Cleaner Chemical Engineering 11 (2025) 100161

Contents lists available at ScienceDirect

Cleaner Chemical Engineering

journal homepage: www.elsevier.com/locate/clce

# Sustainable valorization of textile industry cotton waste through pyrolysis for biochar production

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ARTICLE INFO

*Keywords:*
Waste cotton pyrolysis
biochar
renewable energy
waste management

ABSTRACT

This study presents a novel and sustainable approach to the valorization of textile spinning industry waste cotton (WC) through direct pyrolysis, converting it into high-quality biochar with enhanced energy potential and structural stability. This research systematically examines the impact of pyrolysis temperature (300–500°C) on biochar yield, composition, and physicochemical properties to optimize conditions for maximum carbon retention and energy efficiency. The results indicate that biochar yield decreased from Biochar yield decreased from 50.5 % at 300°C to 26.7 % at 500°C, while fixed carbon content increased from 59.33 % to 68.65 %. Elemental analysis revealed a rise in carbon content (53.13 % to 73.62 %) and reductions in oxygen (46.7 % to 13.27 %) and hydrogen (6.06 % to 2.79 %), enhancing thermal stability. X-ray Diffraction (XRD) analysis demonstrated a transition from amorphous cellulose to condensed graphitic carbon at higher temperatures. Thermogravimetric Analysis (TGA) confirmed superior thermal resistance, with biochar retaining 14.7 % of its mass at 800°C. Differential Scanning Calorimetry (DSC) revealed key thermal transitions, with the endothermic peak shifting from 65.5°C in raw WC to 79.6°C at 500°C, indicating increased thermal stability. The calorific value peaked at 27.31 MJ/kg at 400°C, making it a promising solid biofuel. Additionally, Brunauer-Emmett-Teller (BET) analysis showed a substantial increase in porosity, with the highest specific surface area of 225.24 $m^2/g$ at 500°C, improving biochar's potential for adsorption, catalysis, and energy storage. These findings contribute to optimizing pyrolysis conditions for waste cotton valorization, supporting circular economy principles, reducing environmental pollution, and enhancing renewable energy applications. By integrating pyrolysis into textile waste management, this study offers a scalable and eco-friendly strategy for sustainable energy recovery and environmental remediation.

## 1. Introduction

Cotton spinning is one of the most widely utilized techniques for producing spun yarns, transforming staple fibers obtained from the cotton ginning process into continuous strands suitable for textile manufacturing (Lord, 2003). This process involves multiple critical stages, including opening, carding, drawing, combing, roving, spinning, and winding, each of which enhances fiber alignment and uniformity to achieve high-quality yarn (Negm and Sanad, 2020). However, these advancements have not mitigated the substantial waste generated during the process. Depending on the raw material quality and the desired yarn properties, approximately 13–30 % of the initial cotton bale is discarded as waste during production (Basu, 2003). Given the increasing global cotton production, which currently stands at approximately 26 million metric tons (MMT) annually according to the International Cotton Advisory Committee (ICAC), the resultant accumulation of cotton waste poses significant environmental challenges, necessitating sustainable waste management solutions (Ranjithkumar et al., 2022). The increase in cotton production inevitably results in higher volumes of cotton waste, creating an urgent need for sustainable waste management solutions.

Cotton is the most widely consumed natural fiber in the textile and clothing industry, with global production reaching approximately 24.5 million tonnes in 2013. Cotton cultivation is primarily concentrated in

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https://doi.org/10.1016/j.clce.2025.100161
Received 1 February 2025; Received in revised form 21 February 2025; Accepted 1 March 2025

arid and semi-arid regions, where other crops face significant growth challenges. The leading cotton-producing countries include China (26.4 %), India (20.5 %), the United States (13.9 %), Pakistan (8.5 %), Brazil (6.3 %), Uzbekistan (4.1 %), Australia (3.8 %), and Turkey (3.3 %), collectively accounting for the majority of global cotton lint production (Esteve-Turrillas and de La Guardia, 2017). The global textile industry is a major contributor to solid waste generation, with estimates indicating that approximately 92 million tons of textile waste were produced in 2014, a figure projected to rise to 148 million tons annually by 2030 (Pensupa et al., 2018, Niinimäki et al., 2020). Textile waste includes a diverse range of materials, including natural fibers (cotton, wool, silk), synthetic fibers (polyester, nylon, acrylic), and blended fabrics, each posing unique challenges in waste management and recycling efforts (Koszewska, 2019).

