Bioenergy Generation from Agricultural Residues: A Comprehensive Review of Recent Advances in India

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Abstract - As global energy demands keep rising with the environmental concerns escalating, the sustainable utilization of agricultural residues for bioenergy production has garnered significant attention. India, as an agricultural powerhouse, holds immense potential in this regard. This review explores recent advances in harnessing bioenergy from Indian agricultural residues. It highlights the abundance of untapped energy sources like crop residues, rice husks, and sugarcane bagasse. Diverse conversion methods like anaerobic digestion, direct combustion, gasification, and biochemical processes are analyzed for their efficiency, environmental impact, and scalability within the Indian agricultural context. Emerging trends, research gaps, and future prospects are also identified.

Keywords - Bioenergy, Agricultural Residues, Sustainability, Renewable Energy, Bioenergy Conversion, Anaerobic Digestion, Direct Combustion, Gasification, Environmental Impact, Research Advances

I. INTRODUCTION

Agricultural residues, often considered as waste, hold untapped potential as a valuable resource for bioenergy generation in India. With a rapidly growing population, increasing energy demands, and environmental concerns, the sustainable utilization of these residues presents a compelling opportunity. India, an agricultural powerhouse, produces substantial quantities of crop residues, such as rice straw, rice husk, sugarcane, cotton, and sorghum.

These residues, if harnessed effectively, can significantly contribute to the nation’s energy security while mitigating environmental challenges. India's commitment to sustainable development and its ambitious renewable energy targets align seamlessly with the exploitation of agricultural residues for bioenergy. As this paper will demonstrate, this synergy between agricultural abundance and sustainable energy practices offers a path toward a greener and more energy-resilient future for the nation.

II. BIOENERGY PRODUCTION IN INDIA

A recent examination conducted in India has evaluated the feasibility of harnessing crop residue as a source of bioenergy. This research, which received support from the MoEFCC, presents in-depth insights into the district-specific and monthly availability of crop residue. It also offers data regarding the surplus residue generated from specific crops.

The study’s conclusions reveal that India’s bioenergy potential from surplus crop residue is less than previously thought, amounting to 1313 petajoules (PJ) per year.

The research was a collaborative effort involving sixteen institutions, including prestigious ones like IIT and IISER. It employed a comprehensive methodology that integrated on-site surveys with primary and secondary data to estimate the surplus crop residue present in various districts across India. These research findings hold significant importance in optimizing the use of surplus biomass for bioenergy production while addressing concerns related to stubble burning and air pollution. Findings based on the reviewed research are displayed in fig. 1:

Fig. 1. India’s latest bioenergy potential

The study pinpoints noteworthy bioenergy potential in specific regions. India’s wheat residue management is indicated in fig 2, and the surplus fraction of various crops is shown in fig 3. With these yield potentials, we can consider the portion of residues that promote bioenergy conversion.
III. BIOENERGY PRODUCTION FROM RICE

Generic global rice production and trend in rice consumption are as shown:

Various parts of rice can be utilized to generate bioenergy. Some of the key components include:

- **Rice Straw**: Rice straw, which is the stalks left over after rice grains are harvested, is a significant source of biomass for bioenergy production. It contains cellulose and hemicellulose, making it suitable for bioconversion processes like anaerobic digestion or fermentation to produce biogas or bioethanol.

- **Rice Bran**: Rice bran is the external layer of the rice grain. It can be used for bioenergy production through processes such as biodiesel production. The lipids in rice bran can be converted into biodiesel, a renewable and cleaner alternative to conventional diesel fuel.

- **Rice Husks**: Rice husks are the most external layer of the rice grain. They are often used as fuel in biomass power plants, where they can be burned to generate heat and electricity. Rice husk ash is also used in various industrial applications.

- **Rice Residue**: This includes any leftover rice material that is not used for human consumption. It can be processed and converted into bioenergy, such as biogas, through anaerobic digestion.

- **Rice Milling Byproducts**: Byproducts of rice milling can also be used for bioenergy production. These byproducts can be processed to extract valuable components for energy generation.

- **Rice Starch**: Through fermentation, conversion into bioethanol is done. This is a common method for utilizing the carbohydrate content of rice for biofuel production.

- **Rice Hulls**: Rice hulls, or husks, are another term for the outermost layer of the rice grain. They are used as a biomass fuel in some applications, especially in regions where rice is a major crop.

The choice of which part of the rice plant to use for bioenergy production depends on factors such as local availability, the specific bioenergy conversion technology employed, and the desired end product (e.g., biogas, biodiesel, bioethanol, heat, or electricity). Each of these rice components has its unique characteristics and can contribute...
to sustainable bioenergy production. The major contributors to bioenergy production will be discussed here further.

A. Bioenergy production from rice straw

Rice straw can be converted into bioenergy through several different processes, each with its own advantages and potential applications. Here are the various conversion processes for turning rice straw into bioenergy:

- Anaerobic Digestion (AD)
- Fermentation
- Direct Combustion
- Gasification
- Pyrolysis
- Combined Heat and Power (CHP) Systems
- Biochemical Conversion

The choice of conversion process as shown depends on factors such as the desired bioenergy product, local infrastructure, available technology, and economic viability. Different regions may adopt different approaches based on their specific needs and available resources. The following picture is a generic depiction of rice straw conversion methodologies:

B. Bioenergy production from rice husk

Rice husks can be converted into bioenergy through various processes. Here are some of the common conversion methods:

- Direct Combustion
- Gasification
- Pyrolysis
- Biomass Briquettes
- Bioethanol Production
- Biogas Production
- Activated Carbon Production

Conversion methodology depends on desired end products, local infrastructure, and energy needs. Each of these methods has its advantages and can contribute to sustainable bioenergy production using rice husks as a feedstock.

