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Valorization of Sugarcane By-Products from Waste to Wealth

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Abstract The global sugarcane industry shows great potential in the development of sugar, energy and by-products. Sugarcane by-products such as bagasse, molasses and filter mud are converted into biofuels, chemicals and other high value-added products through value-added technology, reducing waste emissions and improving resource recycling. The study points out that sugarcane bagasse and molasses can be used to produce ethanol, biomass energy and a variety of chemicals, while filter mud and sugarcane waste liquid can be used as organic fertilizers and soil amendments. Despite technical, economic and policy challenges, the value-added utilization of sugarcane by-products offers new opportunities for sustainable development through technological innovation and policy support.

Keywords Sugarcane by-products; Value-added; Biofuels; Environmental sustainability; Resource recycling

As one of the important economic and agricultural pillars, the global sugarcane industry shows great potential in the fields of sugar production, energy and by-products. Sugarcane (*Saccharum officinarum* L.) is a fiber-rich perennial herb that is traditionally widely cultivated in tropical and temperate regions in more than 110 countries around the world, with a cultivated area of 27 million hectares. Between 2000 and 2019, global sugarcane production accounted for 21% of total crop production. In 2020, a total of 18.697 million tons of sugarcane were harvested globally, of which Brazil accounted for 7.571 million tons, India accounted for 3.705 million tons, China 1.081 million tons, Pakistan 810 000 tons, and Thailand 750 000 tons (Ungureanu et al., 2022).

In the process of sugarcane processing, in order to obtain products such as sugar and ethanol, a large amount of solid and liquid waste is generated, including bagasse, molasses, press mud, and sugarcane waste liquid (Spent Wash). and ash from sugarcane bagasse burning. In total, approximately 279 million tons of waste and by-products are generated globally each year. If these wastes are not properly managed, they pose significant risks to the environment and human health. However, in recent years, through waste value-added technology, these sugarcane by-products, as important biomass resources, have gradually become important raw materials for biofuels, high value-added chemicals, composite materials, and organic fertilizers (Ungureanu et al., 2022).

Bagasse is the main by-product of sugarcane processing, accounting for 25%~30% of every ton of sugarcane. Brazil's sugar mills produce approximately 28 million tons of bagasse each year, about half of which is burned in sugar mill boilers to produce steam and electricity, while the remainder can be used for papermaking, biofuel production or chemical processing. Molasses is the main liquid by-product produced in the sugar industry. Each ton of sugar cane can produce about 40-50 kilograms of molasses, which is mainly used to produce ethanol, yeast and feed additives (Silalertruksa et al., 2023). Filter mud is a by-product of clarified sugar juice during the sugar production process. About 30-40 kilograms of filter mud are produced per ton of sugar cane, and it is usually used as organic fertilizer and soil conditioner. Sugarcane waste liquor (such as distillers grains after ethanol brewing) also has value-added potential and can be used for biogas fermentation, fertilizer production and biochemical synthesis.

Value-added utilization of sugarcane by-products has important environmental, economic and social implications. First of all, through the resource utilization of sugarcane by-products, waste emissions can be reduced, waste reduction and resource recycling can be achieved, which can help alleviate environmental pollution and greenhouse gas emissions. Secondly, the value-added utilization of by-products can maximize the economic benefits of the sugarcane industry, expand new sources of income, and improve industrial competitiveness. In addition, it can also create local employment opportunities and promote rural economic development.

However, the value-added utilization of sugarcane by-products still faces many challenges, such as technical challenges, some value-added technologies are not yet mature, or there are technical bottlenecks on an industrial scale; economic feasibility, the economic benefits of some value-added utilization methods have not been fully proven; policies and regulations The impact is the lack of a complete policy support system and incentive mechanism. Promoting the value-added utilization of sugarcane by-products requires the joint efforts of technology, economics and policy to achieve the transformation from "waste" to "wealth" and contribute to global sustainable development and circular economy.

1 Classification and Characteristics of Sugarcane By-products

1.1 Characteristics of sugarcane bagasse

Bagasse is the main solid by-product produced after squeezing juice from sugarcane stems during the sugar production process. It is a fibrous biomass residue, accounting for approximately 25% to 30% of the weight of each ton of sugarcane. As a major by-product of the sugarcane industry, bagasse has significant utilization potential and is produced in large quantities globally. Brazil produces approximately 28 million tons of bagasse every year, and globally, it is expected to produce approximately 279 million tons of bagasse every year, with abundant resource reserves (Ajala et al., 2021).

