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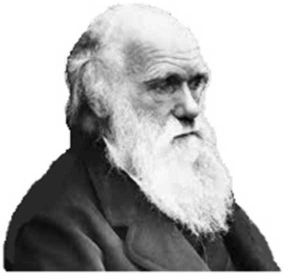

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# Thermocatalytic Conversion of Sugarcane Bagasse (SCB) for Bioethanol Production: A Review

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## ABSTRACT

An estimated 1.6 billion metric tons of sugarcane are produced worldwide each year, producing 279 million tons in metric of sugarcane bagasse (SCB) [1]. In terms of sugarcane production, Brazil leads the world with an annual output of about 739,300 metric tons, followed by India, China, Thailand, Pakistan, Mexico, Colombia, Indonesia, the Philippines, and the United States [2]. Sugarcane production produces waste and, if neglected, will have a serious negative impact on the environment. Alcohols, furfurals, organic acids, butanol, hydrogen, methane, ethanol, and other value-added products have all seen a major increase in output during the past few years [3], [4], [5]. The sustainable bio economy should be expanded via bio-based methods. An economic transformation from linear to circular will occur if the bio economy is more circular and sustainable. In view of the requirement for energy and environmental sustainability, a great deal of research has been done on the various SCB applications. Due to its successful application in the production of bioethanol, SCB is an acceptable source of sustainable feedstock for biofuel production. The SCB's bio products and enzymes demonstrate their economic value. Due to the higher reserve price than the current market price, the feasibility and industrial scale economics of biodiesel with sugar cane bagasse have revealed adverse net present values.

***Keywords*:** Gasification, Pyrolysis, Biomass, Thermocatalytic conversion, Bioethanol, Sugarcane bagasse, Conversion method

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## 1. INTRODUCTION

The hazardous effect caused by continuous burning of non-renewable fossil fuel has reduced greatly due to the utilization of alternative fuel. Bioethanol is to significant use via blending in order to use less conventional fuel when using gasoline. This is widely used around the world in currently running engines [6]. The liquid bioethanol is gotten when sugar is fermented, sugar is product derived from plants that has high level of carbohydrates (starch) [7]. Enzymes produced by microorganisms accelerate the fermentation process [8], [9].

### 1. 1. Sugar bagasse

Sugarcane contains four major divisions; the relative magnitude of each component is determined by the sugar agro industrial process. The four divisions are water, soluble and non-soluble substances, and fiber. Fiber consists completely organic solid portion gotten from the cane's stem; its distinct diverse elements are a major characteristic considered as well. Another part of the division consists of non-soluble solids that does not dissolve in water, it consists mainly of items that are not organic (rocks, soil, and extraneous materials), that do not dissolve in water and is impacted by the caliber of the used cane, cutting procedure and method of harvesting. The main raw material for the manufacturing of 2G ethanol is sugarcane bagasse, which is a lignocellulosic substance made of cellulose, hemicelluloses, and lignin [10].

It is estimated that 279 million metric tons of sugarcane bagasse are produced annually from the 1.6 billion tons of sugarcane that are produced annually worldwide (SCB) [1]. Brazil top the chart globally when it comes to sugarcane production as it produces around 739,300 metric tons every year, with China, Thailand, Pakistan, Mexico, Colombia, Indonesia, the Philippines, and the United States coming in second and third, respectively [2], Sugarcane production directly or indirectly cause waste and will result in serious environmental concern if left unattended to.

As a byproduct, sugarcane bagasse after the recovery of sugar juice through crushing and extraction. It possesses a well-defined energy property which makes it suitable for fuel production world-wide in the sugarcane agro-industry [11], [12]. Sugarcane bagasse is an agricultural waste used to produce bioethanol via a process known as fermentation. In Brazil, ethanol produced from the sugar in sugarcane is a well-known fuel. Sugarcane bagasse can also be used for other purposes like pulp, paper board production and several others. The technique called Response Surface Methodology (RSM), which is based on experimental design, is widely used for the analysis of changes in dependent variables and parameter optimization in the production of bioethanol and biodiesel. [13], [14].

### 1. 2. Previous discussion on potential of bioethanol from sugarcane

Agriculture food crops still remains an important feedstock for the creation of liquid biofuel examples include (wheat, sugar beets, sugar canes, and corn) they are frequently utilized in the manufacturing of bioethanol [9]. In order to produce biodiesel, oil seeds like (Sunflower, rapeseed, soybean, and palm oils) as its principal raw material [15], [16]. Climatic factors play a huge role in the distribution of feed stocks globally. Due to its high oxygen content, high octane rating, and non-toxic qualities, bioethanol is a popular choice for biofuel; and its safety because it reduces the emissions of pollutants like carbon monoxide, sulphur, and nitrogen oxides [17], [18].

### 1. 3. Conversion methods

SCB undergoes several processes to make it suitable for use which include purification and modification of its physical and chemical properties. De-lignification is the first step in the purification process, then preliminary processing and hydrolysis. The SCB must be de-lignified in order to increase its susceptibility to enzyme attack. In certain instances, specialized enzymes or chemicals first degrade and eliminate lignin (such as alkali), Before additional measures are performed to convert the remaining portion of the SCB to bio-ethanol, it is prepared for the synthesis of biofuels and other biochemical [19].

#### 1. 3. 1. Biological Conversion

Biological method utilizes certain enzymes or microorganisms for the conversion process which serve as inhibitor's compounds found in the hydrolysate and convert them [20]. Detoxification method is employed because it reflects an improvement in the process as it generates minimal waste before fermentation, and might be carried out right in the fermentation tank [21]. This approach is still quite practical, environmentally friendly, has lesser negative effects and decreased energy is involved in carrying out the process [22]; though, it takes a lot of time [23].

#### 1. 3. 2. Thermocatalytic conversion

Thermocatalytic conversion involves hydrolysis which is the process of breaking and utilizing enzymes, convert the feedstock's carbs into sugar [24]. In an effort to increase the production of bioethanol, hydrolysis is frequently selected as the key parameter.