IV. PRIMARY RICE CONVERSION APPROACHES

A. Rice straw conversion

In India, the primary conversion processes for generating bioenergy from rice straw include:

1) Anaerobic Digestion (AD): Breaking down of matter using microbes in the absence of oxygen. It is of four phases:

   - Hydrolysis: In the initial phase, enzymes synthesized by bacteria break down insoluble organic substances such as cellulose, protein, and lipids into soluble organic compounds. Carbohydrates undergo conversion into uncomplicated sugars, while fats and proteins degrade into fatty acids and amino acids. This stage holds significant importance in furnishing the foundational materials required for subsequent phases. It is facilitated by facultative anaerobes, which consume dissolved oxygen, thereby establishing favorable conditions for the Anaerobic Digestion process.

   - Acidogenesis (Acid-Producing): Simple organic compounds originating from the hydrolysis stage undergo further modification into volatile fatty acids (VFAs), lengthy-chain fatty acids, propionate, and butyrate through the actions of anaerobic bacteria. The formation of H+ ions during this stage has the potential to impact the outcomes of fermentation. Elevated H+ concentration can lead to a reduction in acetate production. Typically, uncomplicated sugars, fatty acids, and amino acids are subjected to fermentation, resulting in the production of organic acids and alcohol during this phase.

   - Acetogenesis (Acetic Acid-Producing): Intermediate substances derived from the preceding phase, including VFAs and various organic compounds, serve as the substrate for bacteria engaged in the production of acetic acid. This process yields H₂, CO₂, and acetate as byproducts. Notably, acetogenic bacteria coexist alongside methanogen bacteria throughout this stage.

   - Methanogenesis (Methane-Producing): In the ultimate phase, methane is generated within an exclusively anaerobic environment. Methane production is an exothermic process encompassing two distinct mechanisms: the reduction of acetate (CH₃COO) into methane through acetotrophic methanogens and the transformation of H₂ and CO₂ into methane via hydrogenotrophic methanogens. This stage is of paramount importance in the creation of methane gas, a highly valuable source of bioenergy.

These four stages represent the sequential breakdown of complex organic matter into simpler compounds, ultimately yielding methane gas. Methanogenesis is a key component of AD and is responsible for the production of biogas, which can be harnessed as a renewable energy source.
2) **Thermochemical Conversion of Rice Straw:** Thermal processes for biomass conversion, including direct combustion, gasification, and pyrolysis, entail subjecting biomass to elevated temperatures, typically exceeding 300°C. Under these conditions, biomass undergoes decomposition, resulting in the formation of various solid, liquid, and gaseous constituents. The specific characteristics of the produced materials, such as their distribution and quality, are influenced by a range of process parameters. These parameters encompass factors like temperature, reaction duration, heating rate, the presence or absence of oxygen, utilization of catalysts, and pressure levels.

- **Gastification:** Gasification is a thermochemical process that converts carbonaceous biomass in an environment lacking oxygen to generate synthesis gas, commonly known as syngas. This transformation involves a sequence of chemical reactions, including:

1. Partial oxidation: \( \text{C} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO} \) (Heat change: -268 MJ kg\(^{-1}\)C\(_{12}H_{22}O_{12}\))
2. Complete oxidation: \( \text{C} + \text{O}_2 \rightarrow \text{CO}_2 \) (Heat change: -906 MJ kg\(^{-1}\)C\(_{12}H_{22}O_{12}\))
3. Water gas reaction: \( \text{C} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2 \) (Heat change: +118 MJ kg\(^{-1}\)C\(_{12}H_{22}O_{12}\))
4. Water gas shift reaction: \( \text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 \) (Heat change: -42 MJ kg\(^{-1}\)C\(_{12}H_{22}O_{12}\))
5. Steam methane reforming: \( \text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 \) (Heat change: -88 MJ kg\(^{-1}\)C\(_{12}H_{22}O_{12}\))
6. Hydrocarbon reactions: \( \text{C}_n\text{H}_m + n\text{H}_2\text{O} \rightarrow n\text{CO} + (n-m/2)\text{H}_2 \) (Endothermic)

The resulting syngas primarily consists of combustible gases like CO and H\(_2\), with its composition dependent on various factors such as temperature, pressure, reactor design, feedstock characteristics, and the gasifying agent used (air, steam, and oxygen). Additional processing steps aim to enhance the combustible components (\( \text{H}_2, \text{CO}, \text{C}_x\text{H}_y \)) by eliminating noncombustible gases and water. Syngas finds application as an energy source for tasks like heating, drying, cooking, biofuel production, or electricity generation in cogeneration systems. Moreover, it serves as a raw material for manufacturing valuable chemicals and can be converted into alcohols and diesel fuels using the Fischer-Tropsch method. During gasification, the inorganic materials within the biomass are transformed into a solid substance known as slag or vitrified slag or ash.