Sugarcane bagasse is a typical lignocellulosic biomass. Its main components are cellulose, hemicellulose and lignin. Cellulose accounts for about 45%, hemicellulose accounts for 32%, lignin accounts for 17%, and the rest is trace. Minerals and ash. Cellulose and hemicellulose provide the potential of bagasse as a fermentation substrate and the production of biomaterials, while lignin provides the calorific value, making it useful as biomass fuel (Wang et al., 2022).

Sugarcane bagasse can be used as raw material for the production of biomass energy and biofuels, producing ethanol, biogas, biodiesel, etc. Through technologies such as pretreatment and enzymatic hydrolysis, cellulose and hemicellulose can be converted into fermentable sugars for the production of fuels such as bioethanol (Ajala et al., 2021). Pretreatment methods include alkali method, acid method, steam explosion, etc., which can effectively improve enzymatic hydrolysis efficiency and increase sugar production (Wang et al., 2022).

Bagasse is an important raw material for the paper industry, especially in major sugar-producing countries such as Brazil and India. Through techniques such as alkaline pretreatment and mechanical separation, sugarcane bagasse can be made into pulp for the production of paper and paper products. In recent years, high value-added materials such as nanocellulose have gradually become potential uses for bagasse. In addition to biofuels and pulp, bagasse can also be used to produce a variety of high value-added chemicals and materials, such as xylitol, nanocellulose, biochar, etc. Through appropriate pretreatment and hydrolysis processes, soluble sugars can be extracted from sugarcane bagasse and used to produce sweeteners such as xylitol. At the same time, the ash after burning sugarcane bagasse is rich in minerals and can be used as a soil conditioner and fertilizer.

1.2 Characteristics of molasses

Molasses is the main liquid by-product produced in the sugar industry. It is the viscous liquid remaining during the multiple crystallization processes of sugarcane juice. Each ton of sugar cane can produce about 2.2%~3.7% molasses, which is a tan high-viscosity liquid with a density of about 1.4~1.5 g/mL. Its main components include 30%~35% sucrose, 10%~25% glucose and fructose, and other non-sugar compounds (such as organic acids, minerals and vitamins) (Hawaz et al., 2023).

The economic importance of molasses makes it an important carbon source in the food, feed and fermentation industries. Currently molasses is mainly used in ethanol production and as an animal feed additive, but is also widely used in the production of rum, dry yeast, acetone and butanol, among others. In addition, molasses also has rich health benefits, including antioxidant, anti-obesity, anti-cancer, anti-microbial, anti-anemia, improved bone and hair health, etc. (Jamir et al., 2021).

Molasses is an important raw material for the production of bioethanol. Due to its high sugar content, it can be directly used for yeast fermentation to produce ethanol. During the production process, optimizing fermentation conditions plays a key role in improving ethanol production. By optimizing parameters such as molasses concentration, fermentation time, and yeast strains, the fermented sugar in molasses can be effectively converted into ethanol. One study used the yeast strain Meyerozyma caribbica for molasses fermentation, and ethanol production was significantly increased after optimizing fermentation conditions.

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1.3 Characteristics of filter mud and sugarcane waste liquid

Filter Cake/Press Mud, also known as press mud, is the residue formed after filtering sugarcane juice. It has a soft, spongy quality and is dark brown or black in color. Its chemical composition mainly includes 9%~14% wax, 10%~18% protein, 11%~17% cellulose, 15%~27% hemicellulose, and 9%~14% lignin, Oils and resins, etc. In Brazil and China, filter mud is often mixed with sugarcane waste liquor or bagasse ash and used as fertilizer for sugarcane cultivation. However, the high content of organic matter and moisture in filter mud may lead to greenhouse gas emissions during the decomposition process, which requires reasonable management to reduce environmental impacts (Silalertruksa et al., 2023).

Sugarcane waste (Spent Wash) is the liquid waste from the ethanol distillation process. Due to its high content of organic and inorganic substances, it is a potential bionutrient supplement. Sugarcane waste liquor is rich in macronutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S), as well as micronutrients including zinc (Zn), copper (Cu), iron (Fe) and manganese (Mn). Research shows that reasonable dilution and application of sugarcane waste liquid can help increase soil enzyme activity and microbial activity, improve soil structure and organic carbon content, and ultimately increase crop yield and photosynthesis efficiency. However, due to the complex characteristics of sugarcane waste liquid, improper use may lead to environmental problems such as groundwater pollution (Umair Hassan et al., 2021). Through effective management and scientific application, filter mud and sugarcane waste liquid can be used to produce organic fertilizers, biofuels and soil conditioners, realizing resource utilization and promoting the sustainable development and circular economy of the sugarcane industry.