Bangladesh, as one of the world's leading textile and garment producers, generates significant amounts of textile waste. In 2019 alone, approximately 577,000 tons of waste were produced from the country's ready-made garment (RMG) factories and fabric mills. Notably, nearly 250,000 tons-almost half of the total waste-were identified as pure cotton waste, which is 100 % recyclable and valued at approximately 100 million USD (Koszewska, 2019). Given the rapid expansion of the textile sector, this volume is expected to rise, further intensifying waste management challenges. Current disposal methods, including open dumping, uncontrolled burning, and landfilling, contribute to severe environmental problems such as soil and water contamination, air pollution, and greenhouse gas emissions (Wang, 2010, Liu et al., 2019).

Recycling has emerged as a potential alternative, but challenges remain due to the frequent presence of mixed fibers, synthetic additives, and dyes, which limit the quality and usability of recycled cotton fibers (Hamawand et al., 2016). Mechanical recycling, though cost-effective, results in lower-quality fibers, whereas chemical recycling (Yu et al., 2018), despite its potential to produce high-value materials such as functionalized nanomaterials, remains constrained by high operational costs, low recovery efficiency, and the need for harsh processing conditions (Haslinger et al., 2019).

Among various types of textile waste, cotton stands out as a particularly promising candidate for sustainable valorization through pyrolysis. Cotton, a natural cellulose-based fiber, has a high volatile content and calorific value, making it well-suited for thermochemical conversion processes (Esteve-Turrillas and de La Guardia, 2017). Unlike synthetic textile wastes, which may release toxic compounds such as dioxins and furans during pyrolysis, cotton undergoes cleaner thermal degradation, yielding valuable byproducts such as biochar, bio-oil, and syngas (Nanda and Berruti, 2021). Biochar is a carbon-rich material with numerous environmental and agricultural benefits, including soil enhancement, carbon sequestration, and improved water retention capacity. Additionally, biochar can serve as an effective adsorbent for wastewater treatment (Rachiq et al., 2021, Peighambardoust et al., 2025, Peighambardoust et al., 2025), aligning with circular economy principles.

The significance of waste cotton (WC) as a feedstock for biochar production lies in its abundance, renewable nature, and environmental benefits. Compared to other textile waste types, WC is free from synthetic polymer contamination, facilitating its direct use in high-yield biochar production with minimal preprocessing requirements (Parthasarathy et al., 2022). Pyrolysis, the thermal decomposition of biomass in an oxygen-deficient environment, yields biochar, syngas, and bio-oil, offering a sustainable alternative for energy recovery. (Wu et al., 2022). Among these products, biochar-a carbonaceous solid residue-has garnered significant interest due to its potential applications in energy storage (Senthil and Lee, 2021), soil amendment (Brassard et al., 2019), and carbon sequestration (Luo et al., 2023). The physicochemical properties of biochar, including porosity, surface area, and carbon stability, are influenced by key process parameters such as temperature, heating rate, and residence time (Seow et al., 2022).