## 2. SUGARCANE VALORIZATION

The majority of sugarcane is produced in nations like Brazil, India, China, Thailand, Pakistan, and Mexico that are located in tropical regions. One of the most extensively grown crops worldwide, particularly when sugar mills use simple process technologies, a lot of residues are left behind after the extraction of sugar from this crop and are often disposed of poorly. Environmental contamination comes as a result of the enormous amounts of solid waste that are frequently burned inefficiently or incinerated [25]. Among the leftover sugarcane solids are filter cake and bagasse. The fibrous lignocellulosic fiber of the sugarcane stalks is used to make bagasse, a solid residue of the extraction of the stalk juice. The filter cake is what is left over after the sugarcane juice has been filtered. It looks like a slurry of sludge. In 2015, the global production of sugarcane exceeded 1.81 billion tons, and by 2024, that amount is anticipated to exceed 2.21 billion tons. These projections suggest that bioenergy, biofuels, and other goods might be made from 0.6 billion tons of sugarcane bagasse worldwide.

The bagasse which is the initial stage of co-product of sugarcane has an average composition of sugarcane is 40-50% water, 2-5% dissolved sugars , 40 -45% fibres [26]. Bagasse has a dry weight composition of 28% hemicellulose, 42% cellulose, 20% lignin, 2.4 percent ash, and 4.6 percent other polysaccharides [27]. Sugarcane agroindustries exploit lignocellulosic biomass to make second-generation ethanol and other byproducts like xylitol. Through biochemical and thermochemical reactions, the lignocellulosic composition can generate a number of energy products. As an example, sugarcane bagasse is a potential and commercially viable raw material for the synthesis of bioethanol and biomethane [28], [29]. Bagasse can be used to make paper, animal feed, and disposable food containers in addition to providing power and heat in sugar factories (cogeneration). The sugarcane sector currently uses bagasse primarily as a fuel to meet its own energy needs. But there is too much of this bagasse, and it could be used to make ethanol, enzymes, single-cell proteins, and food additives like vanillin and xylitol [30], [31], [32]. More than 40 distinct products are manufactured from the residual sugarcane bagasse, including furfural, animal feed, pulp and paper, and boards [33].

Several paper products, including toilet paper, tissues, corrugated cardboard, newsprint, and writing paper, are made from bagasse, which is a more environmentally friendly source [34], [35], [36]. Bagasse fibers are separated from the pith in the first step of making paper, according to [35], who used a dewatering device to mix the fibers with water. In a steam boiler that is still filled with a black liquid or pulp, the fibers are then cooked for a further 10 to 15 minutes. This pulp is cleaned and screened to get rid of sand and extra fibers after being washed to get rid of the color. The pulp is subsequently treated with $Cl_2$ gas and NaOH to whiten it after thickening, which lowers the water content to about 12%. This pulp is subsequently prepared for delivery to a paper mill after undergoing a series of procedures to produce paper goods. Bagasse from sugarcane as a renewable raw material could be an excellent concept reduces the loss of forests and other issues brought on by the pulp and paper industry.

Applications that have been updated for sugarcane bagasse in the field of materials have recently been developed. For instance, bagasse's better soil conditioning capabilities have increased sugarcane plants' health and output [37]. According to [38], sugarcane bagasse can be used as a binder and in commodities that improve the tensile strength and mechanical qualities of building materials sugarcane plants' health and output [37]. Additionally, the bagasse fibers can be transformed into a powerful adsorbent substance that can be used in the textile sector to remove harmful metals and dyes from wastewater [39], [40], [41]. In more recent years, carbon quantum dots made from sugarcane bagasse have been used as a fundamental material in the production of light-emitting diodes, medication delivery systems, and biosensors [42].

The manufacturing of bioethanol has used sugarcane bagasse, which has been the subject of extensive investigation in recent years [43], [44]. The initial processes in the processing of sugarcane include cleaning and sugar extraction, which includes juice treatment, concentration, and sterilization. Sugarcane juice is processed, clarified, and dewatered before being used in mills to extract sugar, which is then crystallized and centrifuged. In addition to fermentation, ethanol is also produced from juice, molasses, or bagasse through the fermentation processing phases of distillation and dehydration. The process described can be used to create ethanol from molasses, which contains 60% fermentable sugars [25]. A volume ratio of 1:5 (molasses/water) is first used to dilute the molasses. In order to strengthen molasses and give yeasts a suitable source of nitrogen, ammonium sulfate is added when it lacks nitrogen. Then, to make the fortified molasses solution acidic, a small amount of sulfuric acid is added. Adding acid promotes yeast development while preventing the growth of harmful microbes. The resulting slurry is then dumped into a big tank and yeast is introduced to it at 30 °C. The yeast is then allowed to ferment in the tank for two to three days. During this time, the yeast enzymes sucrase and zymase convert the sugars in molasses into ethanol in line with the condensed chemical reactions given below [45].

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 2C_6H_{12}O_6$$

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

Alcohol is only present in 15–18% of the fermentation broth. The soup is passed through a distillation device to produce 92% pure alcohol, often known as rectified spirit or commercial alcohol. To get anhydrous bioethanol that can be mixed with gasoline, you need to use molecular sieves or pervaporation to clean it up even more.

An additional pretreatment step is needed to produce bioethanol from bagasse. To enhance cellulose hydrolysis, the sugarcane bagasse needs to be processed to remove lignin and hemicellulose from the cellulose, reduce cellulose crystallinity, and increase bagasse porosity [46]. Three different polymers make up lignocelluloses: lignin, which surrounds cellulose in cell walls and gives it rigidity; hemicelluloses, which cover the cellulose and reinforce cell walls through interaction with lignin; and encased cellulose microfibrils, which give cell walls tensile strength [47].

Celluloses and hemicelluloses are polysaccharides with C6 and C5 monomers, respectively, linked by (1-4)-glycosidic linkages. The three main alcohol polymers that make up lignin are para-hydroxyphenyl (H lignin), guaiacyl (G lignin), and syringyl (S lignin). Since hemicelluloses breakdown more quickly after pretreatment, they are released first. Hemicellulose liberation separates lignin and cellulose. Pretreatment causes the (1-4)-glycosidic linkages to dissolve, releasing glucose from cellulose. For lignocellulosic materials like sugarcane bagasse, there are numerous pretreatment methods that can be used, including acid hydrolysis, alkaline hydrolysis, steam or ammonia fiber expansion, organosolv, enzyme hydrolysis, microwave heating, ultrasonication, and combinations of these. The method using diluted acid is the most popular. The bagasse from sugarcane and agave plants has also undergone ozonolysis pretreatment [27].

## 2. 1. Thermochemical technologies

The term "thermochemical conversion" refers to the process by which biomass is converted into useful energy or energy sources. By reforming organic matter at high temperatures, biomass macromolecules are broken down and produced directly as solid fuel (biochar), gaseous fuel (synthesis gas), and highly oxygenated liquid fuel (bio-oil or biocrude). Utilizing a variety of technologies, biomass has been converted into useful forms of energy [48]. The kind of conversion technology used depends on a number of factors, including the kind and quantity of biomass and the type of energy required [49]. Sugarcane bagasse can be thermo-chemically processed to produce value-added products that invariably aid in the achievement of energy, environmental, and economic sustainability. Combustion, torrefaction, hydrothermal, pyrolysis, and gasification are all examples of thermochemical reactions. Each of these processes requires temperatures of at least 200 °C [50].

In order to use biomass's heating potential for cooking, house heating, or energy production, combustion involves igniting the fuel into flames. To create charcoal, biooil, and biogas, the pyrolysis process includes heating biomass in a deoxygenated environment [50]. Both air gasification and steam gasification, also known as steam reforming, are two different types of gasification processes that predominantly create gases [51], [52]. As opposed to the latter, which employs a stream of steam, the former uses a continual stream of air. The former creates producer gas, whilst the latter produces synthesis gas. This part tells you more about the many thermochemical processes that are used to turn sugarcane bagasse into more useful products.

### 2. 1. 1. Gasification

One of the first gasifier models built specifically for sugarcane bagasse was by [53]. The system was made up of a reactor, a gas conditioning system, a system for feeding biomass, and a system for instrumentation and control. The biomass is cooked in a gasifier to very high temperatures (500–1400 °C), high atmospheric pressures (up to 33 bar), controlled oxygen injections, a gasification agent, and a catalyst. Synthetic gas, commonly referred to as syngas, is created by this procedure. An alternative is to heat the biomass with steam, which starts a steam reforming reaction that produces more hydrogen ($H_2$) and methane (CH4) but uses a lot of energy [54]. Syngas is composed of hydrogen (H), carbon dioxide ($CO_2$), carbon monoxide (CO), higher hydrocarbons ($CH_4$), and nitrogen ($N_2$). Due to its low caloric value, syngas is suitable for use as fuel in gas turbines that generate electricity, diesel engines, and for heating. Additionally, the syngas can be further processed to extract the hydrogen for use in fuel cells or combustion, as well as to produce liquid fuels using the Fischer-Tropsch method.

The composition of syngas depends on the type of gasifier, the gasification agent, the type of catalyst, and the size of the catalyst particle. When feedstock with high carbon and oxygen content is gasified, a lot of CO and $CO_2$ are created. It has been found that agricultural waste and municipal solid waste frequently produce syngas with higher CO and $CO_2$ levels [55]. The average concentration of sulfur in biowaste feedstocks is 1.5% (wt.), with animal waste and sewage sludge having the highest concentrations at 0.55 (wt.) and 1.0% (wt.), respectively. Gas separation and treatment are made more challenging by the emission of sulfur during gasification of such feedstocks in the form of H2S. Consequently, such feedstocks demand the use of gas treatment procedures [55].

Four main types of gasifiers are generally used to gasify biomass: fixed bed, fluidized bed, entrained flow, and plasma gasifiers. Fixed bed gasifiers come in two flavors: updraft gasifiers and downdraft gasifiers. Downdraft gasifiers are more common than updraft gasifiers due to their ability to produce high yields of high-quality syngas quickly and their ability to process biomass with a variety of moisture levels [56]. The following advantages of a fixed bed gasifier: it is least sensitive to feedstock size and amount; it can manage feedstock with a high moisture content; it accumulates minimal tar; it is least sensitive to feedstock quantity; and it has a high tolerance for ash concentration [57].

On the other hand, a fluidized bed gasifier has a high rate of heat transmission and offers complete mixing of the feedstock and bed material. Numerous feedstock sources can be used with the entrained flow gasifier, which only requires a limited length of residence time. Furthermore, the reactor maintains a constant temperature throughout, creating syngas with less tar [57]. Plasma gasification is an innovative technique for gasification that is effective with hazardous biomass wastes. This all-natural method uses an external heat source to heat and sustain the high temperatures necessary for gasification. The use of extremely high temperatures allows for the treatment of infusion sets, bandages, biological waste, including antibiotics and cytotoxic drugs, as well as laboratory waste containing organisms or macromolecules that are detrimental when released into the environment [9]. Ash and slag removal is made simple, and it is a non-toxic method of handling hazardous material [57]. The typical plasma gasification byproducts include syngas, slag, and ash. The technique employs oxygen-rich air to form plasma and boosts plant efficiency by more than 26%, according to a study by [58] on the plasma co-gasification of MSW and waste plastic solid. The gas produced had an overall concentration of 69.6% (vol.) and 71.1% (vol.), respectively, when plasma gasified bonny tissue (biomedical waste) and domestic waste.

There are certain advantages to gasification over pyrolysis and direct combustion. According to research, this is the most efficient way to create hydrogen gas from biomass [59]. Biomass gasification has been found to have a higher heat capacity and be more capable of recovering energy than direct combustion and pyrolysis. Pyrolysis and liquefaction have poor CO and $H_2$ conversion because these processes are extremely dependent on operating conditions and the presence of secondary reactions caused by hot solid particles and volatiles [56], [57]. The gasification process makes it simple to catalytically methanize CO and $CO_2$ from syngas to create synthetic natural gas [60]. Gasification is a very adaptable process since it can effectively convert a wide range of biomass feedstocks into fuel gas. The fuel gas can also be turned into syngas, which is used to make biofuels, or it can be used directly to heat or make electricity.

### 2. 1. 2. Pyrolysis

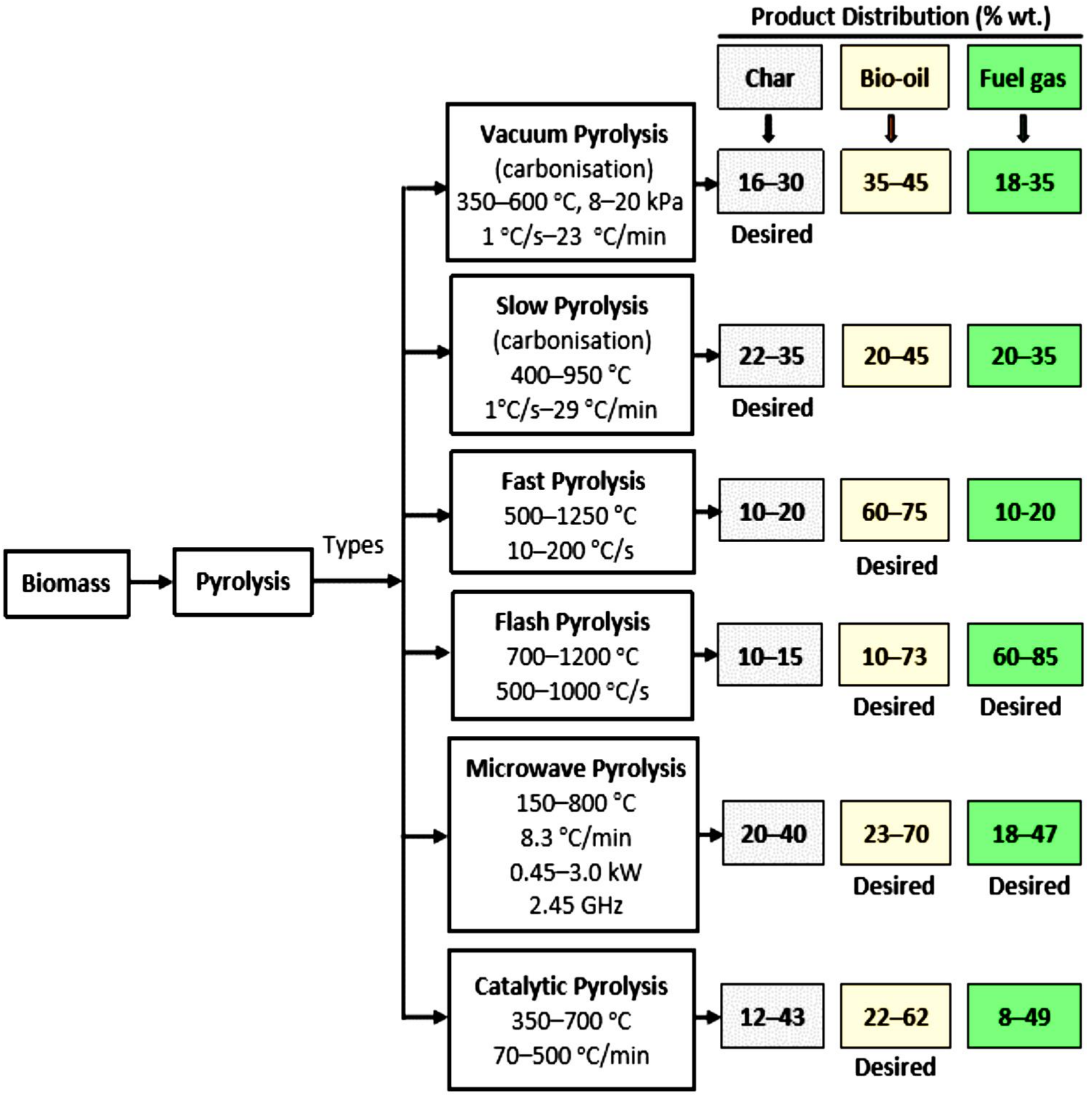

**Figure 1.** Illustration of different types of pyrolysis processes and product distributions.

Pyrolysis is the process of carbonizing or decomposing biomass by heating it to temperatures of 300–800 °C or more while essentially depriving it of free air or oxygen. These are the products: biochar, bio-oil, and syngas [54], [61]. The distribution of the products depends on the pyrolysis process parameters. The following benefits of pyrolysis include: It can be used for a variety of dry biomass, making it more adaptable to changes in feedstock composition; it is scalable and can be run as a batch process; it is a low-pressure process and requires little pre-processing of the feedstock; and it can produce a variety of valuable products (biochar, bio-oil, or biogas) [62]. The bio-oil can then be further processed with hydrogen at high temperatures (260-430 °C) and pressures (up to 6895 kPa) to produce sustainable diesel, renewable gasoline, and renewable jet fuel.

High moisture feedstocks must first go through an energy-intensive pre-drying stage since pyrolysis is only effective on dry feedstocks with a moisture content of up to 20%. Pyrolysis also generates potentially dangerous GHGs and carbon monoxide, in addition to the substantial energy input required for the higher process temperatures. Commercial pyrolysis facilities will thus require an air purification system in order to treat the flue gases produced.

The six main pyrolysis methods differ in their methods of operation. These comprise slow pyrolysis, microwave pyrolysis, flash pyrolysis, vacuum pyrolysis, and catalytic pyrolysis [63]. Pyrolysis is broken down into three categories: slow, quick, and flash, depending on the temperature ramp or heating rate.

## 3. CONVERSION OF SUGARCANE BAGASSE TO BIOETHANOL AND OTHER VALUE-ADDED PRODUCTS

According to statistics, Brazil is the world's leading sugarcane grower and a major player in the sugar and ethanol industries [64]. Sugarcane bagasse (SCB) is the primary byproduct of sugarcane processing, with a yield of between 250 and 270 kilograms (kg) per tons of sugarcane. Per metric ton of sugarcane processed, sugar mills produce about 270 kg of bagasse which would contain 50% moisture [64], [65]. Approximately half of this quantity is all that is necessary to meet the energy demands of the sugar and ethanol facilities [65]. However, sugarcane bagasse is a great substrate for the fermentation-based synthesis of many different bio-chemicals and enzymes [66].

The chemical composition of sugarcane bagasse varies with plant variety, cultivation conditions, harvesting practices, and processing approaches [67]. Additionally, sugarcane bagasse has the potential to be a source for economically valuable goods like fuel or mulch for animal feed [68]. Microbes will have an impact on the production of value-added products, and it might be necessary to convert the substrate by microbial means. The amount of moisture, ash, and advantageous compounds in the bagasse will influence the products or other applications for the converted bagasse [68]. Sugarcane bagasse contains 42–50% water, 2.5–5.5% dissolved sugars and 38–44% fiber [26], and 55–75% carbohydrates [69].

Sugarcane bagasse, which is mostly made up of cellulose, hemicellulose, and lignin [70] is a sustainable biomass with the capability of producing value-added chemicals like hydrogen, methane, and organic acids, thereby resolving contemporary waste disposal issues and lowering reliance on fossil fuels [64]. The potential of these byproducts as a source of biofuel has recently attracted significant attention. Because of its high cellulose and hemicellulose content, sugarcane crop waste can be converted into bioethanol and other liquid transportation fuels

[66]. This article reviews an overview of sugarcane residue availability and the range of commercially significant products that can be derived from it. Research and development on bio converting sugarcane crop residue into value-added goods is also detailed [66].

The bioethanol produced from sugarcane bagasse is a superior alternative fuel for use in today's high-performance internal combustion engines. As a result of its high cellulose content and widespread availability from the sugar industry, bagasse has emerged as a crucial feedstock for bioethanol production [67]. Sugarcane processing bio-wastes are valuable and inexpensive materials for manufacturing densified biofuels (pellets and briquettes), biogas, alcohol, syngas, and, more recently, biohydrogen [9]. Sugarcane bagasse contains a high concentration of lignin, hence pretreatment is typically required before either hemicellulose or lignin fractions can be extracted [67], [71]. Traditional approaches to sugarcane bagasse pretreatment fall short of the efficiency needed to fulfill the demands of industrial adaption. Several earlier investigations have brought to light various pretreatment strategies that fall short in terms of environmental friendliness and efficient bioconversion of sugarcane bagasse [72]. For the production of a wide variety of industrially important products such biofuels, bioelectricity, bio-plastics, bio-adsorbents, and organic acids, this article reviews critically recent developments in the conversion processes of pyrolysis, liquefaction, gasification, cogeneration, lignin conversion, and cellulose conversion via fermentation processes [72].

### 3. 1. Pretreatment of Sugarcane Bagasse

Specifically, the pretreatments get rid of the lignin and hemicellulose, soften the cellulose, make the material more porous, and increase the accessibility of cellulase enzymes to the cellulose, all of which boost the effectiveness of the hydrolysis process [64]. Pretreatment of sugarcane bagasse can be accomplished in a number of ways, each with its own unique characteristics in terms of the mechanism of action on the cell wall components of the biomass and the conditions in which it is applied for optimal performance. Physical pretreatment, which can be achieved through shredding, grinding, ultrasound, and microwaves [67], [73]; chemical pretreatment, which can be accomplished through the use of acids and alkalis, ionic liquids, oxidizing agents, steam explosion, organic solvents, hot water hydrothermolysis, and fiber expansion with ammonia; biological pretreatment, which makes use of a variety of microbes and metabolites that are capable of degrading lignin; and various combined pretreatment techniques [67].

### 3. 2. Physical pretreatment

Physical pretreatments include milling, immersion, washing, drying, and screening. Milling sugarcane bagasse into smaller pieces accomplishes this by grinding, which also diminishes the crystallinity of the cellulose [74]. Water is used in the processes of soaking and washing the sugarcane. Bagasse goes through a drying process to remove moisture. Solar drying, air drying, and mechanical dryers are all viable options. Bagasse is screened so that it has a uniform size. Sugarcane bagasse typically falls within the size range of 0.21 mm 2.20 mm [74].

#### 3. 2. 1. Hydrothermal pretreatment

In order to give the fermenting microbe with access to the cellulolytic substrate, sugarcane bagasse undergoes hydrothermal pretreatment, which entails keeping the bagasse in pressured liquid hot water and encouraging rapid depressurization, after a severity parameter has been reached. The typical operating conditions for hydrothermal pretreatment are 0.5-2.4 MPa and 155-240 °C [64], [75].

Water remains liquid at these sub-critical levels, and it exhibits a wide variety of physicochemical properties that are somewhat different from those at standard room temperature. This means that the biomass's capacity to swell upon decompression (by a factor of 103 times) is not compromised while simultaneously allowing water to more easily penetrate its interior. Since the 1980s, when sustainable energy from waste material was demonstrated, hydrothermal technology has grown popularity. Hydrothermal treatment processes are preferable to chemical procedures since the medium only consists of feedstock and water, eliminating several issues, such as rust and acid reuse and tainted discharge [64], [76].

### 3. 3. Chemical pretreatment

There are a variety of chemical pretreatments, including acid pretreatment, alkaline pretreatment, organosolv, and others.

### 3. 3. 1. Acid pretreatment

The most widely utilized acid in the processing of sugarcane bagasse is sulfuric acid. It has also been considered as one of the most cost effective method [77], [78]. The glycosidic link in hemicellulose and lignin must be weakened by pretreatment with dilute acids. This will improve the porosity of the plant cell wall, allowing enzymes to more easily penetrate it, and dissolve the sugar in the hemicellulose. Due to the low cost and ready availability of the employed acids, acid pretreatment is a widely adopted process for biomass to ethanol conversion. However, acid pretreatments have consequences such the generation of furan and short chain aliphatic acid derivatives, which are powerful barriers in microbial fermentation [77].

Traditional heating or microwave-assisted heating, is an efficient way to pretreat the biomass, and both methods keep the combination of biomass and dilute acid solution at an intermediate temperature. Microwaves utilize an electromagnetic field, which may cause non-thermal effects that speed up the breakdown of crystal formations. Overall, reducing sugar yielded 0.83 g/g dry sugarcane bagasse utilizing the procedure devised by using microwave-alkali (1% NaOH), followed by acid pretreatment (1% $H_2SO_4$), and enzymatic hydrolysis [78].

### 3. 3. 2. Alkaline pretreatment

When compared to acid pretreatment, alkaline pretreatment is performed under more gentle settings. It is not necessary to utilize high-priced materials and unique designs for alkaline pretreatment in order to withstand corrosion and severe reaction conditions [74], [77]. It uses a number of different bases, such as sodium hydroxide (NaOH), calcium hydroxide ($Ca(OH)_2$), potassium hydroxide (KOH), aqueous ammonia ($NH_3$), ammonium hydroxide ($NH_4OH$) in combined effect with hydrogen peroxide ($H_2O_2$), sodium hydroxide (NaOH) in combined application with calcium hydroxide (lime), and sodium hydroxide (NaOH) in mixture with hydrogen peroxide [77]. Lignin and hemicellulose dissolution, as well as intermolecular ester bond de-esterification (saponification), are the primary processes during alkaline pretreatment. Treatment with alkali first dissolves hemicelluloses, lignin, and silica; hydrolyzes uronic and acetic esters; and swells cellulose, thereby destroying the cell wall [74].

Saponification of the intermolecular ester linkages that cross-link xylan hemicelluloses and other components like lignin and other hemicelluloses is thought to be the process by which alkaline hydrolysis works. Swelling caused by dilute NaOH treatment of lignocellulosic material increases the internal surface area, decreases the degree of polymerization, reduces the crystallinity, separates structural links between lignin and carbohydrates, and disrupts the lignin structure [78].

Among the many alkalis tested, sodium hydroxide was found to degrade lignin more effectively than sodium carbonate, ammonium hydroxide, calcium hydroxide, and hydrogen peroxide [74], [77], [78]. Pretreatment with lime (calcium hydroxide) is yet another intriguing alkali pretreatment technique because it raises pH without causing the emergence of fermentation inhibitors, making it a cheap alternative to other methods of lignin solubilization. This method removes about 33% of lignin and 100% of acetyl groups. Lime's activity may be slower than that of other pretreatments, but it is far more cost-effective than other alkalis, is environmentally benign, and is safe to handle [77], [79].

### 3. 3. 3. Organosolv

Organosolv is a delignification method that can also solubilize hemicellulose at different rates. The organosolv process involves the utilization of organic or aqueous organic solvent combinations, acid or alkali catalysts, and lignin extracted from lignocellulosic biomass [77], [78]. Methanol, ethyl alcohol, acetone, ethylene glycol, triethylene glycol, and tetrahydrofuran alcohol are just a few of the many organic solvent combinations that have been employed. Ethanol is a good solvent since it can be made at a large number of bio-refineries. It may be reused and refilled with ease, making it an ideal solvent for the pretreatment procedure. Ethanol is less hazardous to people than other solvents like methanol, and it's cheap [74], [77], [80].

Organosolv preparation successfully delignifies lignocellulosic materials via partial hydrolysis of lignin linkages. However, this method is also effective at dissolving the sugars found in hemicellulose. By breaking down lignin macromolecules, organic solvents lower cellular wall lignin content [74]. In order to convert sugarcane bagasse into bioethanol, various chemical pretreatments are being researched. For sugarcane bagasse, a high level of delignification can be attained through ethanol organosolv pretreatment with formic acid as a catalyst. Delignification was more complete at higher pretreatment temperatures. Research indicates that sugarcane bagasse delignified to an optimal degree, 80 %, at a temperature of 210 °C [77].

## 3. 4. Physico-chemical pretreatment

### 3. 4. 1. Liquid hot water pretreatment

Pretreatment with liquid hot water is done at temperatures between 160 and 240 degrees Celsius; however the water is in its liquid form rather than its steam form [77], [81]. This pretreatment process has several benefits over other pretreatment processes, including the absence of catalysts or chemicals, moderate operating temperature, excellent hemicelluloses recovery, low amounts of inhibitory by-products, and reasonable cost. The main goal of the process is to get the hemicellulose to dissolve, remove some of the lignin, and make the cellulose easier for the enzyme to get to. Also, the formation of unwanted byproducts in the water phase can be slowed down because soluble form of hemicellulose is often found in the form of oligomers [77].

The hemicellulose connections are severed and different acids are released during the liquid hot water treatments. These acids are important because they aid in the hydrolysis of hemicellulose to monomeric sugars, which can then be degraded to aldehydes. In the biorefinery process, this pretreatment method offers promising prospects for adoption as it can be viewed as an environmentally friendly technique [77].

Biomass cell walls are permeable to water molecules during pretreatment at high temperatures, allowing cellulose to hydrate while hemicellulose and lignin are partially removed. Compared to dilute-acid and alkali catalyzed pretreatments, the neutral technique has the benefit of conserving chemicals by preventing corrosion and minimizing the generation of excessive furans during sugar degradation process. In contrast to diluted acid pretreated biomass, liquid hot water pretreated biomass has lower sugar release yields, which necessitates either a higher pretreatment temperature or a longer residence time to get the same results [77].

### 3. 4. 2. Steam Explosion pretreatment

The steam explosion is a combination of chemical and physical processes that are used to disturb the structure of lignocellulosic materials, sugarcane bagasse [74]. Among the most effective techniques for dismantling the macromolecular structure of plant cell walls is the application of steam explosion [77].

This chemical and physical method involves subjecting the bagasse to high temperatures of 160 °C to 260 °C in the presence or absence of an exogenous acid or basic catalyst in the saturated steam for reaction periods of 2-30 minutes [77], [78]. The material is subjected to high pressure and temperature for a brief period of time in this hydrothermal pretreatment procedure, after which the system is rapidly decompressed, therefore disrupting the fibril structure. Hydrolysis of cellulose is aided by the breakdown of fibrils, which makes the cellulose molecule more accessible to hydrolytic enzymes [77], [78].

Compared to other pretreatment methods, steam explosion pretreatment has less negative effects on the environment, is cheaper, uses less energy, and requires fewer or no chemicals. Additionally, the steam explosion approach consumes 70% less energy than the typical mechanical process does while still producing particles of the same size as the substrate. The major setbacks of steam explosion pretreatment include hemicellulose degradation and the production of toxic components that may interfere with the enzymatic hydrolysis and fermentation steps [77].

### 3. 4. 3. Wet Oxidation pretreatment

Biomass is treated with water, oxygen, or air at temperatures exceeding 120 °C during wet oxidation [74], [78]. During wet oxidation, two different processes take place: a hydrolytic reaction at a low temperature and an oxidative reaction at a high temperature [78]. Some hemicelluloses, like Xylan and Arabinan, become more soluble after being subjected to wet oxidation. Similarly, lignin solubility or delignification is enhanced by wet oxidation. The result is an increase in cellulose content.

The solubility of hemicellulose is enhanced by wet oxidation at low pH. Many of the hemicellulose and lignin molecules are dissolved in the oxygen-rich water during the wet oxidation process. The residual hemicellulose and lignin are hence, unaffected by increasing the wet oxidation temperature from 185 °C to 200 °C [74].

### 3. 5. Biological pretreatment

It is common practice to use cellulolytic and hemicellulolytic microorganisms in the biological pretreatment of sugarcane bagasse. The biological pretreatment is viewed as a viable, low-cost, and environmentally-friendly alternative. Microbes, typically filamentous fungi are widely employed because they are abundant and can be separated from a wide variety of sources, including soil, living plants, and lignocellulosic waste [77]. For the majority of lignocellulosic materials, white-rot fungi have been recognized as the most efficient microorganisms for pretreatment [82]. These bacteria use lignin-degrading enzymes, such as peroxidases and laccases, to break down lignin. Brown-rot fungi primarily target cellulose, whilst also white and soft rot fungi target both lignin and cellulose and lignin [77], [83].

The advantages of biological pretreatment, such as its low capital cost, low energy demand, absence of chemical necessity, and relatively benign ecological factors, make it appear to be a viable technology. Yet, its principal drawbacks are a lengthy incubation time, low efficiency, high loss of carbohydrates, the need for careful management of growing conditions, and a lack of room.

The glucose level in the pretreatment with the white-rot fungus is reportedly roughly two times greater than in the others. Improved lignin degradation, glucose release, and hydrolysis yields are achieved with Pycnoporus sanguineus pretreatment of sugarcane bagasse. The common species of fungi typically used in the biological pretreatment of sugarcane bagasse are shown in the table below [77], [78].

**Table 1.** Typical fungal species utilized in biological treatments.

| **Fungi** | **Species** |
|---|---|
| White rot | *Penicillium* spp. |
| | *Phanerochaete chrysosporium* |
| | *Pleurotus ostreatus* |
| | *Penicillium* spp. |
| | *Ceriporiopsis subvermispora* |
| | *Phellimus pini* |
| Soft rot | *Trichoderma reesei* |
| Brown rot | *Fomitopsis palustris* |
| | *Aspergillus niger* |
| | *Gloeophyllum trabeum* |

White-rot basidiomycetes are the most effective and prevalent degraders of lignin. Various ligninolytic enzymes (laccases, manganese peroxidases, and lignin peroxidases) are produced by these microorganisms [77], [78]. These enzymes catalyze the one-electron oxidation of lignin units, leading to the formation of aromatic radicals. Degradation of lignin typically does not occur in the absence of other co-substrates, such as cellulose, hemicellulose, or glucose, and can be traced back to the secondary metabolism or the limited supply of nitrogen, carbon, or sulphur.

Some white-rot fungi predominantly attack lignin more easily and quickly than hemicellulose and cellulose. Members of this species include Ceriporiopsis subvermispora, Phellimus pini, Phlebia spp., and Pleurotus spp. [78].

## 4. INDUSTRIAL SCALE FEASIBILITY AND ECONOMICS OF BIODISEL FROM SUGARCANE BAGASSE

Over the years, a number of techno-economic analysis studies have been conducted to assess the financial profitability and techno-economic viability of sugarcane bagasse (SCB) for a variety of uses. This review evaluated the evidence that support the SCB's status as a feedstock with a long-term economic viability. According to the first's techno-economic analysis generation SCB refining by [84], the ROI of autonomous plants is higher than that of annexed units. Additionally, he noted in his studies that fixed plants had a larger return on investment than flexible plants. It was discovered that annex plants outperform autonomous ones in terms of return on investment (RIR) for both fixed and batch operations. It has been stated that flexibility is a key indicator for maintaining productivity in this industry.

An economic analysis of the production of sugarcane ethanol from a standalone distillery was also done by [85]. His analysis revealed that the SCB would considerably increase the process's profitability when used as fuel for the system of power cogeneration. Another choice is to sell any excess power generated. The price and practicality of different technological SCB electricity options generation were evaluated by [86]. Even though expectations for an increase in the SCB's ability to generate electricity were made up to the year 2030, the current situation still prevails.

[87] Contrasted the thermochemical processing of SCB with the biochemical processing in terms of its techno-economic viability. It was discovered that the steam explosion pre-treatment was energy independent while acid hydrolysis and biological treatment with hot water in liquid form. In addition, [88] looked into the economics of combining sugar-based ethanol production methods with second-generation bio-ethanol synthesis from SCB and leaves. It was found that all kinds of procedures can be economically viable at an average ethanol selling price of 0.53 US$/L (for first-generation and second-generation procedures). As a byproduct of the main sugar refining process, using data from a 2010 study by [89] treating sugarcane wastes biochemically and thermochemically.

They discovered that the thermochemical conversion will provide roughly 0.025 $m^3$ more ethanol per ton of cane and the biological transformation of the leftovers could result in an extra 0.033 $m^3$ ethanol being produced for every ton. Electricity would be a significant additive for the biorefinery, particularly for the biological conversion process, it was also revealed. [90] examined the economics and energy efficacy of various process architectures for the synthesis of bio-butanol from sugarcane molasses.

[91] reported the following chart; it illustrates how significantly the three plants' economic outcomes varied from one another.

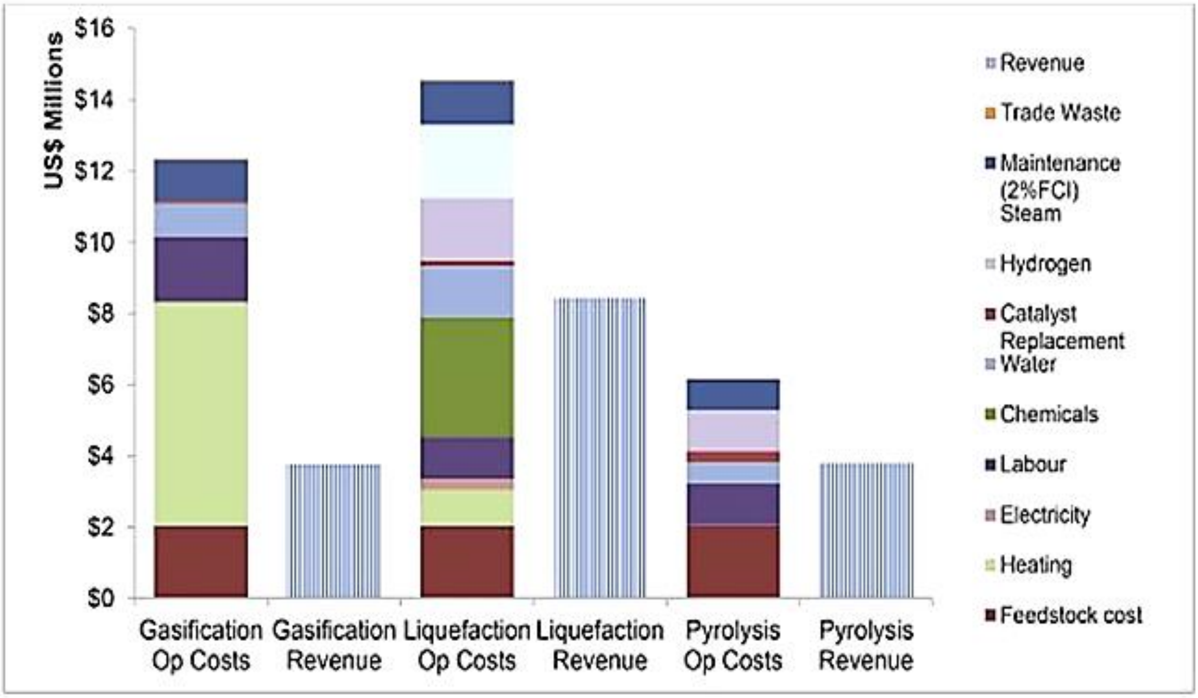

**Figure 2.** The three plants' economic outcomes varied from one another.

According to [92], the cost of preparation and raw materials is the biggest issue with the creation of new products; however, the issue can be resolved by using inexpensive and easily accessible resources.

According to their review study, the least expensive overall technology was pyrolysis, while gasification closely follows liquefaction. The pyrolysis equipment acquired from a vendor was more expensive to install, therefore, despite having greater total installed costs than the other facilities, pyrolysis has lower location-adjusted direct costs. If the considerations were taken into consideration, It's possible that the actual additional costs for the specified pyrolysis equipment's instrumentation, piping, electrical, and civil work will be less than the estimate. With modifications depending on scale and the year of cost assessment, the prices indicated in this research were equivalent to the prices for capital determined in earlier research. The facility described by [93] would have a reduced, adjusted cost of US$ 71 million, which is equivalent to the gasification plant's total capital cost in this study, which is US$ 68 million.

Since pyrolysis requires less separation of by-products and contaminants than the other two processes, it was the least expensive of the three plants to develop. The estimated capital expense was 52 million US dollars, this is greater than the estimated US$ 30 million (scaled, 2017 US$) plant indicated by [94]. Almost the same plant's capital expenses grew to US$ 61 million in a follow-up study to [94], study [95], taking into account the major variations in power generation size and cost estimation methods.

Due to the lack of heating expenses, pyrolysis had an operational cost that was around half that of gasification. The comprehensive breakdown of annual operating expenditures for each process is shown in Figure 2, along with a comparison to annual income. With more than half of the overall cost going toward heating, gasification has the highest cost. With 23% of the overall cost going on liquefaction, ethanol replacement is the biggest expense.

Although labor costs are identical, the gasification plant's yearly labor expenses increased by US$ 642,000 as a result of the numerous columns in gas cleaning that require attention.

This techno-economic evaluation of SCB leads to the conclusion that it is a feasible feedstock for long-term economic viability. This is due to the fact that it may be utilized to produce a variety of goods with a good return on investment and a high profit margin.

## 5. FUTURE PROSPECTS AND CHALLENGES

In the last few years, the production of value-added goods such as alcohols, furfurals, organic acids, butanol, hydrogen, methane, ethanol, and other biochemicals has significantly expanded [3], [4], [5]. One should use bio-based strategies to expand the sustainable bioeconomy. If the bioeconomy is more sustainable and circular, there will be a shift in the economy from linear to circular economy.

The World Bioenergy Association (WBA) predicts a sharp rise in the demand for bioenergy globally. For this reason, it should be necessary to use biomass resources in an efficient manner (such as crops, algae and wastes). The choice of feedstock and the complicated refractory structure of the SCB biorefinery for bioethanol provide several difficulties. The price, accessibility, biological utility, makeup, production, collecting, storing, and conveyance of the feedstock are taken into consideration while choosing it. Therefore, a thorough examination of the substrate's composition, characterization, suitability for using the technology for processing, efficiently produce ethanol in a biorefinery, optimum processing conditions are necessary.

Pre-treatment was needed because SCB structure disruption increased processing costs. Through metabolic engineering, the pre-treatment can be made inexpensively due to changes in the sugarcane content that have been documented in various investigations [96]. To meet the demands for bioenergy and biochemical processes, it is essential to develop novel bio cascading and circular methodologies [97].

The refractory characteristic of biomass may be further overcome by combining hydrothermal and biological processes, which might readily result in the synthesis of biofuels and biochemicals. This integrative method may represent the future of biomass value creation. How sugarcane is used will determine how long SCB biorefineries can operate sustainably [98].

Because they contain a lot of energy, are renewable, and have small carbon footprints, compounds derived from sugarcane can be a sustainable alternative to those derived from fossil fuels [99]. Recent advancements in research have shown that the production of various mixed biofuels requires SCB's biotransformation to generate greater lipid using oleaginous microorganisms. Another area of study is the over-expression of hemicellulolytic and cellulolytic enzymes for better polysaccharide production.

Interest is now shifting toward centralised bioprocessing (CBP). Genes or microbial consortiums are designed into a single microorganism to lower process costs. Another difficulty is ensuring that the fermenting bacterium uses both pentose and hexose carbohydrates entirely and concurrently. The goal of current research is to create modified strains that can consume sugars despite the presence of harmful chemicals produced during pre-treatment [100]. Enzymatic treatment of SCB waste from home garbage, restaurant kitchens, and food processing companies has been the subject of numerous investigations.

A few studies have also focused on developing sustainable methods for using biomass entirely while implementing a zero-waste strategy [101], [102]. Instead of transforming them into inferior items like gasoline or compost, the materials obtained from basic bio refinery operations need be treated once more to create additional value-added goods. SCB bioconversion should be used in more organized ways in the future[102], with enhanced microbial and enzyme activity and a focus on the potential implications on the environment and economy.

The realization regarding the idea of a bio refinery necessitates technological and financial stability as well as certain significant upgrades, such as coproduction techniques in a single process, reusing SCB for optimal resource use, and adding value to the waste produced throughout the process [103]. It has also been noted that a lot of work and study is needed to make SCB bio refinery a financially and sustainably sound solution.

## 6. CONCLUSIONS

The various studies reviewed show that the thermocatalytic process has the potential to produce sugarcane bagasse-derived biofuels, which is a cleaner fuel and reduces solid waste from sugar production. The various SCB applications have been thoroughly researched in light of the demand for sustainable energy and the environment. Due to its successful application in the manufacturing of bioethanol, SCB can be regarded as a sustainable feedstock for the production of biofuels. Bioproducts and enzymes produced by the SCB justify their economic importance.

The feasibility and industrial scale economics of biodiesel with sugar cane bagasse have suggested unfavorable net present values, due to the higher reserve price than the current market price. Additionally, the models highlight future job opportunities to improve cost efficiency for each facility.

Heating costs have a major impact on gasification, while ethanol costs represent an important part of the operating costs for liquefaction. Assumable, SCB is a biomass with significant potential to meet the world's energy needs and advance both environmental and economic sustainability. Generally speaking, the techno-economic model suggests that sugarcane bagasse may be a feasible alternate feedstock for the production of bioethanol.

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