2 Value-added Sugarcane Bagasse

2.1 Sugarcane paper industry

Sugarcane bagasse is a rich fiber resource widely used in the pulp and paper industry. It is a fibrous residue produced by the sugar production process, and its components mainly include cellulose, hemicellulose and lignin. Bagasse pulping in the paper industry is an environmentally friendly process that can replace wood pulp, and has become a viable commercialization option, especially in countries with developed sugar industries, such as Brazil and India (Vangchhia et al., 2024).

The pulping and papermaking process usually includes steps such as pretreatment, cooking, bleaching and pulp production. The pretreatment step is designed to remove wax, grit, and other impurities from the bagasse. A cooking process then uses chemicals, such as lye or acid, to defibrate the bagasse, producing unbleached pulp. In order to improve pulp quality, bleaching treatment is usually performed to remove residual lignin and impurities. Ultimately, pulp can be used to produce various paper products, such as kraft paper, printing paper, and packaging paper (Martinez-Hernandez et al., 2018).

In recent years, the bagasse papermaking process has made significant technological progress. New pretreatment technologies, such as alkali pretreatment, steam explosion and organic solvent methods, have improved fiber separation efficiency, reduced chemical consumption, and improved pulp quality. The use of environmentally friendly bleaching agents such as oxygen and hydrogen peroxide instead of traditional chlorine bleaching improves the whiteness of the pulp and reduces pollution emissions during the bleaching process. In addition to traditional paper products, bagasse can also be used to produce new materials such as nanocellulose, composite materials, and bioplastics, expanding its application in the paper industry (Vangchhia et al., 2024).

Although the bagasse papermaking industry has significant value-added potential, it still faces some challenges, including unstable fiber quality, imperfect process technology, and uncertain economic benefits. However, as the demand for renewable biomass resources continues to increase, the value-added application of bagasse in the paper industry will become an important direction for the recycling of sugarcane by-products.

2.2 Sugarcane bioenergy and biofuel production

Sugarcane bagasse (SCB) is an important raw material for the production of bioenergy and biofuels. As one of the main by-products of the sugar industry, bagasse is rich in cellulose and hemicellulose, which makes it an ideal substrate for the production of biofuels, especially bioethanol. Generally, bagasse accounts for 25% to 30% of the total mass of sugarcane, and its components mainly include cellulose (40% to 50%), hemicellulose (25% to 35%) and lignin (20%).

Key steps in bagasse biofuel production include pretreatment, enzymatic hydrolysis, fermentation and distillation. Pretreatment is a key step in improving bagasse biofuel production. Common pretreatment methods include alkali method, acid method, steam explosion and organic solvent method. The purpose of pretreatment is to remove lignin from sugarcane bagasse and improve the enzymatic hydrolysis efficiency of cellulose and hemicellulose (Ajala et al., 2021). At present, the combined technology of alkali method and acid method shows superiority in sugarcane bagasse pretreatment and can significantly increase sugar yield (Kakasaheb et al., 2021).

In the production of bioethanol, pretreated bagasse undergoes enzymatic hydrolysis to convert cellulose and hemicellulose into fermentable sugars, which are then converted into ethanol through yeast or bacterial fermentation. In recent years, new fermentation technologies (such as co-culture method, combined fermentation) and improved yeast strains (such as Saccharomyces cerevisiae, Candida tropicalis, etc.) have further increased ethanol production.

In addition to bioethanol production, bagasse can also be used to produce other forms of bioenergy and fuels, such as biogas, lignocellulosic biodiesel, and biohydrogen. For example, a combination of alkali pretreatment and enzymatic hydrolysis can significantly increase biomethane production from sugarcane bagasse. In addition, bagasse can also be used as a direct fuel for biomass power generation. Especially in countries with developed sugarcane industries such as Brazil, bagasse has become an important raw material for power generation in sugar factories (Ajala et al., 2021).

2.3 Sugarcane chemicals and materials

Sugarcane bagasse is the fibrous residue left after the extraction of sugarcane juice. Its main components are cellulose, hemicellulose and lignin. In recent years, scientists have actively explored its potential in producing high value-added chemicals and materials, gradually revealing its prospects for diverse applications.

Sugarcane bagasse is considered an important raw material for biomass ethanol production. Through pretreatment, enzymatic hydrolysis and fermentation, cellulose and hemicellulose can be converted into fermentable sugars for use in the production of fuels such as bioethanol. In order to increase yield, methods such as alkali solution, acid solution or steam explosion are often used to pretreat sugarcane bagasse to reduce the lignin content and release fermentable sugars. Optimized pretreatment and fermentation processes can significantly increase ethanol production. In addition, bagasse can produce biodiesel, biogas and other high value-added chemicals such as xylitol, butyric acid and acetone-butanol-ethanol (ABE) solvents.

Bagasse fiber is widely used in the production of composite materials such as fiber-reinforced polymers, fiberboards and bioplastics. In addition, after being activated and modified by alkali, bagasse ash can be used as an admixture for concrete and cement to improve its durability and mechanical properties. These composites show significant potential in the construction, packaging and automotive industries.

After fine processing of sugarcane bagasse fiber, new materials such as nanocellulose and carbon nanodots can be prepared. As an environmentally friendly material, nanocellulose can be used in reinforced plastics, papermaking, coatings and other fields. Carbon nanodots are used in high-tech fields such as sensors, optoelectronic devices and drug delivery. In addition, through pyrolysis or carbonization processes, sugarcane bagasse can be converted into biochar and activated carbon, which can be used to absorb heavy metals and pollutants. Since bagasse fiber has high specific surface area and excellent adsorption properties, it is widely used in wastewater treatment and adsorption of pollutants such as heavy metals and dyes. Pretreated and modified bagasse fiber exhibits high adsorption capacity for a variety of pollutants, making it a low-cost, renewable adsorbent option in the water treatment industry (Ajala et al., 2021).

Bagasse's fibrous content and high organic content make it an excellent soil amendment, improving soil fertility, water retention and aeration. In addition, it can be mixed with other fertilizers and used as organic fertilizer for crop cultivation to improve yield and quality. Sugarcane bagasse can be converted into a variety of high value-added chemicals and materials through reasonable pretreatment and processing techniques, providing broad prospects for the value-added utilization of sugarcane by-products.

3 Value-added Utilization of Molasses

3.1 Sugarcane ethanol and biofuel production

Molasses is a sugar-rich by-product with important value-added potential in ethanol production and biofuels. Each ton of sugar cane can produce 2.2%~3.7% molasses during the sugar production process, which contains a large amount of fermentable sugars, such as sucrose, glucose and fructose. This makes it an ideal raw material for ethanol production, providing the possibility for recycling and sustainable development of the sugarcane industry (Jamir et al., 2021).

The ethanol production process typically includes steps such as molasses pretreatment, yeast fermentation, and distillation. During the pretreatment stage, the molasses is diluted and supplemented with necessary nutrients such as nitrogen sources (such as ammonium sulfate) and acidifiers (such as sulfuric acid) to promote the growth of yeast and inhibit the growth of unwanted microorganisms. The diluted molasses is then fed into large fermenters where it is fermented by yeast. Finally, the fermentation broth is distilled to obtain ethanol (also known as distilled alcohol or commercial alcohol) with a purity of more than 90%. If anhydrous ethanol needs to be produced, further dehydration is required (Hawaz et al., 2023).

In molasses ethanol production, yeast fermentation and process parameter optimization are crucial. In recent years, researchers have achieved efficient conversion of sugars in molasses by optimizing fermentation conditions, such as molasses concentration, temperature, pH value and yeast strain selection. For example, Meyerozyma caribbica strain shows significant acid and high sugar tolerance, achieving a yeast density of 9.52×10^8 cells/mL at a molasses concentration of 12°Bx, and effectively converts sugars in molasses into ethanol.

According to data, oil produced using sugarcane juice enzymatic hydrolyzate and glucose as raw materials can be used to prepare biodiesel. Under the same preparation conditions, the main components are hexadecenoic acid methyl ester ($C_{17}H_{34}O_2$), 9,12-palmitic acid methyl ester ($C_{19}H_{34}O_2$) and 9-octadecenoic acid methyl ester ($C_{19}H_{36}O_2$). These components make up more than 90% of biodiesel. Therefore, the main components of fatty acid methyl esters produced from sugar cane and glucose are similar. In addition, the physical and chemical properties of diesel mainly depend on its main components, so this also shows that the physical and chemical properties of diesel are similar or similar (Table 1) (Hawaz et al., 2023).

Table 1 Relative contents of various fatty acid methyl esters in biodiesel (Adapted from Hawaz et al., 2023)

Element	Relative content of fatty methyl esters	
	Sugarcane juice enzymatic hydrolyzate	Glucose
$C_{15}H_{30}O_2$	0.53	0.18
$C_{17}H_{34}O_2$	8.47	11.34
$C_{18}H_{36}O_2$	0.44	-
$C_{19}H_{34}O_2$	13.59	19.48
9-$C_{19}H_{36}O_2$	71.25	53.75
8-$C_{19}H_{36}O_2$	5.14	0.24
$C_{19}H_{36}O_2$	0.3	4.48
$C_{19}H_{36}O_2$	0.27	-
9-$C_{21}H_{40}O_4$	-	0.51

The global ethanol market is growing rapidly, especially as a blending agent for gasoline and as a biofuel. The International Sugar Organization (ISO) reports that global ethanol production is expected to reach 11.54 billion liters in 2024, and consumption will reach 11.02 billion liters. Big sugarcane growing countries such as India and Brazil are actively promoting ethanol industry policies, such as Brazil's "Proalcool" plan and India's ethanol blending policy, aiming to reduce dependence on imported fossil fuels and promote recycling in the sugarcane industry. As an important raw material for ethanol production, molasses has significant economic and environmental benefits through technological optimization and policy support, and can bring new opportunities to the global biofuels and renewable energy fields.

3.2 Sugarcane feed additives

As a by-product, molasses is sweet and nutritious, making it an ideal additive in the feed industry. Its ingredients mainly include 44% to 48% sugar, such as glucose and fructose, as well as rich minerals and vitamins. Molasses as a feed additive can improve feed palatability, increase livestock intake, improve animal growth and production performance, and reduce feed waste.

As a feed additive, molasses can improve the digestibility of fiber in feed, making the fiber in standard feed easier to digest, which helps animals absorb and utilize nutrients. Due to the sweetness and high energy density of molasses, it can increase animals' feed intake, maintain body condition and appetite, thereby reducing feed waste (Windsor and Hill, 2022). Molasses is rich in fermentable sugars and is a high-energy feed ingredient, especially useful when grain is scarce or expensive. As a substitute for grains, it can effectively increase the energy supply of feed. Feeds added with molasses can improve the growth performance and protein metabolism of animals, helping to increase daily weight gain and feed utilization without affecting animal health. Molasses is rich in key minerals and nutrients such as iron, calcium, magnesium, vitamin B6 and selenium, making it an ideal feed supplement to help livestock maintain good health (https://www.zookag.com/blog /animal-feed-molasses/benefits-of-molasses-for-animals).

In addition, molasses can reduce the urea content in milk and increase the protein content, especially casein. During the dry period of dairy cows, molasses can increase the intake and digestibility of roughage, reduce the risk of metabolic abnormalities during the lactation period, and help improve production efficiency. For beef and pork producers, molasses as a feed additive not only helps to improve the palatability and nutritional supply of feed, but also effectively reduces feeding costs and achieves sustainable livestock production.

4 Challenges and Future Prospects

The main technical challenges facing the value-added utilization of sugarcane bagasse include the optimization of pretreatment technology and processes. Pretreatment processes are crucial for the separation of cellulose, hemicellulose, and lignin, but many traditional methods have low efficiency and high environmental impact. Although new methods such as alkali pretreatment, steam explosion and acid/alkali combined technology have achieved good results in the laboratory, they still face stability and economic challenges on an industrial scale. In addition, the complexity of the pretreatment and hydrolysis processes, as well as the high cost of cellulases, increase the difficulty of the overall process (Khairul et al., 2022).

Adding value to sugarcane by-products also faces market and economic challenges. Although market demand for products such as biofuels, paper and chemicals is growing, the gap between production costs and market prices makes it difficult to commercialize many projects. Biofuel production requires massive investment, fierce market competition, and the lack of comprehensive subsidies and incentive policies have hindered industrial development. In addition, unstable product markets and high logistics costs also increase economic risks.

Government policies and regulations have a significant impact on the value-added utilization of sugarcane by-products, with clean energy and renewable energy policies providing incentive support for biofuels and biomass energy. However, complex regulations and standards and the lack of a unified quality certification mechanism limit the development of the industrial chain and international trade. In addition, the lack of clear waste management policies and mandatory measures leads to improper waste treatment and utilization, affecting the value-added of by-products.

The value-added utilization of sugarcane by-products has broad development prospects in the future. Technological innovation will be the key to solving existing challenges. Through the development of efficient, economical and environmentally friendly pretreatment and hydrolysis technologies, process efficiency and product quality will be further improved. In addition, sound policies and incentive mechanisms will promote the integration and sustainable development of the industrial chain and provide strong support for the value-added utilization of sugarcane by-products. Ultimately, achieve the transformation from waste to wealth and contribute to global sustainable development.

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