Recent studies have revealed that the pyrolysis of cotton waste predominantly results in the formation of biochar, with minimal or negligible yields of bio-oil and syngas. This is primarily due to the high cellulose and hemicellulose content of cotton fibers, which decompose into solid carbonaceous residues rather than volatile compounds (Hoang et al., 2021). Unlike lignin-rich biomass, which produces significant liquid fractions during pyrolysis, cotton fibers lack the necessary polymeric structures that facilitate bio-oil generation (Rubi et al., 2023). Additionally, the thermal degradation of pure cotton waste occurs through dehydration and char-forming pathways, leading to a predominantly solid-phase product with limited gaseous emissions (Sharma et al., 2015). However, co-pyrolysis, where cotton waste is processed alongside synthetic polymers or other biomass materials, has been shown to significantly alter the product distribution by enhancing the formation of bio-oil and syngas. The presence of polymeric materials, such as polypropylene (PP), polyethylene (PE), or polystyrene (PS), introduces hydrocarbon-rich volatile compounds into the reaction environment, promoting secondary cracking reactions that increase bio-oil and gas-phase yields (Li et al., 2025).

This study introduces a novel approach to sustainable textile waste management by focusing on the direct pyrolysis of cotton spinning waste for biochar production. Unlike previous research that primarily examines mixed textile waste, this study targets high-purity cotton waste, which has superior energy recovery potential due to its high cellulose content. The research not only explores the thermochemical conversion of cotton waste but also evaluates the energy potential and environmental benefits of the resulting biochar, filling a critical gap in waste valorization strategies. By integrating pyrolysis into the textile industry's sustainability framework, this study provides a scientific basis for transforming a significant waste stream into a valuable resource, supporting circular economy principles, reducing fossil fuel dependency, and mitigating the environmental impact of textile waste accumulation.

## 2. Experimental

### 2.1. Materials

Cotton waste obtained from blow room operation was obtained from Makson Spinning Ltd., Ashulia, Savar, Dhaka, Bangladesh.

### 2.2. Raw materials conditioning

Cotton waste samples were ground using a knife mill. The ground material was then sieved through a 100-mesh screen to ensure a uniform particle size distribution. Prior to the pyrolysis experiments, the sieved samples were dried in an oven at 105°C for 3 h to remove moisture. To ensure consistent processing, small batches of the prepared sample were used in each pyrolysis run. The knife mill speed was adjusted as needed to achieve the desired particle size reduction. This controlled particle size reduction and drying procedure is crucial for efficient heat transfer during the pyrolysis process and contributes to the consistency and reproducibility of the resulting biochar characteristics.

### 2.3. Design and setup of the pilot pyrolizer

The mini-pilot pyrolysis plant was designed to simulate the process of converting biomass into biochar as shown in Figure S1 (in the supporting materials). Constructed primarily from stainless steel 306, the plant ensures durability and resistance to high temperatures. At the heart of the plant lies a cylindrical reactor, 50 cm in length and 75 mm in internal diameter, with 5 mm thick walls. To minimize heat loss and maintain precise temperature control, the reactor is insulated with glass wool and equipped with three 3000W spiral heating wires, capable of reaching temperatures up to 800°C. The feedstock, waste, was loaded into a cylindrical stainless-steel sample holder, measuring 36 cm in length and 60 mm in diameter, within the reactor.

A vacuum pump, operating at 50–100 psi with a 1400 rpm motor, creates a negative pressure environment within the reactor, facilitating the flow of nitrogen gas through the system. The flow rate of nitrogen gas is carefully controlled using a rotameter and valves, ensuring optimal conditions for the pyrolysis process. As the feedstock was heated in the absence of oxygen, it undergoes thermal decomposition, breaking down into various products. Gaseous products, including syngas, are collected from the pump outlet. The biochar, a solid carbon-rich residue, remains in the sample holder after the pyrolysis process. The reactor was thoroughly cleaned between runs to prepare for the next experiment. The control panel provides a user-friendly interface for monitoring the temperature, adjusting heating settings, and implementing an emergency stop for safety. This mini-pilot pyrolysis plant offers a valuable platform for research and development in the field of biomass conversion. It enables scientists to study different feedstocks, process parameters, and product yields, contributing to the advancement of sustainable energy technologies.

### 2.4. