trash along with bagasse has been extensively studied for power generation using biomass integrated-gasifier/gas turbine combined cycle technology (BIG/GT-CC), especially in Brazil and Cuba (Balakrishnan and Batra 2011). However, BIG/GT-CC technology has not yet been commercialized (Rasche and Del Diego 2020). Utilization of 9 and 27% of the cane trash recovered from the field, in combination with bagasse for electricity production, increased the surplus electricity generation by 22 and 57%, respectively, in Brazilian sugarcane biorefinery scenario (Sampaio et al. 2019). Production of 2G biofuels, such as lignocellulosic ethanol from cane trash in combination with bagasse, has also been explored (Chandel et al. 2012; Krishnan et al. 2010). Another study looked at optimal utilization of cane trash for energy demands in a sugar mill to produce bagasse derived ethanol. This study highlighted the trade-off between the economic benefit of utilizing trash and the environmental cost of the added fertilizer requirement (Vikash et al. 2018). Additional fertilizer is required to meet the necessary nutrient content deficit caused by trash removal from the farm, which in turn increased the

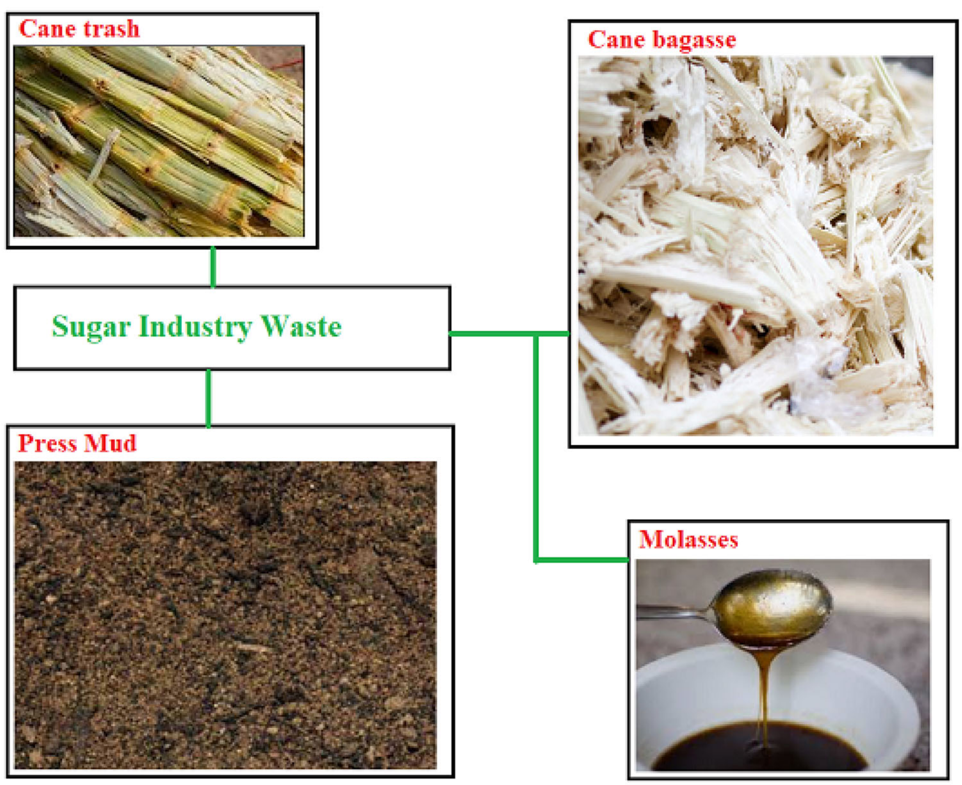

Fig. 3 Summary of major wastes from the sugar industry

Table 1 Some key areas for the utilization of cane trash

Application area	Key findings	References
Electricity generation	27% cane trash–bagasse ratio increases electricity generation by 57%	Meghana and Shastri (2020)
Green Cane Trash Blanketing	Improve soil structure, reduce soil compaction	Tayade et al. (2017)
Bioethanol production	Use of cane trash as a lignocellulosic biomass leads to significant improvement in bioethanol production	Dias et al. (2012)
Biochar production	The slow pyrolysis of cane trash and bagasse could generate over 1MWhr of electricity with a biochar recovery of approximately 33%	Quirk et al. (2012)

environmental burdens due to fertilizer production. Higher content of lignin (36.1%) and silica (6.96%) in sugarcane leaves limits its industrial applications (Chandel et al. 2012).

In India, Brazil and Thailand, cane trash is generally retained in the fields that have adapted green harvesting (Chandel et al. 2012; Rasche and Del Diego 2020). Blanketing replenishes the soil condition by the addition of organic nutrients. Further, it retains the moisture of soil and prevents weed growth and ill effects due to extreme temperatures (Ram et al. 2006; Yadav et al. 1994). Conversion of sugarcane leaves into biochar for cooking applications is another eco-friendly practice of valorization (Bhatnagar et al. 2016). Appropriate Rural Technology Institute of India (ARTI) developed kilns that can produce charcoal briquettes from cane trash. These briquettes can be utilized as fuel in non-pressurized cooker developed by ARTI (Meghana and Shastri 2020). This practice of charcoal briquettes production has been adapted in some regions of South India (Balakrishnan and Batra 2011). Charcoal briquettes production is economically viable and environmental benign practice that also aids in the reduction of deforestation (Bhatnagar et al. 2016).

Molasses

This section discussed the composition and applications of molasses, the by-product of the sugar processing mill. The composition and applications of molasses are clearly presented in the subsections that follows. Sugarcane molasses (SCM) is the viscous liquid produced after sucrose crystals have been removed from the concentrated juice by centrifugation. In the sugar manufacturing process, three vacuum evaporator crystallizers are employed. The juice is fed into the first vacuum which removes the crystalline sucrose and the by-product is called 'molasses A'. This by-product goes through the second vacuum, and the by-product is 'molasses B', and then through the third vacuum to ensure complete extraction of the crystalline sucrose, leaving behind the final by-product 'molasses C', a dark viscous liquid also called blackstrap molasses (Bhatti et al. 2019; de Oliveira Lino et al. 2018; Gutiérrez-Rivera et al. 2015). Molasses has a molecular formula of $C_6H_{12}NNaO_3S$, a molecular weight of 201.22 g/mol and a density of 1.41 g/cm^3 (Jain and Venkatasubramanian 2017). On estimate, 100 tons of sugarcane produces 7 tons of molasses (Boviatsi et al. 2020), with over 160 m ton/year produced globally (Vidra et al. 2017). SCM is mainly used in the production of ethanol, rum and as a supplement in livestock feeds. It has also been utilized in the production of butanol, sorbitol, citric acid, succinic acid, lactic acid, among others.

Composition of SCM

The general composition of SCM differs according to the geographical location of the producing country (Jamir et al. 2021). Molasses has a complex composition with different studies reporting several components and varying ranges of the components. This is attributed to the sugar type and method of refining. SCM contains on average, 62.3% of easily fermentable sugars (Palmonari et al. 2020), proteins, vitamins and trace elements. The sugars in SCM are mostly sucrose (48.8%), glucose (5.29%) and fructose (8.07%), with very little amounts of galactose (0.04%), raffinose (0.03%) and arabinose (0.01%). Besides sugars, SCM also contains, brix, ash, pH, minerals such as calcium, magnesium, sodium, potassium, iron, copper, manganese and zinc. Increase in concentrations of these metal ions results in an increase in inhibition against the activity of the enzyme, invertase, secreted by yeast to convert sucrose to reducing sugar (Raharja et al. 2019). Table 2 presents a summary of the findings of the compositions of SCM (but not restricted to that). The values are not final determinants but on average or simply as reported in the literature.

Applications of Sugarcane Molasses

SCM is widely used in many industries ranging from foods, plastics, to agro industries and many more, for the

Table 2 Composition of SCM

Component	Value	References
Brix (degree)	84	Gasmalla et al. (2012)
Dry matter %	79.0	Ghorbani et al. (2011)
Reducing sugar %	20.5	Raharja et al. (2019)
Sucrose %	48.8	Palmonari et al. (2020)
Glucose %	5.29	Palmonari et al. (2020)
Fructose %	8.07	Palmonari et al. (2020)
Galactose %	0.04	Palmonari et al. (2020)
Raffinose %	0.03	Palmonari et al. (2020)
Arabinose %	0.02	Palmonari et al. (2020)
Total sugar %	62.3	Palmonari et al. (2020)
Ash %	12.7	Gasmalla et al. (2012)
pH	5.7	Bento et al. (2020)
Calcium %	0.60	Raharja et al. (2019)
Magnesium %	0.43	Palmonari et al. (2020)
Sodium %	0.08	Palmonari et al. (2020)
Potassium %	1.82	Palmonari et al. (2020)
Iron %	0.70	Jain and Venkatasubramanian (2017)
Copper mg/L	17.0	Mangwanda et al. (2021)
Manganese mg/L	52.0	Mangwanda et al. (2021)
Zinc mg/L	19.0	Mangwanda et al. (2021)
Phosphates %	2.03	Palmonari et al. (2020)
Sulphates %	2.09	Palmonari et al. (2020)
Nitrates mg/kg	464	Palmonari et al. (2020)
Chlorides mg/kg	60.0	Palmonari et al. (2020)

production of many value-added products. Some of these areas that highly utilize molasses are highlighted below.

Bioethanol Production

Bioethanol is ethanol produced by microbial fermentation. It is one of the most important biofuels proposed as an alternative to the depleting and price fluctuating fossil fuels (Akhabue et al. 2019). Unlike fossil fuels, bioethanol can reduce the amount of carbon dioxide and hydrocarbons released into the atmosphere and lowers environmental degradation because of its high octane number (Mayzuhroh et al. 2016). Molasses is the by-product of sugar manufacturing process primarily used in the production of ethanol because of its low cost, availability and ability to produce fermentable sugars without any prior treatment (El-Gendy et al. 2013). One litre of ethanol can be produced from approximately 4 kg of molasses, though this can vary depending on the extraction method and sugar content of the molasses (Rasmey et al. 2018). In 2013, 60% of total ethanol produced globally came from molasses (Boviatsi et al. 2020). The process of bioethanol production from molasses involves direction fermentation of the already stored substrate (molasses) since the content sugars are easily converted to ethanol be anaerobic fermentation.

Fermentation is normally carried out using microorganisms such as yeast, bacterial or fungal. The yeast *saccharomyces cerevisiae* (*S. cerevisiae*) is the most commonly used microorganism in the fermentation of molasses to ethanol, accounting for majority of ethanol production by anaerobic process. The bacteria *zymomonas mobilis* (*Z. mobilis*) have also been recently utilized in fermentation of sugar to ethanol (Khoja et al. 2018, 2015), though not yet on a commercial scale. Many factors are considered in the selection of yeast for fermentation which include osmotic stress in molasses caused by the high quantity of salts of non-carbon origin, tolerance to yeast cells, flocculation capacity that is dependent on the process demands and good specific ethanol productivity (Bhatti et al. 2019; Fadel et al. 2013). Bacteria contamination which grows under the same conditions as the yeast and competes with the yeast for the available sugars can also drastically reduce the efficiency of the yeast, resulting in decreased ethanol yield (Inaba et al. 2013). The use of lactatic can effectively remove this contaminant. The anaerobic reaction between molasses and *S. cerevisiae* produces zymase enzyme which acts as catalyst to convert sugar into ethanol, carbon dioxide and heat according to the following equation (Bhatti et al. 2019; Gasmalla et al. 2012).

$$C_6H_{12}O_6 \rightarrow CH_3CH_2OH + 2CO_2 + \Delta \quad (1)$$

The CO_2 is captured and liquefied for sale to other industries such as beverages and refrigerator-producing companies (Bhatti et al. 2019). The fermented liquor is then introduced to the distillation column where ethanol is produced. Table 3 presents some of the studies on bioethanol production by SCM, with the yeast and the optimum operating conditions (pH, temperature and fermentation period). Using locally isolated *S. Cerevisiae* Y-39, El-Gendy et al. (2013) designed and optimized a statistical model for maximum bioethanol production and obtained a maximum ethanol production of 255 g/L in a batch fermentation process. Wu et al. (2020) replaced the fermentation gene, *PHO4,* from fast-growing *S. cerevisiae* strain, MC15 to MF01 via homologous recombination to yield an industrially engineered strain, MF01-*PHO4*. The ethanol yield rose to 114.7 g/L, an increase of 5.30% in ethanol production and 12.5% decrease in fermentation time when compared to that of the original strain, MF01, one of the highest ethanol-producing strains in SCM fermentation.

Production of Lactic Acid

Lactic acid (2-hydroxypropanoic acid) is the most common hydroxycarboxylic acid with the molecular formula CH_3-CHOHCOOH. It is an organic acid with α-hydroxyl and acid functional group (Alves de Oliveira et al. 2018), used in many industries such as food, textile, pharmaceutical and chemicals, and as a monomer in the production of the biodegradable and biocompatible polymer, polylactic acid (PLA), which has several applications (Chaisu et al. 2014). Pure sugars are often used as raw material for the production of lactic acid. However, the high cost of pure sugars and that of the subsequent lactic acid produced make the process economically disadvantaged (Farooq et al. 2012). The high cost of lactic acid produced from pure sucrose has also limited the production of PLA which has to compete with the traditional petrochemical-based plastics to remain competitive in the market (López-Gómez et al. 2019). Hence, the need for an alternative low-cost substrate like SCM is also readily available and enhances lactic acid yield.

On a commercial scale, lactic acid is produced either by chemical synthesis or by biotechnological fermentation. The chemical synthesis is based on the use of lactonitrile hydrolysed with strong acid (Rodrigues et al. 2017), while the biotechnological fermentation is based on the use of microorganisms to degrade the substrate (molasses) into metabolites such as lactic acid (Komesu et al. 2017). Production of lactic acid by microbial fermentation has many merits over chemical synthesis, such as low temperature, high purity, low concentrations of inhibitors and ability to be stored and use all year round (Alves de Oliveira et al. 2018; Oliveira et al. 2016b, a). In addition, microbial fermentation produces the more desired stereoisomer, optically pure L- or D-lactic acid, while chemical synthesis produces the racemic mixture of DL-lactic acid. Currently, fermentation process accounts for about 80–90% of the global lactic acid production and it is estimated that the demand for this product will rise from 1220 kilotons in 2016 to 1960 kilotons in 2025 (López-Gómez et al. 2019). The commonly used microorganism in lactic acid production is *lactobacillus sp*., because of its tolerance to acid medium, and also being able to be modified to produce a specific lactic acid optical isomer (Oliveira et al. 2016b, a). The presence of metal ions in SCM may inhibit cell growth and affect the medium pH during fermentation. Therefore, pre-treatment with dilute acid may be required before fermentation (Vidra et al. 2017), though this may increase the production cost. In the polymer industry, lactic acid is dehydrated in the presence of acid catalyst to give lactides according to the equation below. The lactides are then polymerized to obtain the biodegradable thermoplastic polymer, PLA (Komesu et al. 2017).

$$2CH_3CHOHCOOH \rightarrow C_6H_8O_4 + 2H_2O \quad (2)$$

Table 4 presents some published works on lactic acid yield and productivity using SCM substrate. Sun et al. (2019) used a microbial consortium, CEE-DL15, consisting of *Clostridium sensustricto*, *Escherichia* and *Enterococcus* in batch fermentation process to produce one of the best published lactic acid productivity from molasses (4.49 g/Lh) with a yield of 0.81 g/g. Vidra et al. (2017) produced lactic acid from SCM using two *Lactobacillus* species: *Lactobacillus casei* and *Lactobacillus sp. MKT87*. The concentration of lactic acid produced after 150 h was 83 g/L and 68 g/L, respectively, with a yield of 0.57 g/g and 0.76 g/g. The amount of enzyme utilized or the length of pre-treatment time was not sufficient as a result of lack of invertase to fully hydrolyse the sucrose. This leads to the low lactic acid productivity reported.

Table 3 Ethanol production from SCM by microbial fermentation

Microorganism (strain)	Productivity (g/L)	Optimum conditions	References
S. cerevisiae (Y-39)	255.0	pH 5.6, 38 °C, 71 h	El-Gendy et al. (2013)
S. cerevisiae (F-514)	13.60	pH 5.2, 20 h	Fadel et al. (2013)
S. cerevisiae (MF01-*PHO4*)	114.7	30 °C, 56 h	Wu et al. (2020)
Pichia veronae (HSC-22)	32.32	pH 5.0, 35 °C, 60 h	Hamouda et al. (2015)
Z. mobilis	160.0	pH 5.0, 30 °C, 48 h	Khoja et al. (2015)
S. cerevisiae	140.0	pH 4.6, 30 °C, 48 h	Khoja et al. (2015)
Z. mobilis	160.0	pH 5.0, 34 °C, 48 h	Khoja et al. (2018)
Z. mobilis	58.40	pH 5.1, 31 °C, 44 h	Maiti et al. (2011)
Z. mobilis	93.80	pH 6.0, 35 °C, 62 h	Pinilla et al. (2011)
S. cerevisiae	49.00	pH 4.5, 30 °C, 72 h	Zentou et al. (2017)

Production of Rum

Rum is the alcoholic beverage produced from SCM. It is a fairy tasteless and neutral spirit produced from fermentation and distillation of molasses and sugar juice or syrup, traditionally produced by the West Indies and Central Americans (Pino and Roncal 2016; Pino et al. 2012). Rum is one of the most popular alcoholic beverages with a global consumption of over 1 billion litres per year (Hinojosa-Nogueira et al. 2020). The French-speaking Caribbean commonly uses sugarcane juice for the production of rum, but about 97% of rums are produced from molasses (Medeiros et al. 2017). Several countries produce different types of rums, but the major types include the white, dark, gold, over-proof, spiced and Demerara rums. However, the grade and quality of a rum ultimately depend on the quality of molasses, the production process, the desired product specifications and the countries legislations. The production of rum from SCM commonly follows 3 processes: the fermentation of the molasses, distillation of the ethanol produced, ageing in barrels and finally dilution, to adjust the desired alcohol content (at least 37.5 vol.%) (Franitza et al. 2018).

Fermentation is the process by which the sugars in molasses are converted to ethanol by the action of a microorganism (usually yeast). The major difference between the types of rum produced depends on the type of microbial strain used for fermentation. Typically, strains of *S. cerevisiae* are employed in the fermentation of molasses for rum production. Water is first added to the must (sugary molasses) before fermentation enhances the growth of the strain. Fermentation can last from 20 h to 4 days for light rums and up to 3 weeks for heavy rums (Medeiros et al. 2017). During this time, more than a hundred different aroma-active compounds are formed (Franitza et al. 2016; Hinojosa-Nogueira et al. 2020). Such compounds like alcohols, ethyl acetate, acetic acid, ethyl esters, benzoic acid, vanillin, vanillic acid, among others, all help to confer on the rum, its flavoury taste. Distillation is carried out after fermentation to separate the volatile components of the fermented products and concentrate the ethanol produced (Mangwanda et al. 2021). Distillation can be carried out in either the pot still or column still (still commonly refers to the distillation unit) with the former preferred industrially. Alcohol in the fermented broth is evaporated during distillation, re-condensed and collected as raw spirit (Mulye 2019).

Rum needs time to mature, and just like other spirits, ageing or maturation is carried out to improve the quality of the final product. Rum ageing is carried out in oak barrels previously used in whisky or brandy production (Franitza et al. 2016). The period of the ageing depends on the producing country. However, rums require a minimum of 1–2 years to be matured, except over-proof rum which can be sold in some countries without ageing (Mangwanda et al. 2021). Over-proof rum, unlike other rums, also contains up to 70–80% alcohol vol% (Mangwanda et al. 2021). Oxidative reactions, condensations, esterifications and other reactions going on in the oak casts give the freshly distilled rum its final character and colour (Pino and Roncal 2016). Blending is carried out on the final rum by the master blender, modifying it to the desired alcohol content. The addition of sugar up to 6 g/L may be allowed depending on the rum type, so did caramel for colouration and activated charcoal for decolouration, and other desired ingredients (Medeiros et al. 2017).

Livestock Feed Supplement

In developing countries, only about 20% of agricultural outputs are attributed to livestock production despite the increasing demand for milk and meat in these countries (Windsor et al. 2020). The main reason for this low output is the poor quality of diets the animals are fed on, especially during the dry season. The major sources of feed for dairy cows are natural grass hay, elephant grass, purchased concentrate feeds (soya bean, grass pea and maize) and brewery grain (Demoz et al. 2018). However, these crop residues and forages are low in nitrogen and high in the crude fibre, lignin, restricting their intake and digestibility

Table 4 Lactic acid production from SCM

Microorganism	Conce (g/L)	Yield (g/g)	Productivity (g/Lh)	References
Microbial consortium CEE-	112.3	0.81	4.49	Sun et al. (2019)
DL15	83.00	0.57	0.55	Vidra et al. (2017)
Lactobacillus casei	68.00	0.76	0.45	Vidra et al. (2017)
Lactobacillus sp. MKT87	50.60	–	1.10	Jaimes et al. (2014)
Lactobacillus plantarum	84.50	–	3.40	Srivastava et al. (2015)
Lactobacillus delbrueckii	77.60	–	–	Farooq et al. (2012)

(Lawania and Khadda 2017), and continuous feeding of the animals with these poor quality forages with little amount of energy and concentrate ultimately leads to a lower milk production and poor productive performance (Jayawickrama et al. 2013). Different strategies have been employed in a bid to improve the quality of dairy feeding, of which feed treatment and supplementation have been regarded as the best feeding strategy. Including sources of readily fermentable sugars and nitrogen to the feeds of ruminants to ensure their good body conditions has been recommended as they improve the digestibility and bioavailability of nutrients (Assefa and Nurfeta 2013). Urea, a non-protein nitrogen-rich compound, has been widely used to treat livestock feed as its nitrogen content can be used by microbial organisms in the rumen to produce protein. Inclusion of urea in dairy feeds, however, leads to a release of excess nitrogen that far overweighs the energy in the rumen for microbial protein synthesis, and consequently leading to the absorption of this nitrogen as ammonia by the rumen and lost as urea (Kiani et al. 2013). To avoid such occurrence, a readily available sugar source, such as SCM, is supplemented to the feed. Feeding a sugar-based product in diet to livestock can result to a change in ruminal fermentation patterns and decrease ammonia concentration (Martel et al. 2011). Sugars are fermented rapidly in rumen than starch. SCM, in dry or liquid form, is added to dairy feeds to improve microbial growth in rumens which promotes the digestion of fibre and non-protein nitrogen (Rahiman and Pool 2016). In addition, SCM is classified as concentrate, which is a component of feed that provides nutrients such as protein, carbohydrate and fat at higher levels and contains less than 18% crude fibre, and reduced moisture (Trivedi and Shah 2014).

Urea-molasses mineral block (UMMB) has been for years, considered as one of the easiest and effective way of treating and supplementing cattle feed as it provides readily available source of energy and protein in the form of molasses and nitrogen in the form of urea, as well as fibre and minerals (Jayawickrama et al. 2013). Supplementation with UMMB can increase fibrous feed digestibility by up to 20%, feed intake by 25–30% productivity and reproducibility of diary animals (Mengistu and Hassen 2017). Lawania and Khadda (2017) supplemented the diet of zebu lactating cows with UMMB and the result revealed an improved nutrient intake and milk production. Similar result was obtained by Windsor et al. (2020), Kebede et al. (2018), and host of others. An improvement in the productive performance of sheep was also reported (Sheikh et al. 2017). However, Jayawickrama et al. (2013) found no effect no effect on milk production of dairy cows after being fed with UMMB-supplemented basal diet. This was attributed to the fact that the basal diet (rice straw) is a good quality feed with sufficient amount of concentrate and, hence, needs no supplementation.

SCM has also been used exclusively to supplement livestock diets at relatively low concentrations, leading to an enhanced growth, increased milk and meat quality. Osman et al. (2020) reported improved growth performance, protein metabolism and efficient rumen fermentation of goat kids fed with molasses-supplemented diet for 3 weeks without harming their growth and immunity. Assefa and Nurfeta (2013) supplemented molasses in wheat brain in a concentrate mixture to improve the intake of dietary dry matter, organic matter, metabolizable energy and growth performance of female crossbred heifer calves. The ability of sugars to ferment rapidly in rumen leads to production of lactic acid but a decrease in ruminal pH, which could potentially depress fibre digestibility (Martel et al. 2011). Siverson et al. (2014) reported that replacing molasses-based products for corn did not influence productivity and had little impact on milk fatty acid production. Similar results on no effect on milk production and animal performance were also reported by Martel et al. (2011), Baurhoo and Mustafa (2014), Salvador-Loreto et al. (2016), among others. A decrease in milk productivity was even reported by Trivedi and Shah (2014) after introducing molasses to the basic feed plan of dairy farm. Although SCM may be a good source of energy and protein, several others factors like timing of the supplementation, ease of feeding, lactation stage of the ruminants and environmental factors need to be assessed to determine its viability in animal feeds supplement (Trivedi and Shah 2014). The summary of some of the results in open literature on the treatment and supplementation of livestock feeds with urea-molasses mineral block and sugarcane molasses is presented in Table 5.

Therapeutic Potentials and Other Applications

Molasses is categorized as 'Generally Regarded as Safe' (GRAS) product, by the US food and drug administrator. SCM is known to contain a high amount of polyphenols, making it a very good antioxidant agent, and a potential agent in the prevention of several chronic diseases that involves oxidative stress (Iwuozor 2019b). The antioxidant effect of SCM has been studied by many groups (Asikin et al. 2013, 2016; Deseo et al. 2020; Valli et al. 2012). SCM was found to be a very god agent that could protect against oxidative DNA damages caused by peroxyl radicals (Asikin et al. 2013) and free radicals (Asikin et al. 2016). This validates its use in bioresource-based products. SCM has been reported to produce lowered peak and global responses to glucose, insulin, amylin and gastric inhibitory polypeptide in healthy rats (St-Pierre et al. 2014), making it a potential save alternative to refined sugars. SCM also decreased mutation and oxidation and inhibits reactive nitrogen species in lipopolysaccharide stimulated macrophages, showing its biological activities in antioxidation, antimutation and anti-inflammation (Wang et al. 2011). This antimutation effect of SCM has been consolidated in its successful inhibition of heterocyclic amine compounds (Cheng et al. 2021), and advanced glycation end-products (Yu et al. 2017). A filtered SCM concentrate has shown potentials to lower blood glucose level and insulin responses, reduces obesity and helps in diabetes treatment (Ellis et al. 2016).

A polyphenol-rich sugarcane extract (PRSE) consisting of sugarcane juice and molasses has been reported as a potential antiageing agent that should be considered in skin care cosmetics industries with more works (Ji et al. 2020b). PRSE also exerts anticancer properties on a range of cancer cells including colon cancer cell lines, human lung cancer, human ovarian cancer, pro-monocytic human leukaemia and mouse melanoma cell lines (Prakash et al. 2021). PRSE was recently reported to halt the uptake of glucose and fructose in the intestinal epithelial barrier, Caco-2, and revive insulin production in dysfunctional β-cells (Ji et al. 2019). Furthermore, the extract also has reportedly shown potentials to exert neurological benefits through promotion of genes that encode neurogenesis-related growth factors and regulate neuronal differentiation while also preserving neuronal DNA oxidative stress damage (Ji et al. 2020a). The antibacterial potential of SCM has also been demonstrated (Shafiqa-Atikah et al. 2020). This medicinal value of SCM is as a result of its phytochemical properties and in particular, its phenolic and flavonol content. The complex nature of SCM, however, makes it difficult to underpin the components responsible for its vastly researched antioxidant property (Deseo et al. 2020).

In the food industry, SCM is commonly used in foods like cookies or pies, barbecue sauces, ginger bread, among others, because of its special characteristics flavour and sweetish aroma (Mulye 2019). SCM extract can reduce hazardous compound formation during meat processing (Cheng et al. 2021). It also has potentials as a natural functional ingredient capable of modifying carbohydrate metabolism and contributing to glycaemic index reduction of processed foods and beverages (Wright et al. 2014). Moreover, SCM can also be used in the production of

Table 5 Results of treatment and supplementation of livestock feeds with molasses

Feed supplement	Livestock	Result	References
UMMB	Zebu lactating cattle	Improved efficiency, milk production and reproductive performance	Lawania and Khadda (2017)
UMMB	Livestock young calves, growing calves, lactating cows	Improved cattle growths	Windsor et al. (2020)
UMMB	Crossbred lactating dairy cows	Increased milk yield, milk fat content and net benefits of production over the traditional feeding practice	Kebede et al. (2018)
UMMB	Crossbred lactating dairy cows	Increases milk yield	Demoz et al. (2018)
UMMB	Corriedale sheep	Nutrient improvement, body weight gain, feed intake, nutrient digestibility, enhanced rumen fermentation. No effect on rumen pH	Sheikh et al. (2017)
UMMB	Dairy cows	No effect on the production performance of the cows	Jayawickrama et al. (2013)
SCM	Nubian goat kids	Improved growth performance, protein metabolism and efficient rumen microbial fermentation	(Osman et al. (2020)
SCM	Female crossbred heifer calves	Improved intake of dry matter, organic matter, crude protein, metabolizable energy and growth performance	Assefa and Nurfeta (2013)
SCM	Primiparous and multiparous Holstein cows	No influence on productivity and minute effects on milk fatty acid profile	Siverson et al. (2014)
SCM	Lactating Holstein cows	Increases ruminal pH and enhances ruminal fatty acid biohydrogenation pathways	Martel et al. (2011)
SCM	Lactating Holstein cows	Increased milk urea nitrogen but had no effect on animal performance	Baurhoo and Mustafa (2014)
SCM	Multiparous Brown Swiss cows and calves	No productive advantage on milk yield, insignificant beef production profit	Salvador-Loreto et al. (2016)
SCM	Lactating dairy cows	Decrease in milk productivity of the cows	Trivedi and Shah (2014)

succinic acid (Chan et al. 2012), citric acid, butanol, sorbitol, among others. It is used in hookah to add flavour to tobacco and shisha (Jamir et al. 2021).

In spite of this numerous potentials of SCM, it is still not fully utilized. Molasses is a by-product that is easily affordable and accessible to livestock farmers in many sugarcane producing countries, yet not utterly utilized in that regard. In order to meet the global projected 19% and 33% increase in meat and milk production, respectively, by 2030 (Windsor et al. 2020), a mechanistic farming method needs to be adopted, and these include improvement of the livestock feeds. Having shown its efficiency, feed supplementation with SCM and other additives should be made a conventional livestock feeding strategy, and awareness created for local farmers to fully take advantage of this. In addition, most of the therapeutic potentials of SCM are pre-studies that requires more works for support. This opens an interesting research area that researchers should be further explored to provide more insights on the medicinal efficacies of this by-product.

Press Mud (PM) or Filter Cake

The dark brownish amorphous residue obtained during the clarification of cane juice is called press mud, and it is generated at about 3% of sugarcane processed (Gupta et al. 2011). The composition of press mud generated is influenced by locality, cane variety, milling process and the clarification process chosen for sugar purification. Main components of press mud are moisture (50–65%), fibre (15–30%), crude wax (5–14%), sugar (5–15%), crude protein (5–15%) and nitrogen (2–2.5%) (Gangavati et al. 2005). Sugarcane industries from all over the world are producing large amounts of PM every year, and the disposal of this by-product is a vital concern. Usually, PM is being dumped as garbage in open fields or sold/given to farmers to use as fertilizer. This disposal method pauses some environmental challenges such as air pollution due to odour, surface and ground water pollution and overall pollutes the environment. Recently, much attention has been focused on better use of PM as shown in Table 6. Ansari and Gaikar (2014) reported PM could be a potential source of hydrocarbons and valuable chemicals on thermochemical conversion.

Several intermediate products such as enzymes, biogas/methane, compost, wax and protein have been produced from sugarcane PM (Sarker et al. 2017). In India, press mud is utilized for field applications usually in combination with the spent wash as fertilizer or sold as compost or burnt in kilns to manufacture bricks (Ansari and Gaikar 2014; Kumar and Chopra 2016). In Brazil and China, press mud is used as fertilizer in combination with spent wash or bagasse ash in sugarcane cultivation (Xu et al. 2019). The decomposition of press mud in such land application practices is detrimental to the environment due to leaching and emission of greenhouse gases (George et al. 2010).

The extraction of residual sugar, wax and protein from sugarcane press mud has been studied (Partha and Sivasubramanian 2006). In particular, it is possible to obtain microcrystalline wax with degree of crystallinity comparable to that of carnauba wax (Phukan and Boruah 1999). Press mud has also been used as a substrate in solid state fermentation for production of citric and lactic acids (Shankaranand and Lonsane 1993; Xavier and Lonsane 1994). The organic components in press mud make it a possible source for biogas production by anaerobic digestion. Such a facility was set-up in a sugar factory in western India with the biogas obtained being piped to households in the factory premises (Kumar 1996). The yield was reportedly 165 L biogas/kg press mud with 60% methane content. In another study, press mud treated in a biphasic reactor resulted in a yield of 9m3/ton biogas with 70–75% methane content (Balakrishnan and Batra 2011). Additionally, the resulting sludge had a high N/P/K value and is suited for use as a fertilizer. On the whole, for the production of high-value chemicals from press mud, process development and scale-up, ensuring consistent product quality, etc., still needs to be investigated.

There are continuing studies on the ability of press mud to provide adequate nitrogen and phosphorus for specific crops (Gupta et al. 2008; Jamil et al. 2008; Muhammad and Khattak 2009). In this context, enrichment of press mud by vermicomposting has been studied by mixing with other wastes like cow dung (Prakash and Karmegam 2010), bagasse and sugarcane trash (Kumar et al. 2010). Press mud has also been used in aquaculture for promoting the growth of carp (Keshavanath and Gangadhara 2006). Yet another application is as an adsorbent. Based on its porous structure and presence of polar groups, it is predicted that press mud would be a good biosorbent for metal ions, dyes, etc. (Gupta et al. 2011). Utilizing press mud as a fertilizer either directly or after biocomposting with distillery effluent is a popular practice. Bulk usage is possible, and the approach is perceived to be an environment friendly way of increasing the nitrogen and phosphorous contents in the soil. In contrast, other waste-based soil amenders like municipal waste compost have associated environmental concerns such as accumulation of heavy metal and other pollutants in the soil over time (Déportes et al. 1995). However, recent reports indicate that decomposition of press mud generates acid leachate and also emits significant amounts of greenhouse gases (George et al. 2010). Further, press mud can also lead to immobilization of inorganic nitrogen (Rasul et al. 2006). Because land application is well established, there is relatively less

Table 6 Some application areas for the utilization of press mud

Application area	Key finding	References
Soil enrichment	On application to soil, press mud have the ability to significantly enrich macronutrients in soil and restore soil composition	Saleh-e-in et al. 2012
Diet supplementation	Press mud has the potential to replace rice bran up to 50% as a nutritional supplement in fish diet	Singh et al. (1999)
Biomethane production	Energetic profiles and profitability of biomethane production can be improved when press mud is co-digested with other conventional organic substrates	Marlin et al. (2020)
Cement production	Press mud could improve the later age strength of cement. It also improves settling and blending consistency of cement	Radwan et al. (2021)
Sorption	Press mud has been found to be a promising reactive material for the removal of Cd^{2+}	Raimondi et al. (2020)
Biobutanol production	Press mud contains consequential amounts of cellulose (22.3%) and hemicellulose (21.67%), making it a good substrate for biobutanol production	Nimbalkar et al. (2017)

incentive for developing alternative products from this waste.

Bagasse

In this section, the composition and applications of the sugarcane waste, bagasse, are discussed. The composition and major applications were presented step by step in the subsequent subsections for further explanations with more emphasis on the value-added products. Table 7 presents some of the published chemical composition (on average) of the sugarcane bagasse.

Sugarcane bagasse (SCB) is the fibrous lignocellulosic residue of sugarcane after it has been crushed for the extraction of its juice used for sugar and ethanol production (Ajala et al. 2021). It is estimated that about 700 m tons of bagasse are produced annually throughout the World (Monteiro et al. 2016), corresponding to about 25–26% of the total sugarcane production (Frías et al. 2011; Moretti et al. 2018). Bagasse is the most important by-product of sugarcane production and the most abundant agricultural waste in the world (Candido et al. 2017). This waste is mostly used in the generation of electricity for cogeneration boilers in sugar production, and the surplus electricity exported to the grid. The use of SCB as conventional electricity distribution has been reported in even developing countries such as Cuba (Gil et al. 2013) and South Africa (Mashoko et al. 2013). SCB contains several functional groups such as hydroxyl, carbonyl, phenolic, sulphate and amine groups which can be functionalized to new compounds with different qualities (Ding et al. 2014; Gupta et al. 2015). The presence of these functional groups makes SCB a good adsorbent material (Adeniyi et al. 2020c).

Chemical Composition of SCB

The chemical composition of SCB as shown in Table 7 and Fig. 4 contains mainly cellulose, hemicelluloses and lignin, with small amount of ashes and extractives. The complex chemical compositions of the cell walls limit the use of SCB as feed for cattle and ruminants, thus making it more abundant and desirable by-product for commercialization (Chandel et al. 2012). The sugarcane age, method of harvest, soil topography and the extraction method are factors that can affect the composition of the SCB (Bezerra and Ragauskas 2016). SCB is chemically composed of cellulose, hemicellulose, lignin, extractives, and ashes.

Cellulose is a highly linear homopolysaccharide composed of β-1,4-linked anhydro D-glucose units. The primary structure of cellulose is represented by a linear polymer β-glucopyranoside residues, with up to 20,000 residues in polymerization (Candido et al. 2017). It is a homopolymer of glucose, a hexose, and can be converted to the six carbon sugar by hydrolysis (De Moraes Rocha et al. 2015). Cellulose is one of the most abundant, renewable and biodegradable natural polymers existing in many plant-based materials such as SCB and has potential as an excellent industrial material (Corrales et al. 2012; Li et al. 2012). In fact, most of the applications of SCB are as a result of its high cellulose content.

Hemicellulose is the second major fraction of SCB and the second most abundant naturally occurring polysaccharide after cellulose. The hemicellulose in SCB is comprised of β-(1 → 4)-xylopyranose backbone, having about 200 β-xylopyranose residues linked by 1,4-glycosidic bonds (Bezerra and Ragauskas 2016). It is a heterogeneous polymer of pentoses (xylose, arabinose), hexoses (mannose, glucose, galactose) and uronic acids, dominated by xylose, a five carbon sugar (Peng and Wu 2011). Unlike cellulose, hemicellulose is easily hydrolysed by an acid or

Table 7 Chemical composition of SCB (% w/w)

Component	De Moraes Rocha et al. (2015)	Canilha et al. (2011)	Nakanishi et al. (2017)	Ferreira et al. (2018)	de Oliveira et al. (2016b, a)
Cellulose	42.2	45.0	42.6	44.6	45.0
Hemicelluloses	27.6	25.8	26.2	30.3	29.9
Lignin	21.6	19.1	22.5	23.8	21.2
Extractives	5.63	9.10	5.3	0.83	0.80
Ashes	2.84	1.00	4.30	0.66	0.40

base because of its non-crystallinity, although the resulting sugar, xylose, is very difficult to ferment. Hemicellulose is the bridge linking cellulose through hydrogen bonds and lignin through covalent bonds, and these bonds can either be ester bond type, ether bond type or glycosidic bond (Hamzeh et al. 2013).

Lignin is a polyphenol that consists of the primary lignols, coumaryl, coniferyl and sinapyl alcohols (José et al. 2015; Lu et al. 2017; Sella Kapu and Trajano 2014). The lignin from SCB is mainly made up of alkyl-aryl ether structures (β-O-4', 83%) followed by minor amounts of phenylcoumarans (β-5', 6%) and other condensed bonds (José et al. 2015). Unlike cellulose and hemicellulose, lignin is not a polymer but an amorphous complex macromolecule consisting of three hydroxycinnamyl monomers that helps in cell wall water transport and provides support to the structure of the cell wall, as well as resistance to pathogenic attacks (De Moraes Rocha et al. 2015; Karp et al. 2013). Two bond types are found in lignin: an ester bond type and an ether bond type that are, respectively, sensitive and insensitive to basic solution (Kumar et al. 2014). The phenyl-propane precursor monomer units present in lignin make it very difficult to biodegrade (Maurya et al. 2015). Indeed, lignin is the recalcitrant in lignocellulosic materials, surrounding cellulose and hemicellulose and preventing them from breaking down without pre-treatment. The chemical structure of lignin is too complex, but the widely accepted basis is that it is formed through anomalous biosynthesis process modelled from its three primary lignols (Lu et al. 2017).

Sugarcane bagasse ash (SCBA) is the by-product of bagasse after being burnt in cogeneration plants. Approximately 7–8% of bagasse consumed are converted to ash which can never be further reduced but landfilled (Bahurudeen et al. 2016; Madurwar et al. 2014). Hence, constituting environmental nuisance SCBA has been reported as a non-biodegradable solid waste produced in high quantity in Brazil (2.5 m tons/year) (Faria et al. 2012), India (44,000 m tons/day) (Bahurudeen et al. 2016) and Thailand (424,700 m tons/year) (Somna et al. 2012). This black solid waste is highly rich in crystalline silica (SiO_2) (66.89%), Al_2O_3 (29.18%), Fe_2O_3 (29.18%), CaO (1.92%), MgO (0.83%) and SO_3 (0.56%) (Kawade et al. 2013). The presence of these compounds in SCBA makes it a very useful additive to cement, concrete and mortars. This

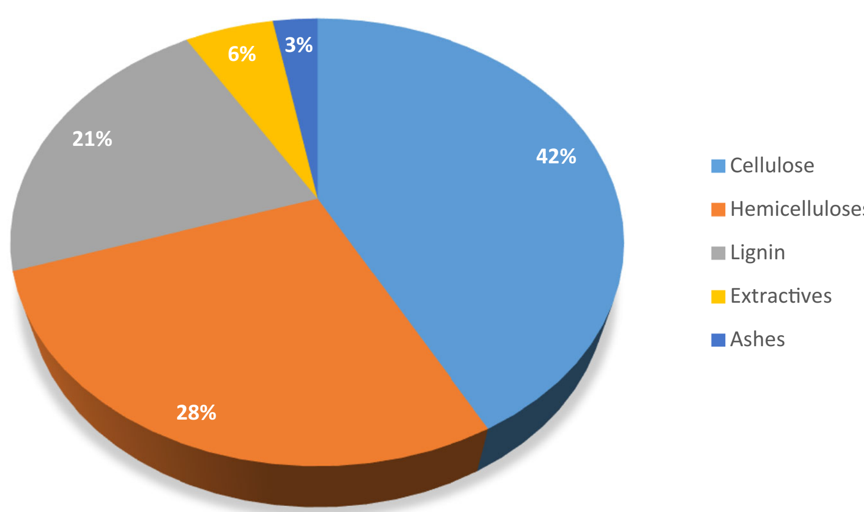

Fig. 4 Graphical representation of the component of SCB (De Moraes Rocha et al. 2015). *Reproduced with data from* De Moraes Rocha et al. (2015) *with permission from Elsevier*

application is further discussed in the subsection that follows. The soluble compounds in lignocellulosic materials are collectively called extractives. They are materials in biomass which during pre-treatment dissolves in water or ethanol (Zhou et al. 2017). Extractives, commonly removed from the bagasse, are hydrophobic and can be fatty acids, waxes, proteins, among others (Bezerra and Ragauskas 2016).

Applications of Sugarcane Bagasse

SCB is one of the most highly utilized renewable materials and one of the most widely researched, with De Moraes Rocha et al. (2015), noting that there are over 40 different applications of SCB. Aside from generation of heat in sugar production plants, many value-added products have been produced from SCB, with many of them directly linked to its high content of the crystalline cellulose and fibre. Bulk of the published papers, however, focused on one or more of the following applications.

Second Generation Bioethanol

The global climate change as a result of greenhouse gas emissions, the uncertainty in the prices and sustainability of fossil fuel and its general negative environmental impact have ignited interest in developing alternative sources of energy that are renewable and environmentally friendly (Dias et al. 2012; Velmurugan and Muthukumar 2011). This led to the use of agro products from the industrial production of such products like sugar, starch and oil to produce bioethanol known as first generation (1G) ethanol for vehicle fuel. As of 2012, over 80% of cars manufactured in Brazil are flex-fuel (able to run in gasoline, bioethanol or mixture of both) (Furlan et al. 2013; Hofsetz and Silva 2012). The demand for this bioethanol has, however, resulted in a direct competition with food crops in land usage, and hence, a threat to food security (Bezerra and Ragauskas 2016; Maryana et al. 2014). In a bid to mitigate this problem, inedible feedstock such as lignocellulosic biomass has been used to produce this bioethanol, and they are called second generation (2G) ethanol. In sugar industries, the ethanol produced from the fermentation of sugar is the 1G bioethanol. Half of the bagasse produced are used in the mill plant, while the remnant is dumped in the field. Chandel et al. (2012) remarked that a ton of SCB can yield up to 300 L of ethanol depending on factors such as the quality of the bagasse and the method of ethanol production. The processes involved in the production of bioethanol from lignocellulosic materials are more complex and expensive than the 1G bioethanol production, although the possibility of coproduction with the 1G bioethanol plants can reduce the production cost (Rabelo et al. 2011). The lignin–cellulose–hemicellulose complex, the crystallinity of the cellulose and the moisture content of the SCB are some of the problems inhibiting the fermentation of the lignocellulosic biomass to ethanol (Dantas et al. 2013; Rabelo et al. 2011). These problems can be mollified by following the biological route of production (Fig. 5) where the SCB is first pre-treated and hydrolysed before fermentation takes place.

Pre-treatment is carried out to separate the recalcitrant structure of lignin, increase the surface area of the bagasse and disrupt the cellulose–hemicellulose complex. It is done to make easy the hydrolysis that will follow before the subsequent fermentation. Pre-treatment separates the lignin by breaking the α-aryl ether bonds in its polyphenolic monomers and causes the swelling of cellulose by weakening the hydrogen bond linking the cellulose–hemicellulose complex (Rezende et al. 2011). Several methods have been employed by different researchers for the pre-treatment of SCB, which include alkaline pre-treatment (Canilha et al. 2011), acid pre-treatment (Rezende et al. 2011), steam explosion (Rocha et al. 2012), hot water pre-treatment (Yu et al. 2013), extrusion method (Moro et al. 2017), organosolv pre-treatment (Mesa et al. 2011), liquid ammonia pre-treatment (Hans et al. 2021), among others. Acid pre-treatment is the most widely used method, and according to Canilha et al. (2011), pre-treatment with dilute acid has become the state-of-the-art technology for the pre-treatment of lignocellulosic biomass. On the other hand, Hans et al. (2021) noted that the selective removal of lignin by saponification of the ether bonds and swelling of the cellulose makes alkaline pre-treatment the most efficient method. Organosolv has also been considered the most promising method for potential production of 2G bioethanol (Mesa et al. 2011). However, from the available papers, we can plausibly say that combination of two or more pre-treatment methods will yield better results.

Hydrolysis is carried out after pre-treatment, and it converts cellulose and hemicellulose to glucose and xylose, respectively (Dantas et al. 2013). Hydrolysis of pre-treated SCB can be carried out in two methods: acid hydrolysis and enzymatic hydrolysis. Acid hydrolysis breaks down the heterocyclic ether bonds between sugar monomers in polymeric chain (Velmurugan and Muthukumar 2011), but it has the demerit of generating some products that inhibits the process. Enzymatic hydrolysis, though more commonly used and less toxic, could also be limited in its actions by the bagasse concentrations. However, this could be avoided by performing the hydrolysis in a fed-batch mode (by gradually adding the bagasse to prevent precipitation and maintain low concentration) (De Albuquerque Wanderley et al. 2013). Without pre-treatment, the hydrolysis yield is less than 20% compared to 75–80% for acid hydrolysis and

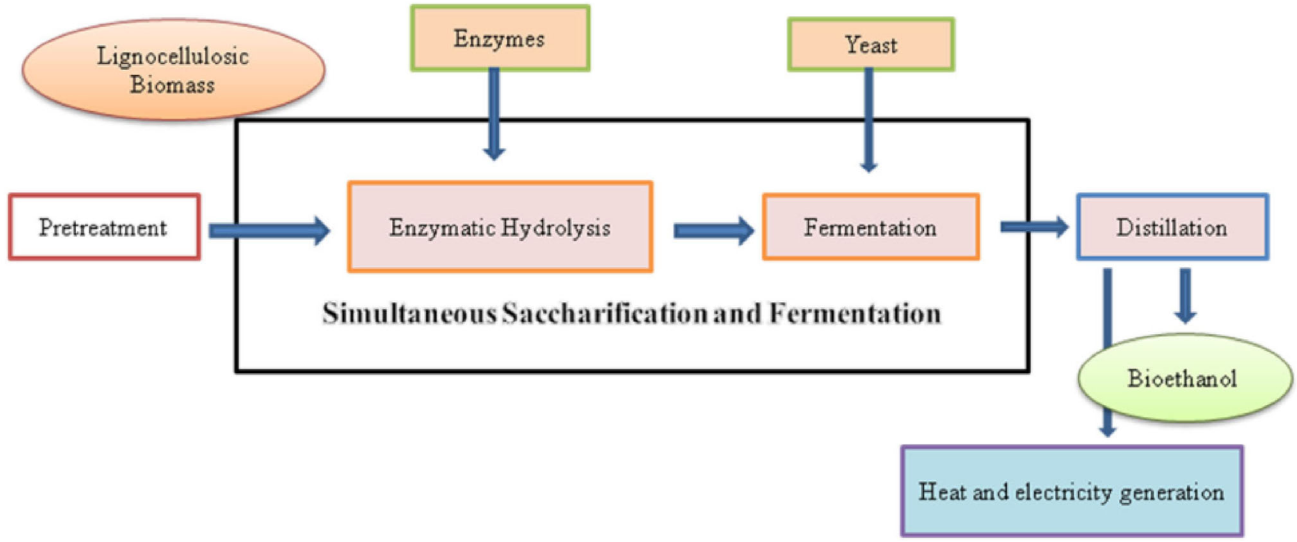

Fig. 5 Biological route of converting lignocellulosic biomass to bioethanol (Maurya et al. 2015). *Reprinted from* Maurya et al. (2015) *with permission from Springer nature*

up to 95% for enzymatic hydrolysis using pre-treatment (Dantas et al. 2013).

Fermentation is carried out to finally convert the sugars from cellulose and hemicelluloses to ethanol, and it is usually carried out by yeast or bacteria. Some of the commonly used yeasts include *scheffersomyces stipitis*, *spathaspora passalidarum*, *S. cerevisiae*, *kluyveromyces marxianus*, among others. One promising means of reducing process time and cost in the production of 2G ethanol is carrying out hydrolysis and fermentation simultaneously, a process known as simultaneous saccharification and fermentation (SSF). SSF is designed to reduce the inhibitory product from hydrolysis and make room for fermentation (de Souza et al. 2012). However, fermentation on its own is always difficult because most of the yeasts that ferment glucose cannot ferment xylose. Xylose, the main hemicellulose sugar, can be fermented by several yeasts, but only 1% can ferment it into ethanol (Nakanishi et al. 2017). This is because the fermentation rate of these yeasts is restricted in xylose, leading to low ethanol tolerance, difficulty in maintaining the rate of oxygen supply and sensitivity to inhibitors generated during pre-treatment and hydrolysis (Ji et al. 2011). Ultimately, temperature, pH, initial xylose volume, accessibility of oxygen, cell concentration and degree of inhibitors are all factors that determine the fermentation of xylose by yeast (Nakanishi et al. 2017). The ethanol obtained after fermentation can then be collected by distillation and purified to meet fuel requirements. Figure 5 shows a schematic representation of the processes involved in the conversion of lignocellulosic biomass to 2G bioethanol.

Nanocellulose

Cellulose is naturally linked in chains by hydrogen bonding to form longer chains called microfibrils, or simply nanocellulose. Nanocellulose is a cellulose in nanometre scale with a size range of 10–350 nm and a surface area higher than cellulose (Plermjai et al. 2018). Based on their size differences, function, method of preparation and source, nanocelluloses, which has both crystalline and amorphous parts, can be divided into cellulose nanocrystals (CNCs), cellulose nanofibrils or nanofibrillated cellulose (CNFs) and bacterial nanocellulose (BNC) (Feng et al. 2018).

CNCs are cellulosic materials that have at least one dimension equal or less than 100 nm with high crystalline nature and high aspect ratio (Kumar et al. 2014) and can take needle-like shape, rod-like shape or spherical shape. Acid hydrolysis has been extensively employed in the extraction of CNCs. When subjected to a strong acid hydrolysis, the unorganized amorphous part of cellulose, being more susceptible to acid attack, is preferentially hydrolysed, releasing the ordered crystalline part in the form of CNC (Kumar et al. 2014; Sofla et al. 2016).

CNFs are nanocelluloses with at least one dimension in the nanometre range, and having a diameter range of 5–60 nm (Feng et al. 2018). CNFs are extracted by mechanical processes such as high-pressure homogenization, ball milling, grinding and high-intensity ultrasonification. BNC is a cellulose with a high degree of crystalline and polymerization, synthesized by microorganisms. The basic microbial producer of BNC is the bacteria, *Gluconacetobacter xylinus* (Abba et al. 2020; Singh et al. 2021). According to Singh et al. (2021), the synthesis of

BNC from *G. xylinus* follows three steps: (i) polymerization of glucose residue in β-1,4-glucan, (ii) extracellular secretion of linear chain and (iii) arrangement and crystallization of glucan chains through hydrogen bonds and van der Waals forces.

The biodegradability, renewability, high potential of reinforcement in nanocomposites, high specific surface area and rigidity are all qualities of cellulose-based nanomaterials that make them high applicability in different industries. Some potential industrial applications of nanocellulose include high-quality paper products, nanofillers for polymer nanocomposites, thickener in cosmetics, scaffolds for tissue engineering, drug delivery and biomedical applications, supercapacitors, exceptional stabilizing agents in food industries, water-based latex paints as well as for industrial coating and suspensions (Abba et al. 2020; Mandal and Chakrabarty 2011).

Pulp and Paper

In the industrial production of paper, wood and other fibre-containing materials are used as raw materials. Over the years, countries such as China and India without much forest reserves for woody trees have in a bid to reduce their paper import rate, successfully exploited the use of non-wood materials such as SCB to produce pulp and the corresponding paper and paperboards (Rainey and Covey 2016). SCB is one of the most promising non-wood pulp because of its fast growth, high yield and high fibre content. The production of paper from SCB follows four practical processes: (a) removal of the non-fibrous pith cell (parenchymatous tissue) from the bagasse, (b) pulping of the bagasse, (c) bleaching of the pulp and (d) the paper making process. However, the bleaching process can be ignored if non-white paper types are to be produced.

The presence of the pith in SCB is the major constraints in its use for industrial paper production. Pith causes filtration difficulties in the production plants and increases the chemical consumption of the pulping and bleaching processes (Hemmasi et al. 2011). The high hygroscopic nature of the pith means it contains up to 20 times its own weight in water, in comparison with about five times the normal clean bagasse fibre (Lois-Correa 2012), hence, the need for depithing. Depithing can be carried out either by cutting the cane lengthwise and removing the soft central part (pith) (Rainey and Covey 2016), or by the use of depithing equipment such as *S.M Caribe*, *Kimberly KC-4* and *Horkel* depithers (Lois-Correa 2012). Depithing may not remove the whole pith from the SCB, but it increases its fibre content by up to 80% (Hemmasi et al. 2011).

Pulping is carried out after depithing. Pulping is aimed at removing the lignin and hemicellulose structures of the SCB without depolymerizing the cellulose. The process can be carried out either by chemical method (mostly used) or the mechanical method. Soda, soda anthraquinone and kraft process are the commonly used chemical pulping processes (Rainey and Covey 2016), and about 80–90% of the lignin and 50% of the hemicellulose are removed using these chemical processes (Hamzeh et al. 2013). Remnants of the lignin after pulping may impede the brightness of the pulp and the resulting paper; therefore, additional treatment may be required—bleaching.

Bleaching is commonly carried out with chlorine dioxide (ClO_2). The chemical reacts with the pulp to increase its brightness. Afterwards, the pulp is filtered and washed with cold water and little drops of methanol to recover the chemicals and the bleached pulps (Novo et al. 2018). Ecotoxicological issues associated with the use of chlorine chemical for bleaching in the pulp and paper industries led to the development of new bleaching technology known as elemental chlorine-free (ECF) bleaching and subsequently total chlorine-free (TCF) bleaching. These methods are effective in oxidizing lignin remnants and decreasing environmental production loads (Zhang et al. 2018). The bleached pulp is then used, after drying, to produce the paper sheets using an automatic sheet making machine by the standard method. Fibre mat is formed whereby a suspension of fibres is deposited one layer at a time and water drains through it, and then, the fibres overlay one another forming a sheet of paper (Rainey and Covey 2016). The paper sheets are then dried, cut and packaged.

Biosorbent for Heavy Metals Uptake

Increase in population, industrialization and urbanization has all resulted in an increase in heavy metals-containing effluents (Emenike et al. 2021; Iwuozor 2018; Ogunlalu et al. 2021). Different methods have been employed in the removal of these metals from aqueous solutions, and they include precipitation, ion exchange, adsorption, reverse osmosis, filtration membrane, among others (Emenike et al. 2021; Ighalo et al. 2021; Igwegbe et al. 2022). These methods are, however, generally costly to operate and can generate some toxic wastes, hence the need to develop alternative methods that are biodegradable, reusable, less expensive and environmentally friendly (Alomá et al. 2012; Dos Santos et al. 2011; Vera et al. 2019). These properties have been found in biological wastes, generally known as biochar, such as SCB. Biochar is the remnant of sustainable feedstock thermochemical processing such as pyrolysis, gasification and retort carbonization (Iwuozor et al. 2021b). SCB, just like other biochars, have been receiving attention of late for sorption process due to their strong affinity to organic pollutants and heavy metals (Ding et al. 2014), and their porous structures which can provide binding sites for the uptake of heavy metals from aqueous

Table 8 Maximum sorption capacity for biosorption of metal ions by SCB

Metal ion	q_{max}(mg/g)	pH	Method of determination	References
Au(III)	1498	2.0	Langmuir	Rubcumintara (2015)
Cr(VI)	52.70	2.0	Langmuir	Ullah et al. (2013)
Cr(III)	41.70	5.0	Langmuir	Ullah et al. (2013)
Hg(I)	35.71	4.0	Langmuir	Khoramzadeh et al. (2013)
Cu(II)	31.53	5.0	Langmuir	Dos Santos et al. (2011)
Pb(II)	4.540	6.0	Thomas	Duga et al. (2016)
Cu(II)	3.980	5.0	Thomas	Duga et al. (2016)
As(V)	2.375	7.0	Langmuir	Gupta et al. (2015)
Ni(II)	2.234	5.0	Langmuir	Alomá et al. (2012)
Cr(VI)	1.760	2.0	Langmuir	Alomá et al. (2014)
As(III)	1.203	7.0	Langmuir	Gupta et al. (2015)
Cd(II)	0.110	5.0	Experiment	Vera et al. (2019)
Pb(II)	0.094	5.0	Experiment	Vera et al. (2019)

solution, a process known as biosorption (Emenike et al. 2022; Iwuozor et al. 2021c, 2022b).

Biosorption involves the use of inexpensive and non-hazardous technique for the removal of contaminants from aqueous solution using biomass as the biosorbent (Ighalo and Adeniyi 2020b; Khoramzadeh et al. 2013). Mechanisms involved in the biosorption process include inter- and intra-particle diffusions, chelation, precipitation, physical adsorption and complexation (Alomá et al. 2012; Ding et al. 2014). The presence of different functional groups in SCB plays a major role in the sorption process as they can be activated physically through pyrolysis and subsequently treated with steam or CO_2 to enhance their sorption of heavy metals (Inyang et al. 2011).

Table 8 presents some published works on the maximum sorption capacity of different heavy metals onto the surface of SCB, reported in decreasing order and to 4 significant figures. These sorption capacities are normally determined experimentally or by use of isotherm parameters. The optimum pH was also reported. This is because in biosorption, pH has great impact on the sorption capacity as it affects the biosorbent surface charge, ionization rate and metal speciation (Alomá et al. 2014). From Table 8, the pH was seen to favour the acidic medium with a range of 2–7. This is probably because SCB has more acidic medium than basic medium as a result of the bagasse functional groups (Vera et al. 2019), and precipitation may occur at higher pH. Another reason for this is because at higher pH, the charges on the surface of the bagasse may likely become negative, resulting in formation of resistant forces between the metallic ions and the biosorbent (Ullah et al. 2013). Rubcumintara (2015) reported the highest maximum sorption capacity of the metals presented in Table 8 as 1498 mg/g uptake of Au^{3+} from aqueous solution by SCB.

Pozzolanic Material

Ordinary Portland cement (OPC) is often used as a cementing agent to improve the properties of soft clay in civil engineering projects because of its comprehensive strength and compressibility (Jamsawang et al. 2017). OPC, however, poses environmental danger because of the high rate of CO_2 it emits (Ighalo and Adeniyi 2020a). Therefore, replacing cement with other lower carbon materials with cementitious properties is one of the four levers for carbon emissions reduction by the World Business Council for sustainable development (Moretti et al. 2018). Agricultural wastes such as silica fume fly ash, rice husk ash and waste paper ash have been used to partially replace cement in concrete and mortar (Meko and Ighalo 2021a, 2021b; Ofuyatan et al. 2021), and recently, SCBA has served this purpose. The bagasse used in sugarcane mill plants for electricity generation if burned under controlled conditions displays pozzolanic properties, allowing their use as cement substitutes in construction (Bahurudeen and Santhanam 2015). Pozzolanic materials are materials rich in silica (SiO_2) and alumina (Al_2O_3) that can react with $Ca(OH)_2$ generated from hydrating cement to form supplementary cementitious materials (Jamsawang et al. 2017). The crystallinity of the silica, the presence of impurities and the particle size of any material are all factors that determine its pozzolanic/cementitious aptness (Ofuyatan et al. 2022).

SCBA, rich in crystalline silica if burned above 700 °C, can be used as an admixture to partially replace 20% wt.%

of OPC in concrete, mortar or bricks without any effect on the product in terms of development of early strength, chloride penetration and low water permeability (Alavéz-Ramírez et al. 2012; Amin 2011). This 20% replacement gives concrete and bricks of higher strength and is ascribed to its surface area, amorphous phase and degree of reactivity between the silica and calcium hydroxide in the bagasse ash (Amin 2011). This pozzolanic activity of SCBA could perhaps be due to the likely contamination of bagasse waste with soils before being used in cogeneration plants (Frías et al. 2011). The result of this technique is a decrease in environmental pollution, reduction in construction cost and preservation of natural resources (Faria et al. 2012).

Other Applications

Another important environmentally acceptable application of SCB is in its incorporation into polymer and epoxy composites. This is as a result of its high fibre content, as an increase in fibre content increases the strength of a composite (Adeniyi et al. 2022). SCB has been widely used as a reinforcer to improve the strength of composites, and this has been reported by many researchers (Acharya et al. 2011; Anggono et al. 2019; Monteiro et al. 2016; Singh et al. 2021). This waste has also been applied in thermal insulating board to reduce air conditioning loads (Panyakaew and Fotios 2011), in the synthesis of cellulose acetate for preparation of membrane (Candido et al. 2017), and reported to serve as soil fertilizer (Faria et al. 2012), although their provision of nutrient for this purpose is still in doubt.

In the food industry, nanocelluloses from SCB are used in fillings, crushes, chips, wafers, soups, gravies, puddings, among others. Ditto to its use as a biosorbent, SCB has also been used extensively as an adsorbent for the removal of organic dyes from aqueous solution. Dyes such as Rhodamine B (Zhang et al. 2013), methylene blue (Zhang et al. 2013), Congo red (Zhang et al. 2011), brilliant red (Da Silva et al. 2011), novacron orange (Noreen and Bhatti 2014), eosin yellow (Shaik et al. 2020) and indosol turquoise (Sadaf et al. 2014) have all been removed from aqueous solution using SCB adsorbent. In addition, because of its high silica content, SCBA has been utilized in the production of clay and ceramic materials (Souza et al. 2011), and in the synthesis of different types of zeolites such as Na-A (Moisés et al. 2013) and Na-X (Purnomo et al. 2012), which are also useful in the adsorption process and catalysis.

Despite the diverse applications of SCB, the waste is still being underutilized. A large amount of bagasse is still disposed as waste in the open field, especially domestically, while the locals commonly employed the practice of incineration in a bid to get rid of the waste. These actions result in an increase in the amount of CO_2 in the atmosphere, putting the environment at risk. If the incineration is performed in the cogeneration plant, these risk would be avoided since the amount of CO_2 released during combustion in ethanol production plant is equivalent to the amount of CO_2 consumed during plant photosynthesis as opined by Zanatta et al. (2016).

Finally, from the available studies, the use of SCB for the production of 2G ethanol has not been completely feasible till today. In spite of the amount of resources and capitals infused into the system by governments, it remained highly underutilized and many countries are abandoning the project for the more established 1G ethanol. Nevertheless, not even the 1G ethanol is economically viable. Thus, integration of 1G and 2G bioethanols for better economic and environmental performance is plausibly recommended. This has already been proven by the works of Dias et al. (2012), and Furlan et al. (2013). However, more works need to be performed on this to elucidate more on its potency.

Knowledge Gap, Recommendations and Future Outlook

The novelty of this paper is in evaluating recent research outcomes on the conversion of sugar industry by-products into value-added products. It can lead to guidance for further research in this domain. Some interesting areas were observed by this review which can become the basis for further investigations in the future.

There exists very little knowledge in published literature on the properties of sugarcane leaves. Apart from the study conducted by Yahaya and Shu'aib on the phytochemical characteristics of sugarcane leaves, no other study has evaluated the possible phytochemical as well as antimicrobial characteristics of the leaves of sugarcane. Such study should be encouraged as they could provide more information geared towards the usage of the leaves as food or medicine for humans and also encourage its use as feed for animals.

Bagasse contains large amount of fibre which makes it a good source of dietary fibre. It can be used in the production of biscuits, bread and for other bakery products. One problem that has limited its usage in this regard is the presence of lignin present in the bagasse. The human body lacks the capacity to digest lignin which acts as a covering to the cellulose and hemicellulose present in the bagasse. To solve this problem, research geared towards the delignification of bagasse to make it edible for consumption should be encouraged.

Even after more than a decade of research, further diversification from the sugar–ethanol–electricity scenario to biofuels like biohydrogen and biobutanol, as well as high-end chemicals like sugar replacements, enzymes, organic acids, bioplastics and bioadsorbents, is still in the research phase. Despite substantial study in the domain of process design to develop efficient pre-treatment methods and fermentation processes to achieve better yields of biochemicals, cost-effective processes and energy-efficient downstream processes are still lacking in most cases. One of the technological hurdles for commercialization of biochemicals such as acetic acid, levulinic acid, and adipic acid derived from C5 and C6 sugar feed-stocks is the lack of separation technology to accomplish the requisite purity. Downstream procedures are critical in high-end chemical manufacturing from sugarcane wastes in order to achieve the purity standards required for medicinal and industrial applications. The downstream processes, which account for 50–70% of total production costs, determine the economic sustainability of various bio-based chemical synthesis pathways. This is primarily owing to the low concentration obtained during the conversion stage, such as fermentation, which raises downstream separation costs. As a result, considerable advancements in separation technologies are urgently required. Another barrier in commercializing these bio-based approaches is waste collection supply chain logistics. Because waste is only available during certain times of the year, storage is essential. Improper waste storage can result in decomposition of the wastes, which can be harmful to the environment. Large-scale storage facilities can catch fire in extreme situations because of rising warmth produced by gradual microbial decomposition (Meghana and Shastri 2020).

A collaboration between the sugar industry and the construction industry that aims to use sugar industry waste for sustainable construction practices can provide additional avenues for sustainability in addition to the valorization routes proposed (Gopinath et al. 2018). Holistic study with a thorough understanding of the technological route, accompanying obstacles and exhaustive studies in economic and environmental assessment of a product/process under consideration is critical for the successful implementation of these methods. The system's robustness is provided via many valorization paths. If the sugar mill's sole product is sugar, it is extremely vulnerable to price and demand fluctuations in the market. Diversification of products, on the other hand, allows the flexibility to respond to changing circumstances. This will make the industry more resilient in the long run. Designing such complicated biorefineries, on the other hand, is extremely difficult. Process design, operations and control become more intricate, necessitating the use of advanced methods. Mass and heat integration, process synthesis, improved process control and other process systems engineering technologies must be investigated. Despite the fact that a few life cycle assessment studies have looked at bagasse to bio-based chemicals such as lactic acid, succinic acid and xylitol, studies focusing on techno-economic studies covering various other geographical areas and other wastes such as press mud and spent wash are completely lacking. Systematic research employing techniques like multi-objective optimization and multi-criteria decision making is required. These will aid in measuring trade-offs and offering policy/investment suggestions for specific regions (Meghana and Shastri 2020).

Concluding Remarks

Product, process and value chain design and operation must also include systems engineering methodologies. In this paper, the authors reviewed the variety of applications of sugar industry by-products that has been physically and chemically transformed. It was observed that the degree to which various applications have been researched and adopted varies greatly. It was also observed that the technology for producing power from the by-products has advanced, while the manufacture of value-added chemicals has not. The key technological challenges in this area are downstream separation and purification. Most of the researches that has been carried out on these materials for decades are yet to be commercialized. This appears to be the result of a combination of technological issues and a lack of aggressive industry participation. In contrast, industries' engagement has resulted in scale-up initiatives for applications with high-value markets, such as biofuels. Government cooperation is expected to help commercialize these uses in addition to industry participation. Finally, product, process and value chain design and operation must also include systems engineering methodologies to produce products with a wide range of applications.

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