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ORIGINAL RESEARCH ARTICLE

Assessing the potentials of rice straws as a solid fuel for the production of clean energy

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ABSTRACT

Environmental contamination increased as a result of the extensive use of fossil fuels, large-scale industrialization, and population growth. It has become an urgent need to reduce carbon emissions for environmental sustainability. The revolution in renewable energy may be the best option for lowering carbon emissions. In this research, rice straw was considered as a possible wellspring of bioenergy production. The aim of the study is to determine the best way to use biomass by comprehending its thermal qualities. Several state-of-the-art techniques were used to characterize the rice straws to understand their potential as a solid fuel for clean energy production. Elemental analysis reveals the predominance of carbon and oxygen content while nitrogen and sulfur are minor constituents in the studied rice straws. Fourier transform infrared (FTIR) spectroscopy analysis suggested the presence of cellulosic and ligneous constituents. Pyrolysis is one of the appropriate choices to make esteem expansion and contributes to biomass utilization. The thermogravimetric analysis (TGA) analyses revealed that rice straw pyrolysis has occurred in three distinct stages i.e., dehydration, active pyrolysis, and passive pyrolysis. The differential thermogravimetric graph (DTG) depicts how the temperature peak at the greatest weight loss shifts as the heating rate rises. Based on the characterization and subsequent analysis, it can be concluded that rice straw is a critical biomass and suitable to be used in clean energy production and maintain environmental sustainability.

Keywords: rice straw; thermogravimetric analysis; renewable energy; decarbonization; environmental sustainability

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1. Introduction

Nowadays, fossil fuels constitute the leading energy source globally, accounting for over 80% of the world's energy supply. Extraction, transportation, and combustion of fossil fuels result in the emission of substantial quantities of greenhouse gases, such as carbon dioxide, methane, and nitrous oxide[1–3]. These emissions are recognized as a major contributing factor to climate change, air pollution, and various environmental and health issues[4,5]. Climate change and the rapid depletion of non-renewable energy sources are the two most burning issues against sustainable development.

Increased economic activities, deforestation, and burning of fossil fuels have all been identified as major contributors to rising levels of atmospheric pollutants[6]. The energy and environment relationships lead scientists towards the finding of alternative renewable energy resources for a sustainable environment[3,7]. In this connection, a new root of energy generation from waste materials has been adopted in this study[8].

Bioenergy is an excellent candidate to substitute fossil fuel-based energy. Biomass is comprised of a wide variety of organic feedstocks, including agricultural and forestry waste, livestock manure, energy crops and food waste, etc.[9]. Biomass can be utilized for the generation of various forms of energy via different thermochemical processes such as combustion, pyrolysis, and gasification. Rice straw is considered the most promising feedstock for biofuel production due to its abundant availability in the world, especially in Asia[10]. Approximately 90% of the world’s rice is produced in Asia, where 140 million hectares of land are devoted to rice growing. It was estimated that the mass ratios of rice straw and rice husk to rice production were approximately 100% and 20%, respectively[11]. Due to its huge production, currently, a significant portion of this important organic raw material is going to be wasted or open burning in the field[12]. Open burning of organic matter produced a lot of problems such as particulate matter emission, unburnt hydrocarbon emissions with excess of thermal and fuel bond NO_x. These unburnt hydrocarbons and NO_x combine together to produce a chemical which is called peroxyacetyl nitrate (PAN) which is smog causing compound in winter season[13]. Proper waste management is very crucial for environmental safety and to minimize human health risk. It is well known that crop residue is a lignocellulosic biomass due to its richness in natural constituents, such as cellulose, hemicellulose and lignin[14]. It is the most important renewable feedstock (e.g., rice straw, rice husk), thus indicating considerably cheap, clean, and environment-friendly (carbon-neutral) features as compared to fossil fuels. As a result, there is increased interest in developing biomass-derived fuels for direct energy use or converting them into higher energy-density biofuels via thermochemical processes, including torrefaction, pyrolysis and gasification[15]. The sulfur and ash in lignocellulosic biomasses are relatively lower than those of coal, the so-called slagging, fouling or agglomeration often causes challenges during direct energy use (i.e., combustion) and/or co-firing with coal in boilers and power plants. Therefore, the potential for using this biomass to produce energy is enormous[16].

Biomass to energy production process looks very attractive due to renewable nature but it has many challenges such low calorific value, high moisture content, its drying and processing and its commercial applications for clean energy production[13]. Ash is a major component of biomass which has a lot of challenges during its combustion process and conversion such as slagging and fouling which cause detrimental effect on boiler and cause rapid corrosion which decreased the ultimate heat transfer rate[17]. The major drawback of biomass utilization is its heterogeneous nature depending on the different variety of species and location of plants even though it changes with the age of the plant of same species[18]. Proper application of biomass needs various analysis prior to its commercial scale application which is cost ineffective and time consuming. The main objective of our research group is to develop the simple methods with least experimental work which cost least time and energy to give some useful insight about the quality and design parameters of biomass conversion process to achieve optimized yield of desired product.

In this study, an effort was made to look into the use of rice straw as a potential renewable energy source[14]. Energy from biomass under the current installed system is very complicated along with the complex chemical structure and composition of different biomasses and their combustion behavior. Another possible way of the utilization of biomass is to convert it into different products, improving their quality to make it compatible with already commercialized fuels[19]. Biomass conversion and selective transformation into targeted products is a multistep process where the first step is the understanding of biomass conversion behavior under different process conditions[20]. In this study, an effort was exerted toward the understanding of rice straw degradation (pyrolysis) behavior and quantification of the different proximate components and elemental constituents for its better investigation as a suitable fuel for energy production.

The current study aims to: (i) characterize rice straw in order to effectively utilize it as a substitute fuel for the production of clean energy, (ii) to investigate the characteristics of rice straw, its potential as a fuel source, and the methods and equipment that can be applied to turn it into energy, (iii) to investigate the use of rice straw as a substitute fuel, which could aid in the creation of environmentally friendly and sustainable energy sources.

2. Material and methods

2.1. Study area and sample collection

Table 1. Geographical locations of the selected study areas.

Sample code	Study area	Geographical location	
		Latitude	Longitude
RS-1	Ghatcheck (Rangunia)	22.472757371072884	92.05426693041244
RS-2	Bazalia (Sathkania)	22.12188780990971	92.13653903154399
RS-3	Hithkandi (Mirsarai)	22.76568308576829	91.58619846038793
RS-4	Borodargarhat (Sitakunda)	22.679307021923574	91.6279660415714
RS-5	Haildhar (Anwara)	22.194399651009373	91.93682704317582
RS-6	Subarna char (Noakhali)	22.60184334855384	91.17061838043826
RS-7	Sonagazi (Feni)	22.81780720612325	91.36092278911947
RS-8	Bakerganj (Barisal)	22.540009452284817	90.34786726217534
RS-9	Shatgara (Rangpur)	25.73791347128492	89.21382557246537
RS-10	Birampur (Dinajpur)	25.3919790991708	88.9950590618239

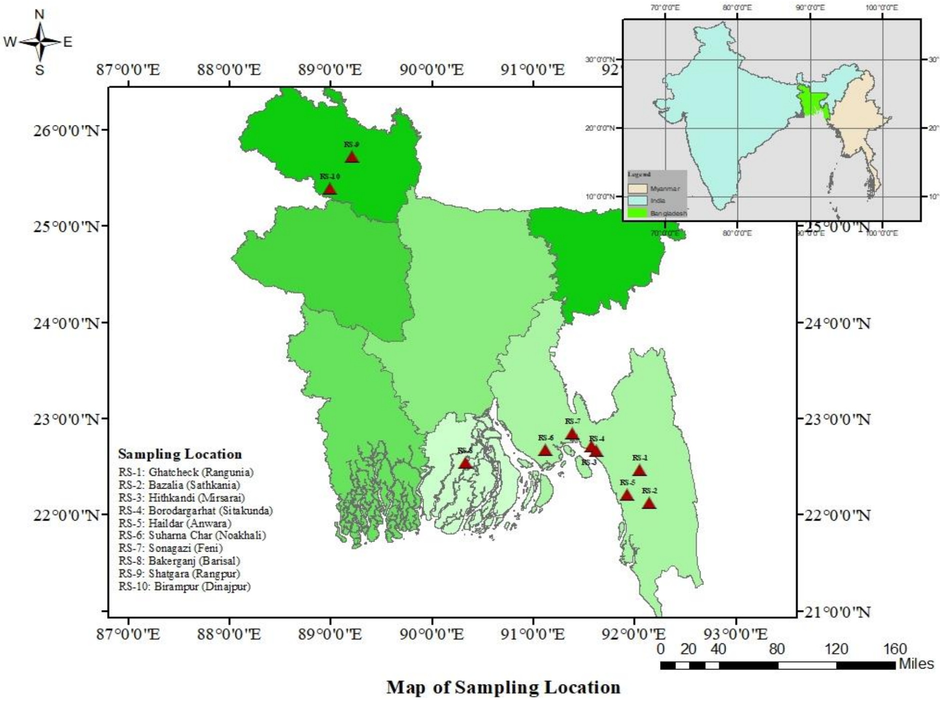

Figure 1. Rice straw samples collection spots within the study areas.

The biomass used in this research was rice straw, a readily available agricultural waste obtained from local fields in Bangladesh. Ten different locations in Bangladesh were selected as study areas based on the importance of rice production. Rice straw samples were collected from the selected areas such as Ghatcheck (Rangunia), Bazalia (Sathkania), Hithkandi (Mirsarai), Borodargarhat (Sitakunda), Haildhar (Anwara), Suharna char (Noakhali), Sonagazi (Feni), Bakerganj (Barisal), Shatgara (Rangpur), and Birampur (Dinajpur). Using GPS, the locations of every sampling point were noted (**Table 1**). A total of five kilograms of rice straw samples were gathered and brought to the lab to be processed, characterized, and examined later. **Figure 1** displays the study areas' sampling points.

2.2. Sample preparation

After being cleaned and sun-dried for several days, the rice straws were kept apart from physical contaminants. The dried rice straw was ground in a rotary cutting mill into 4 mm size and kept in over at 40 °C for 24 h for air dry loss (ADL) to remove the surface moisture. ADL sample was ground into a very fine powder with a particle size of less than 250 μm. The prepared sample was stored into an airtight plastic bag to avoid any type of environmental contamination.

Sample analysis:

Biomass sample was analyzed for carbon, oxygen, hydrogen, nitrogen, and sulfur compositions. The proximate analysis of the air-dried sample was performed by ASTM standards as given in our previous study[1,21]. Following an hour of heating at 110 °C with a N_2 purge, the mass loss of the samples was used to calculate their moisture content. A ceramic crucible was filled with about 1 g of air-dried biomass (Minimal-BC). After being initially purged with N_2 gas for at least 25 min at a flow rate of 6 L min^{-1}, the samples were placed inside the oven. In the next heating stage, N_2 was pumped into the oven at a flow rate of 3 L min^{-1}. The sample was immediately moved to a desiccator, allowed to cool for an hour, and then weighed after the oven was turned off after the one-hour heating period. The oven-dry samples were heated for seven minutes at 950 °C under N_2 purge to determine the volatile matter content. The biomass-filled crucibles were placed inside a stainless-steel box within a muffle furnace (Thermo Scientific Lindberg/Blue M Box Furnace BF51894C-1) and covered with ceramic lids during the heating process. Through a tiny opening in the stainless-steel box cover, a N_2 purge line and thermocouple were inserted through the top of the furnace and down into the stainless-steel box. For at least fifteen minutes, the box was purged with N_2 gas at a flow rate of six liters per minute, or roughly ten box volumes. Following the first purge, the flow rate of N_2 dropped to 3 L min^{-1}. Using the same muffle furnace, the same samples were heated to 550 °C in an air atmosphere to determine the ash content of the biomass. Crucible lids were taken off, and the furnace was continuously flushed with a low air flow of 1.5 L min^{-1} to guarantee full combustion. After being brought to 550 °C, the furnace was maintained there for four hours. Following full combustion, the furnace was turned off, and the samples were moved to a desiccator to cool for an additional hour. After the crucibles were weighed, the ash mass was calculated by deducting the weight of the empty crucible. The arithmetic means of measurements made in triplicate constitutes all reported proximate analysis data in this manuscript.

3. Results and discussion

3.1. Proximate analysis

Proximate analysis of rice straws in **Figure 2** showed the highest value of fixed carbon and volatile matter with a lower value of moisture and ash content. The high value of volatile matter indicated the presence of a lower range of hydrocarbons with higher hydrogen content and oxygenated species. Unwanted components such as ash and moisture reduced the heating value of the sample and thus, they are in the least quantity as compared to other biomasses and coals reported in the literature[22–24]. Higher amounts of carbon-containing biomasses are usually preferred for energy production for various applications[25]. Volatile matter (VM) is responsible for the many important factors for biomass conversion and direct combustion[26]. VM reduced the ignition temperature of biomasses and facilitated chemical reactions[27]. Moisture increased the ignition temperature and absorbed a lot of heat in the form of water vapor when it left the system. That’s why the higher the water content the lower will be the heating value. Ash is another impurity present in coal and biomass samples plays a significant influence on combustion and conversion. The usual problem of ash is sintering and fouling in the combustion chamber and with the walls of the boiler. If the ash contains metal oxides with low melting points, they can cause the problem of sintering which may affect the combustion chamber or reactor bed. Scaling is also caused by the metal particles in the air which stuck with the inner walls of the reactor and reduced the heat conductance resulting in the lower efficiency of the process. In the context of various advantages and disadvantages of the proximate composition, the rice husk has a good proximate composition for its effective combustion and conversion with the lowest possible and manageable disadvantages.

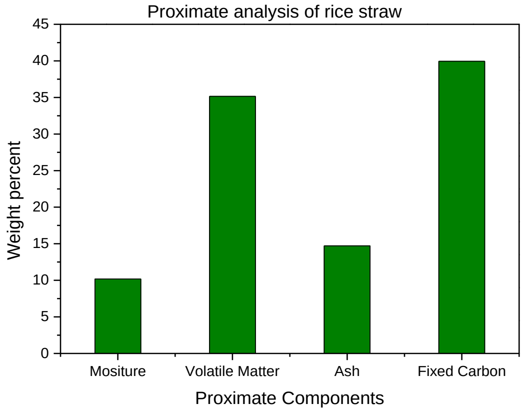

Figure 2. Proximate analysis of rice straw.

3.2. Effect of elemental composition

An elemental analyzer (EA) performed a preliminary analysis on the elemental contents of the rice straw in this study. A sample with a known weight is completely burned in the EA instrument to produce gases (such as CO_2 and H_2O). Following their separation, the combustion products are examined to determine the elemental contents through comparison with the standards. As a result, one can ascertain the specimen’s elemental composition by looking at peaks in the spectrum. The two most common elements were carbon (C) and oxygen (O), with trace amounts of sulfur (S) and nitrogen (N). The lignocellulosic constituents were linked to the high concentrations of carbon and oxygen. $(C_6H_{10}O_5)_n$ and $(C_5H_8O_4)_n$, respectively, are the chemical formulas for cellulose and hemicellulose. The experimentally determined proportions of carbon (C), oxygen (O), and hydrogen (H) in the lignocellulosic residues are therefore, as shown in **Figure 3**, roughly 42 wt%, 53 wt%, and 6 wt%, respectively.

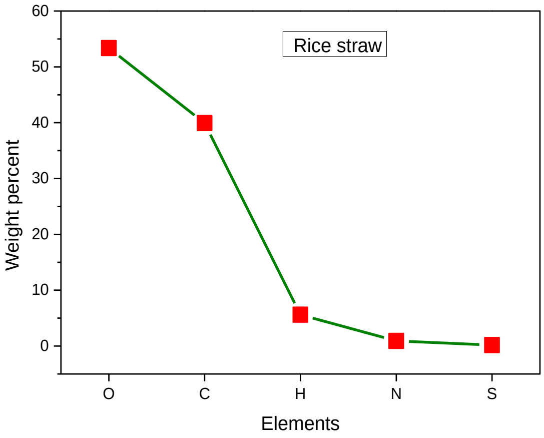

Figure 3. Elemental analysis of rice straw.

3.3. FTIR characterization

According to the FTIR analysis shown in **Figure 4**, a high peak at roughly 3400 cm^{-1} was seen in the spectra, indicating the presence of strong hydrogen bonding between the cellulose group and O–H stretching. The presence of aliphatic groups (–CH$_n$) stretching within the methyl and methylene of cellulose is indicated by the absorption peaks at 2650 cm^{-1}. The evidence for C–H stretching, C=O stretching of the ester bond, and C=C stretching in the aromatic ring was shown by peaks at 2925, 1734, and 1621 cm^{-1}, respectively.

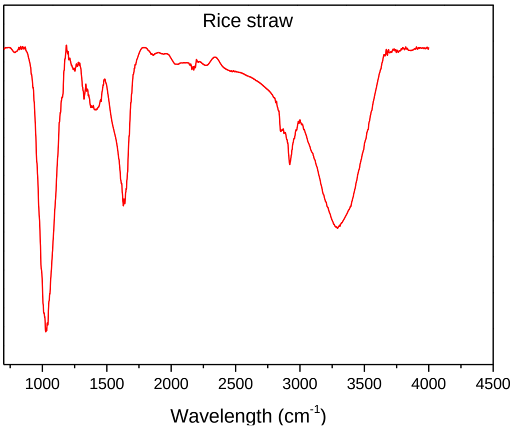

Figure 4. FTIR spectra of rice straw.

Because of the vibration of the C–C aromatic ring, the vibrations, which are primarily responsible for lignin, occur in the 1500–1640 cm^{-1} range. A few peaks that showed up between 700 and 1600 cm^{-1} may indicate the presence of ligneous and cellulosic components. Moreover, the structural properties of cellulose and hemicellulose were linked to the vibration band between 900 and 1200 cm^{-1}. The presence of C-O-C ring skeleton vibration and glycolic bond (C–O–C) was indicated by the absorption band 910 cm^{-1}[28].

3.4. Thermogravimetric analysis (TGA) characterization

In **Figure 5**, the TGA curves of rice straw heated to 900 °C at a rate of 50 cm^3/min of nitrogen flow are shown. The peak corresponding to the thermal decomposition processes can be linked to the lignocellulosic components of the biomass by examining the first derivative of the resulting TGA curve, also known as the DTG curve. The biomass samples first dried and became devolatilized at temperatures below 200 °C. Within the 200–400 °C temperature range, there was a noticeable decrease in weight as the temperature rose. A shoulder or plateau at the lower temperature region is one of the two peaks. Hemicellulose's thermal breakdown was represented by this area. That of cellulose was, nevertheless, frequently represented by the second peak, which was found in the region of higher temperatures. The majority of the devolatilization should be brought on by the breakdown of lignin above about 400 °C. The following should be in order of thermal stability: hemicellulose (low), cellulose, and lignin (high). Conversely, the curves were shifted to higher temperature values the higher the heating rate was from 5 to 20 °C/min. This is the usual behavior of effects resulting from processes related to heat transfer. This was brought on by the lignocellulosic biomass's non-conductive quality, which delayed thermal degradation as heating rate rose. The peak of the rice straw revealed a significant mass loss in the temperature range of 336–379 °C, depending on the biomass sample and heating rate. Higher mass loss was typically seen at lower pyrolysis temperatures, and this loss tended to decrease as the temperature at which biochar was produced rose.

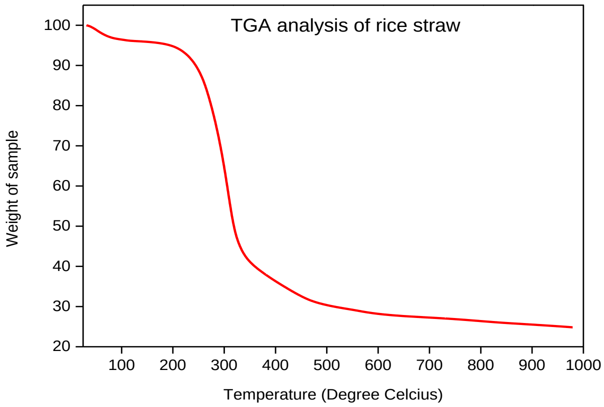

Figure 5. Thermogravimetric analysis curve of rice straw.

Three separate regions on the mass loss curve represent active, passive, and dehydration pyrolysis, respectively. Rice straw loses moisture in the first zone, which is between 30 and 110 °C. Whereas cellulose has a highly disordered crystalline structure, hemicellulose is a branched polymer with a low degree of polymerization. Because lignin has surface functional groups with high thermal stability and is more stable than the other two constituents, its decomposition temperature range is wider. The temperature range in which pyrolysis occurs is 190–900 °C. In this area, lignin degradation (passive pyrolysis) commences at 190 to 900 °C, while active pyrolysis, or hemicellulose and cellulose decomposition, takes place between 190 and 400 °C. The breakdown of hemicellulose, cellulose, and lignin was also found to occur at temperatures between 220 and 330 °C, 300 and 440 °C, and $T > 340$ °C, respectively [15]. According to Asif et al., lignin decomposes more slowly than cellulose and hemicellulose at temperatures between 160 and 900 °C[8]. Around 190–200 °C is when the rapid weight loss begins, and it slows down to 400 °C before reaching the ultimate temperature. The yield of solid residue was roughly 27% of the initial mass. **Figures 5** and **6** illustrate the impact of varying heating rates on the TGA and DTG plots, respectively. The maximum de-volatilization rate, the position of the extreme temperature peak, and the curve position are all influenced by the heating rate.

A more pronounced peak that was seen at 300 °C could be the result of cellulose and hemicellulose breaking down. The purging gas needed less instantaneous thermal energy and took less time to reach the equilibrium state inside the system when the sample was heated more quickly. Additionally, a faster reaction rate brought about by a higher heating rate led to higher peak temperatures, and the DTG peak grew as the heating rate increased. It could be because higher temperatures are needed for the material to break down at higher reaction rates. As a result, the DTG curve moved to the right. The phenomenon of heat transfer limitation, also referred to as thermal lag, was responsible for this effect.

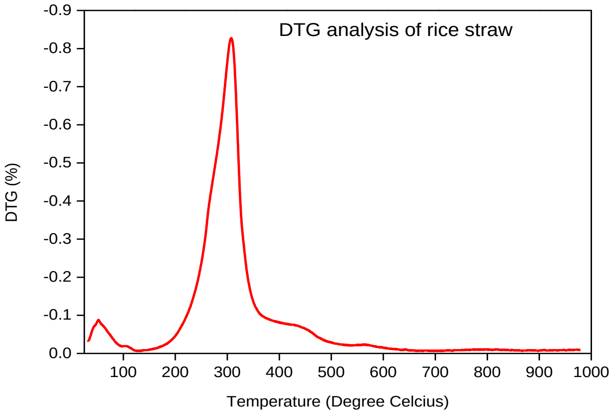

Figure 6. Differential thermal analysis of rice straw.

4. Comparison with existing literature worldwide

A literature review on bioenergy production from different types of biomass waste showed that there are several challenges in the commercial scale application. The main challenge is the different nature of biomass depending on origin and types of the species[1]. The understanding of the chemical structure and its conversion and combustion behavior is very important for commercial scale applications[24,29,30]. In this regard many researchers investigated the proximate composition of different biomasses with their elemental analysis to investigate the heating value and SO_x and NO_x production during biomass utilization[31,32]. Most of the biomass samples have very high ash content or moisture content which make them unfit for commercial scale application due to low GCV and scaling and fouling effect in the boiler due to low melting temperature of ash[33]. Rice straw showed very good proximate composition for higher heating value and low ash content. Rice straw also has minimum environmental impact due to low nitrogen and sulfur content. Based on the proximate analysis, elemental analysis and thermal analysis rice straw showed good potential for its commercial scale application for bioenergy production[34,35].

5. Limitations of the study

Based on thermal analysis, further in-depth kinetic and thermodynamic parameters could be investigated using different model free and model fitting approaches. The pyrolysis process is a very complex process so its approximation for mechanism investigation can be done through different statistical models. So, the investigation of thermodynamic and kinetics parameters of rice straw may be the subject of future research.

6. Conclusion

In many Asian countries, rice residues, or rice straw, might be the most significant crop residue. The objective of this study was to investigate the basic characterization of rice straw for the commercial application as raw material for biofuel production. Details proximate analysis for the weight percentages of moisture, volatile matter, ash and fixed carbon, elemental analysis for the determination of carbon, hydrogen, oxygen, sulfur, and nitrogen content and TGA analysis for thermal behavior investigation were performed. Based on proximate analysis and elemental analysis it is concluded that rice straw has about 80% weight fraction of combustible material and lower contents of nitrogen and sulfur were present. Thermogravimetric analysis (TGA) results showed that the contents of volatile matter in the rice residues varied within a narrow range of 30–35 wt% (dry basis). Moreover, FTIR analysis confirmed the presence of cellulosic and lignocellulosic material that can be utilized for biofuel production, and hence plays a crucial role in sustainable energy systems and climate change mitigation.

Author contributions

Conceptualization, AMMH, MUK and FY; methodology, AMMH, MUK and FY; software, MA and MRU; validation, MA and MRU; formal analysis, AMMH, CY, MA and MRU; investigation, MA and MRU; data curation, AMMH; writing—original draft preparation, AMMH; writing—review and editing, MAA, MUK and FY; visualization, CY; supervision, FY. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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