Gasification technologies have largely evolved from coal gasification, and three fundamental types of reactors are commonly employed: (1) moving-bed or fixed-bed gasifiers, (2) fluidized-bed gasifiers, and (3) entrained-flow gasifiers. Table 4.6 provides an overview of the distinctions among these three gasification configurations.

Research focusing on rice straw gasification has exhibited promising initial outcomes for bioenergy production. Utilizing rice straw in fluidized bed gasifiers to generate syngas has yielded a high gas efficiency of 61% and a cold gas efficiency of 52%, with a higher heating value of approximately 5.1 MJ N m\(^{-3}\). One method for mitigating bed agglomeration issues involves substituting the conventional alumina-silicate bed with a mixture of alumina-silicate sand and magnesium oxide (MgO). Another study revealed that the introduction of potassium carbonate (K\(_2\)CO\(_3\)) enhanced the production of H\(_2\)-rich gas, achieving yields of up to 59.8% H\(_2\).

The primary challenge encountered in gasification is the formation of tar in the producer gas. Addressing this issue involves various strategies, such as tar removal through filters, scrubbers, or condensers, as well as in situ tar conversion through catalytic cracking or reforming, both of which are still in the developmental stages.

- **Direct combustion:** Combustion is a controlled process of burning organic materials like biomass and waste using an adequate amount of air to produce heat, mechanical power, or electricity. It typically occurs at temperatures between 700 and 1350 °C and is facilitated by equipment such as stoves, furnaces, or boilers. Combustion can significantly reduce waste volume, up to approximately 90% (by mass), depending on the materials and conditions. However, efficient air pollution control mechanisms are necessary to manage the flue gases, which may contain various pollutants like NO\(_x\), SO\(_x\), PMs, and dioxins. Inorganic ash residues known as bottom ash and fly ash are generated from the non-combustible fraction of the fuel. Combustion systems vary in scale, ranging from small domestic heating units to large industrial facilities.

The chemical reaction for complete combustion of hydrocarbons is expressed as follows:

\[
\text{C}_n\text{H}_m + (n+m/4)\text{O}_2 \rightarrow n\text{CO}_2 + (m/2)\text{H}_2\text{O}
\]

For rice straw, direct combustion is a well-established and straightforward thermochemical process that offers high efficiency. It is particularly suitable for economically generating heat from biomass due to its simplicity and effectiveness. An experiment conducted at IRRI utilized a bench-scale direct combustion rice straw furnace to heat air for paddy drying. The results indicated that the furnace, when fed with 20 to 30 kg h\(^{-1}\) of rice straw, produced energy ranging from 200 to 350 MJ h\(^{-1}\), elevating the drying air temperature by more than 30 °C above ambient, which was sufficient for paddy drying purposes. Additionally, the drying air efficiency ranged from 60 to over 85% in this bench-scale application. However, manual ash removal was required due to ash accumulation issues.

When combusting rice straw and similar herbaceous biomass, various ash-related challenges can arise, including accumulation, slagging, fouling, and boiler corrosion, primarily due to chlorine and alkali content. Although there were no reported large-scale direct combustion power plants utilizing rice straw as of 2018, it appears highly feasible, as demonstrated by European combined heat and power plants (CHPs) that utilize wheat and oat straw. These CHPs feed straw bales directly into combustion chambers, often combining straw with coal in fluidized bed systems for increased efficiency. Nevertheless, pretreatment of rice straw may be necessary to address specific challenges, such as particle size reduction, compression into denser forms, or leaching to mitigate issues related to slagging and fouling. Biomass combustion systems come in various sizes, ranging from a few kW to over 100 MW.
B. Rice husk conversion

In India, the primary conversion processes for generating bioenergy from rice husk include:
1. Direct Combustion
2. Gasification
3. Biomass Briquettes
4. Biogas Production
5. Activated Carbon Production
6. Bioethanol Production

- **Direct combustion and gasification** are the primary methods for generating bioenergy from rice husk in India, that are very similar to procedures followed for rice straws, followed by biogas production. The remaining methods, such as biomass briquettes, activated carbon production, and bioethanol production, contribute to a lesser extent in terms of bioenergy production from rice husk.

- **Biogas production**: The researchers should gather locally sourced rice husk and rice straw, clean and air-dry them, and then further dehydrate them in a hot air oven for 24 hours. Afterward, they should reduce the particle size through ball milling. They should utilize standard testing methods to assess the overall solid and volatile matter content, while carbon and nitrogen content should be examined.

V. BIOENERGY PRODUCTION FROM COTTON

The utilization of agricultural cotton residue for bioenergy production represents an economically viable and sustainable approach. India stands as a leading producer of cotton, boasting an impressive production of 365 lakh bales during the 2019-2020 period. Within this context, each hectare of cotton crop yields approximately 2-3 tonnes of cotton stalks annually.
However, when comparing Cotton Stalk to other biomass sources, such as corn stover, it has been observed in numerous studies that Cotton Stalk exhibits superior burning efficiency and longer burn periods. The duration of combustion even extends with increasing density, which may necessitate pelletizing the feedstock for certain applications.

a) Gasification: Gasification is a thermochemical process utilized for the conversion of biomass into valuable syngas. This process involves partial oxidation with oxygen followed by reformation with steam, carbon dioxide, or other gasification agents, resulting in the production of syngas, a versatile chemical compound with various applications.

Gasification is an extremely efficient means of transforming the chemical energy contained in biomass into heat and other beneficial types of energy. According to various estimations, the overall exergetic efficiency of this process ranges from 80.5% to 87.6%.

During gasification, various substances are generated, including carbon dioxide (CO\(_2\)), carbon monoxide (CO), methane (CH\(_4\)), water (H\(_2\)O), gaseous hydrocarbons, hydrogen (H\(_2\)), condensed oil, limited char residue and tar. To achieve the desired outcome of gas production, an oxidizing agent, often in the form of air, O\(_2\), or steam, is introduced into the process. Subsequently, the gaseous tar or oil within the gas stream is condensed. Although the resulting gas may possess an energy content ranging from 3 to 5 MJ/m\(^3\), which constitutes only a fraction, 10% to be precise, of the heat value found in natural gas, it still contains enough energy to drive gas engines. This effectively enhances the value of raw materials that might otherwise be considered waste, underscoring the economic significance of gasification.

Due to the relatively low temperatures involved in the gasification process, residual char remains, which can be effectively gasified by subjecting it to high-temperature conditions, typically around 1000°C, while introducing steam into the operation. In this process, steam undergoes decomposition, yielding hydrogen and oxygen, which subsequently conjunction with the carbon present in the char to produce carbon monoxide (CO) and hydrogen (H\(_2\)). After eliminating contaminants like ammonia (NH\(_3\)), sulfur (H\(_2\)S), and tar, the resulting syngas, characterized by their high-quality CO and H\(_2\) composition, can be generated by employing oxygen (O\(_2\)) rather than air. This syngas, when subjected to the Fischer-Tropsch process, has the capability to be transformed into valuable commodities. These include methanol (CH\(_3\)OH), a versatile liquid fuel, along with a range of hydrocarbon compounds. Notably, the overall efficiency of the entire gasification process can vary, ranging from 40% in simpler designs to approximately 75% in processes characterized by optimal engineering and design considerations.

b) Pyrolysis: Pyrolysis, described as the thermochemical breakdown of a substance in the absence of oxygen, assumes a critical role in converting biomass into a variety of valuable products. Typically occurring within the temperature range of 400 to 600°C, pyrolysis plays a pivotal role in converting biomass into a high-energy liquid. This liquid, referred to as bio-oil, acts as a versatile resource that can be directly utilized as a fuel or employed as an intermediate pretreatment step in the generation of power.

In the specific case of Cotton Stalk, it is crucial to recognize that this biomass possesses a notably high ash content in comparison to low-ash biomass sources. This high ash concentration introduces several disadvantages to the combustion process. The residual ash content tends to accumulate on internal heating surfaces, giving rise to slags and fouling, thereby impairing heating efficiency and overall process effectiveness. It is worth noting that the presence of ash exerts a detrimental influence on combustion processes. In the case of Cotton Stalk, its ash content, standing at 5.5 wt% db (dry basis), is relatively elevated.

### PROPERTIES OF COTTON RESIDUES

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<tr>
<th>Properties</th>
<th>Unit</th>
<th>Biomass Cotton stalks</th>
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</thead>
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<tr>
<td>Proximate analysis</td>
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<tr>
<td>Ash</td>
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<td>Volatile matter</td>
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<td>Fixed carbon</td>
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<td>Oxygen</td>
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</tr>
<tr>
<td>Lower heating value (LHV)</td>
<td>MJ/kg</td>
<td>17.1</td>
</tr>
</tbody>
</table>

Fig. 12. Properties of cotton residues

Procedures To convert Cotton Harvest Residue into Bio-Energy:

1) **Thermochemical Conversion**: The technique of using heat and, in rare instances, chemical reagents to convert biomass into more energy-efficient products is known as thermochemical conversion. The process produces heat, gaseous, liquid, or solid fuels as its output. Combustion, gasification, pyrolysis, and hydrothermal carbonisation processes are the four main thermal processes used to transform biomass into usable energy.

   a) Combustion: Combustion, defined as the rapid chemical combination of a substance with oxygen resulting in the generation of heat and light, is a fundamental process widely employed for energy generation. However, this process entails inherent challenges, particularly in the context of environmental impact. Combustion typically yields a range of pollutants and particulates, necessitating specialized treatment methods to mitigate its adverse effects on the environment.

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heat, biofuels, and chemicals. Pyrolysis offers the potential of being a more adaptable, environmentally conscious, and efficient approach compared to alternative methods.

A study conducted on the pyrolysis of cotton stalks within a fixed-bed reactor has explored the product yield variations across different temperature ranges. Significantly, it was observed that raising the temperature from 650 to 800°C had the effect of promoting gas production while reducing the production of char. The char yield decreased from 66.5 wt% towards 26.73 wt% as the temperature increased from 250°C towards 650°C. This phenomenon can be attributed to the elevated temperatures causing more volatile components to evaporate from the char, leading to an overall decrease in yield but an increase in the carbon content within the char. Concerning the liquid product fraction, an optimal temperature was identified, approximately 550°C, where the highest oil yield of around 41% was obtained. Further elevations in temperature resulted in the cracking of tar and liquids into gases, ultimately leading to higher gas production, corroborating findings reported elsewhere.

Furthermore, it's essential to note that the higher heating value (HHV) of pyrolysis oil falls within the range of 16–23 MJ/l, which is lower in comparison to the HHV of fossil fuels, standing at 37 MJ/l. Additionally, the pyrolysis oil exhibits a low pH value, approximately 3, necessitating special considerations in its handling and utilization. Moreover, the bio-oil produced in the process is characterized by water contents typically ranging from 15% to 35% by weight, with phase separation becoming prominent when the water content exceeds approximately 30–45%.

When it comes to the configuration of pyrolysis systems, various types of reactors are available, including continuous and batch modes. Continuous pyrolysis reactors, such as fluidized-bed, auger/screw-type, and rotary kilns, provide benefits by maintaining a steady feedstock input and a continuous production of biochar, bio-oil, and syngas. These systems typically yield larger quantities of biochar and exhibit improved operational efficiencies in comparison to batch processes. Nonetheless, it's crucial to acknowledge that continuous reactors, despite their greater complexity and cost in terms of design and operation, are especially suitable for medium- to large-scale biochar production systems that depend on centralized feedstock sources. Some continuous reactor designs can also be adapted for small to medium-scale applications.

When it comes to utilizing cotton stalks as feedstock, the recommended method is to employ a continuously operated, indirectly heated rotary kiln reactor. This choice is underpinned by its robustness and established industrial viability, which extends not only to biomass but also waste processing applications. Moreover, this technology is readily accessible for decentralized deployment in cotton-producing regions. An important consideration is that this method retains critical elements like chlorine and potassium in the resultant pyrolysis char fraction. Additionally, it allows for the export of roughly 50% of primary fuel energy through the gas and oil fractions. Furthermore, if the char is returned to the soil without further processing, it may have beneficial effects as a nutrient source while mitigating carbon release as CO₂. As a result, scientists are actively investigating the potential use of pyrolysis char as a soil enhancer to enhance crop yields or as a component of a strategy aimed at achieving negative emissions.

c) Hydrothermal Carbonisation: Hydrothermal carbonization (HTC), a cutting-edge technology for converting biomass into a valuable bioproduct called hydrochar, offers several promising advantages. HTC not only facilitates the creation of hydrochar but also enables the recovery of essential nutrients, including silicon, phosphorus, nitrogen, and potassium, from the process water. This method increases the carbon content in the resulting hydrochar compared to the original biomass by reducing oxygen- and hydrogen-rich compounds. These eliminated compounds are primarily present in the process water and, to a lesser degree, in the resultant process gas. An important characteristic of hydrochar is its increased hydrophobicity compared to the source material, leading to a less energy-intensive dewatering process compared to fresh biomass.

Furthermore, many critical reactions within HTC are exothermic, resulting in the release of heat energy during the carbonization process. Consequently, the hydrochar exhibits an enhanced heating value due to its higher carbon content. Hydrothermal carbonization has also demonstrated its effectiveness in eradicating pests like pink bollworm eggs and other pathogens when applied to cotton stalks.

Nonetheless, further research is required to minimize impurities and optimize nutrient accumulation in the resulting
coal. Through the adjustment of diverse process parameters like pressure, temperature, residence time, heating rate, pH, and the inclusion of catalysts or additives, it is feasible to precisely regulate the allocation of nutrients among the solid, liquid, and gaseous phases.

In a research study led by Al Afif, the application of HTC for producing hydrochar from cotton stalks was investigated. The findings underscore the substantial potential of hydrothermal carbonization as a technology for converting Cotton Stalk into bioenergy. Notably, the study identified a robust correlation between residence time and hydrochar quality, with extended residence times leading to increased heating values (LHV) for the hydrochar derived from Cotton Stalk, albeit with a trade-off of reduced overall hydrochar yield.

1) Biochemical Conversion: Cotton stalk, as a lignocellulosic biomass, presents unique challenges for effective hydrolysis due to its intricate structure and high lignin content. The bioconversion process of lignocellulosic biomass involves several essential steps, including pretreatment, hydrolysis, and fermentation, each serving a distinct purpose.

Pretreatment, which can encompass physical, chemical, biological, or combinations thereof, plays a pivotal role in breaking down the rigid cell wall structure of lignocellulosic materials, including cotton stalk. This step is indispensable because of the recalcitrant nature of lignin and its propensity to bind with holocellulose components. By subjecting the biomass to pretreatment, the various cell wall constituents can be effectively fractionated. Importantly, pretreatment serves to enhance the enzymatic digestibility of cellulose by exposing its surface, making it more susceptible to enzymatic attack.

Hydrolysis is another critical phase in the bioconversion process, involving the breakdown of complex carbohydrates into soluble sugars. This step can be accomplished through acid or enzymatic hydrolysis, with the latter often being preferred for its specificity and environmental friendliness.

Subsequent to hydrolysis, the resulting soluble sugars can be fermented, typically using bacteria or yeast, to produce valuable products such as ethanol. This fermentation step represents a key transformation in the conversion of lignocellulosic biomass into biofuels and other bioproducts.

It's worth noting that among these essential processes, pretreatment stands out as a significant financial expense in the biochemical conversion of lignocellulosic biomass. However, it is a crucial investment to ensure the effective breakdown of the intricate structure of cotton stalk and similar materials, ultimately enabling the production of valuable biofuels and chemicals.

   a) Alcoholic fermentation: Naturally occurring microorganisms have the capability to ferment all three six-carbon sugars: glucose, galactose, and mannose, into ethanol. The conventional use of Saccharomyces cerevisiae, often recognized as yeast, in the brewing industry has long facilitated ethanol production from these hexoses. Recent advancements have led to the development of engineered yeasts with the capacity for efficient fermentation of xylose, arabinose, and even combinations thereof. To make cotton stalks a feasible feedstock for ethanol production, it is essential to apply an optimal pretreatment process to the cellulose fibers. This procedure enhances their responsiveness to hydrolytic enzyme activity.

   Significantly, alkaline pretreatment has emerged as the preferred method, this approach is particularly effective when applied to cotton and other herbaceous plants, as well as agricultural residues. This approach underscores the potential of cotton stalks and similar feedstocks for ethanol generation and emphasizes the importance of selecting the most effective pretreatment techniques.

   In a study conducted by researchers led by Christopher et al., alkali-treated biomass exhibited an impressive hydrolytic efficiency of 80% when cellulase and beta-glucosidase were applied. This significant finding underscores the substantial promise of cotton stalks as a valuable bioethanol feedstock. It also underscores the critical role of efficient pretreatment techniques in optimizing their utility for ethanol production.

   Isci and Demirer conducted a notable study to explore the feasibility of biogas production from cotton waste. Their findings demonstrated that cotton wastes could effectively undergo anaerobic digestion, yielding biogas at rates ranging from 65 to 86 liters of methane per kilogram of volatile solids per day over a 24-day period. Additionally, a two-stage digestion approach, involving the co-fermentation of various organic wastes, including maize, rice, and cotton, was examined in this study. The research uncovered that under anaerobic conditions, the key components of cotton stalks, especially the cell wall carbohydrates, were successfully preserved, and the levels of soluble carbohydrates remained relatively low under anaerobic conditions.

   Highlighting the pivotal role of pretreatment in addressing challenges related to lignin and enhancing solubilization in lignocellulosic biomass is essential. In this context, Al Afif et al. conducted a study on the anaerobic digestion of cotton stalks and introduced an organosolv and supercritical carbon dioxide (SC-CO2) pretreatment process. Their research revealed the substantial potential of SC-CO2 pretreatment in significantly increasing energy output. Specifically, the pretreatment of cotton stalk samples with organosolv and SC-CO2 resulted in methane yields up to 20% higher compared to untreated samples. The highest methane yield, reaching 177 liters of methane per kilogram of volatile solids, was achieved through pretreatment with organosolv and SC-CO2 at 100 bars and 180°C for 140 minutes. Importantly, the quality of the biogas also improved with pretreatment, leading to an increase in methane content from 50% to 60%.

   In summary, cotton stalks can indeed undergo anaerobic digestion effectively for biogas production. Nonetheless, it is the crucial pretreatment step for cotton stalks that plays a vital role in enhancing the efficiency of the overall bioconversion process, making cotton stalks a promising feedstock for bioenergy production.
role in enhancing solubilization and, as a result, improving methane production.

VI. BIOENERGY PRODUCTION FROM SUGARCANE

India has over 500 sugar mills and produces 91 million tons of sugarcane bagasse each year. India leads in sugarcane farming and sugar-making, which is great for making bioenergy. They're turning sugarcane into things like ethanol and bioelectricity to help the environment, boost energy security, and help people in rural areas.

In the sugar industry, the main waste is bagasse, the leftover fibers when sugarcane is juiced. There's also stuff like vinasse from making ethanol and molasses. They gather bagasse and take it to the energy plant.

A. Sugarcane conversion

1) Combustion and Steam Generation: It can be split into the following 2 types:
   - Biomass Power Plants: Bagasse is typically used as the main feedstock in biomass power plants. It is first dried to reduce its moisture content, enhancing its combustion efficiency. The dried bagasse is then burned in specialized boilers. During combustion, the bagasse releases heat energy in the form of steam.
   - Steam Generation: They use the heat from burning bagasse to make high-pressure steam, which goes to a steam turbine to turn heat into power.

2) Electricity Generation: It can be split into the following 2 types:
   - Steam Turbines: The mechanical energy produced by the steam turbine drives a generator, which converts it into electricity. This electricity can be used to power various processes within the sugar mill or be exported to the grid.
   - At some places, they use Combined Heat and Power (CHP) systems. They don't just make electricity with extra steam; they also use it to heat the sugar plant. This saves energy and cuts down on waste.

3) Environmental Controls: To meet environmental regulations and reduce emissions, modern biomass power plants employ various control technologies, such as electrostatic precipitators and scrubbers, to capture particulate matter and reduce air pollutants.

4) Integration with Ethanol Production: In some sugar mills, the process of converting sugarcane into ethanol for biofuel production is closely integrated with electricity generation. The vinasse produced during ethanol fermentation can be used as a feedstock for anaerobic digestion to generate biogas, which is then used for energy or heat production.

5) Biogas Production (Optional): It can be split into the following 2 types:
   - Anaerobic Digestion: Besides bagasse, they can also use a process called anaerobic digestion on the liquid waste from making ethanol, called vinasse. Tiny organisms break down stuff in the vinasse to make biogas, which is methane and carbon dioxide.
   - Biogas Utilization: They can use the biogas to make more power or heat. It can even be turned into biomethane and put into natural gas pipes, or used as fuel for transportation.

6) Energy Efficiency and Sustainability: Sugar mills and biomass power plants are designed for maximum energy efficiency, utilizing as much of the waste as possible. Sustainable practices, such as crop rotation and responsible land management, are also essential to ensure a long-term and environmentally friendly energy supply.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Part of the Sugarcane Plant</th>
<th>Dry Matter by Weight %</th>
<th>% Energy Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Roots</td>
<td>2</td>
<td>1.23</td>
</tr>
<tr>
<td>2</td>
<td>Stalk</td>
<td>58</td>
<td>62.63</td>
</tr>
<tr>
<td>3</td>
<td>Leaves</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>Top</td>
<td>26</td>
<td>12.14</td>
</tr>
</tbody>
</table>

Fig. 13. Sugarcane residue properties

7) Indian Electricity Sector Scenario: The Biomass Energy Sector in India, particularly involving sugar industry waste, has shown significant growth and potential. Dry matter in Sugarcane Plant Revenue from SPR (Sugarcane Plant residue) as shown in the figures below:

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Particulars</th>
<th>Unit</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cane crushed per day</td>
<td>TCD</td>
<td>5000</td>
</tr>
<tr>
<td>2</td>
<td>Season Days</td>
<td>Days</td>
<td>160</td>
</tr>
<tr>
<td>3</td>
<td>SPR (dry)</td>
<td>MT</td>
<td>196960</td>
</tr>
<tr>
<td>4</td>
<td>50% SPR (dry)</td>
<td>MT</td>
<td>99840</td>
</tr>
<tr>
<td>5</td>
<td>Steam Produced at 125 ata /540 deg</td>
<td>MT</td>
<td>364376</td>
</tr>
<tr>
<td>6</td>
<td>Power Produced</td>
<td>Lakh Units</td>
<td>958.9</td>
</tr>
<tr>
<td>7</td>
<td>Sale @ Rs 5% per unit</td>
<td>Lakh ₹</td>
<td>4794.4</td>
</tr>
<tr>
<td>8</td>
<td>Cost of SPR (dry)</td>
<td>Lakh ₹</td>
<td>2462</td>
</tr>
<tr>
<td>9</td>
<td>Cost of Conversion</td>
<td>Lakh ₹</td>
<td>1438.3</td>
</tr>
<tr>
<td>10</td>
<td>Net saving</td>
<td>Lakh ₹</td>
<td>894.1</td>
</tr>
<tr>
<td>11</td>
<td>Sugar Production at 10% Recovery</td>
<td>MT</td>
<td>8000.0</td>
</tr>
<tr>
<td>12</td>
<td>Revenue/ MT sugarcane</td>
<td>₹ MT Cane</td>
<td>111.8</td>
</tr>
</tbody>
</table>

Fig. 14. Sugarcane Plant residue statistics

B. Sugarcane potential in India

1) Installed Capacity
   - As of recent data available, India had an installed electricity generation capacity of approximately 382.0 GW.
- Renewable power plants accounted for 25% of the total installed capacity, with biomass-based co-generated power contributing 11% of the renewable energy capacity.

2) **Biomass Power Growth**
- In the past five years, biomass power capacity increased by 130%. By early 2020, the sector reached a goal of 10.0 GW in capacity, with power made from bagasse playing a big part.

3) **Potential of Power Export from Sugar Industry**
- The Indian sugar industry can sell extra power to the national grid. If you consider the whole country and an average of 300 million metric tonnes of sugarcane crushed in a season, they could export about 12.5 GW of electricity.
  - This potential is based on power generation at a rate of approximately 150 kWh per tonne of cane using advanced co-generation technologies.

4) **Advanced Co-Generation Technologies**
- To unlock the full potential of power export from the sugar industry, advanced co-generation technologies are being adopted.
  - This involves using higher steam conditions with extra high pressure and temperature settings, changing how they handle fuel, mixing more types of biomass with bagasse, making pollution control better, and improving how they treat water.

5) **Biomass Gasification and Combined-Cycle Systems**
- The future of biomass-based energy generation in the sugar industry may involve high-efficiency gasification combined-cycle systems.
  - These systems use gas turbines powered by gas made from changing biomass through heat and chemistry.
  - The gases coming out are used to make steam in heat recovery systems, which makes the power generation better and more efficient.

6) **Bio-Gas and Bio-CNG**
- Filter cake, a waste product in the sugar industry, is being explored for bio-gas or bio-compressed natural gas (CNG) production.
  - When you use anaerobic digestion on filter cake, you can get a lot of biogas. It's estimated that 1 tonne of press mud can make between 85 to 120 m³ of biogas.
  - Bio-CNG production from filter cake has the potential to add value to the sugar industry and reduce greenhouse gas emissions.

7) **Compressed Bio-Gas Potential**
- India has the potential to make about 62 million metric tonnes of compressed bio-gas (CBG) each year. From that, spent wash and filter cake can contribute around 2 million metric tonnes.
  - Using spent wash and filter cake for CBG production can greatly cut down on the need for fossil fuels and help make more green energy.

8) **Bio-Energy from Spent Wash (Vinasse)**
- Vinasse, the effluent of ethanol production, holds potential for bio-energy generation.
  - It can be transformed into bio-gas for boiler fuel or concentrated and incinerated along with other biomass (e.g., bagasse) to produce bio-electricity. This approach can help maximize energy recovery from the ethanol production process.

VII. **BIOENERGY PRODUCTION FROM SORGHUM**

A. **Sweet Sorghum conversion**

1) **Collection and Preparation of Sweet Sorghum Waste:**
- Sweet sorghum is a versatile crop known for its high sugar content. After harvesting, the primary waste product is the residue left from squeezing the juice out of the sorghum stalks. This residue, similar to bagasse in sugarcane, is collected and transported to the energy production facility.

2) **Juice Extraction and Bagasse Production:**
- Sweet sorghum stalks are processed to extract their juice, which is commonly used in the production of ethanol. During this process, bagasse, the fibrous residue, is generated.

3) **Combustion and Steam Generation:**
   a) **Biomass Power Plants:** Bagasse from sweet sorghum can serve as the primary feedstock in biomass power plants. To enhance combustion efficiency, bagasse is dried to reduce its moisture content. Specialized boilers are used for burning dried bagasse.
   b) **Steam Generation:** Heat released during bagasse combustion generates high-pressure steam. This steam can be directed toward a steam turbine, where it is converted into mechanical energy.

4) **Electricity Generation:**
- The steam turbine makes mechanical energy, which turns into electricity using a generator. This electricity can run things in the sorghum processing plant or be sold to the grid.

5) **Combined Heat and Power (CHP):**
- Similar to sugarcane processing, some facilities implement CHP systems. Excess steam from electricity generation can be utilized for providing heat to the sweet sorghum processing plant, improving overall energy efficiency.

6) **Environmental Controls:**
To comply with environmental regulations and minimize emissions, modern biomass power plants incorporate control technologies like electrostatic precipitators and scrubbers. These technologies capture particulate matter and reduce air pollutants.

7) Integration with Ethanol Production:
Sweet sorghum processing often includes ethanol production. The residue from juice extraction can be utilized as feedstock for ethanol fermentation. This integrated approach optimizes resource utilization.

8) Biogas Production (Optional):
   a) Anaerobic Digestion: Biogas can be produced through anaerobic digestion of the liquid waste generated during ethanol production from sweet sorghum. Microorganisms break down organic materials in the liquid waste, generating biogas (methane and carbon dioxide).

   b) Biogas can be used for more electricity or heat. It can even be turned into biomethane and put into natural gas pipes or used as fuel for transportation.

9) Energy Efficiency and Sustainability:
Places that process sweet sorghum and biomass power plants focus on saving energy and making less waste. They also use good farming methods, like crop rotation and taking care of the land, to make sure they have a sustainable and eco-friendly energy source.

Sweet sorghum, like sugarcane, offers significant potential for bioenergy production and contributes to sustainable energy practices in the agricultural sector.

B. Sweet Sorghum potential in India
India has a significant biomass energy sector due to its rich agricultural resources. Biomass energy is generated from organic materials, including crop residues, forest waste, and energy crops like sweet sorghum. Here are some key points regarding the biomass energy sector in India:

   a) Diverse Biomass Resources: India has lots of different kinds of biomass resources, like farm leftovers (rice straw, wheat straw, and sugarcane bagasse), stuff from forests, animal poop, and special plants for energy, like sweet sorghum.

   b) Sweet Sorghum for Ethanol Production: People in India are looking at sweet sorghum as a way to make ethanol. The juice from sweet sorghum stalks has a lot of sugars that can be turned into biofuel ethanol.

   c) Government Initiatives: The Indian government is doing things to support biomass energy, including sweet sorghum. They have a National Policy on Biofuels and policies in different states that promote growing energy crops and making biofuels.

   d) Bioenergy Projects: India has several bioenergy projects, both in the public and private sectors, focused on utilizing biomass resources for electricity generation, heat production, and biofuel manufacturing. Some of these projects may include sweet sorghum as a feedstock.

   e) Biogas Generation: In rural India, making biogas from things like crop leftovers and animal poop is common. They use this biogas for cooking, lighting, and making a little bit of electricity.

   f) Biomass Power Plants: Biomass power plants in India utilize various biomass sources, and sweet sorghum bagasse can be one of them. These plants generate electricity through combustion or gasification of biomass materials.

   g) Rural Electrification: Biomass energy plays a crucial role in rural electrification in India, where grid connectivity is limited. Biomass-based mini-grid systems provide electricity to off-grid communities.

   h) Challenges: Despite the potential, the biomass energy sector faces challenges related to resource availability, logistics, and technological advancements. Efficient harvesting, storage, and transportation of biomass materials remain areas of focus.

   i) Research and Development: Researchers are working to make biomass technology better, use energy more efficiently, and find new things to turn into biomass, like sweet sorghum

Fig. 15. Sorghum conversion technique

REFERENCES


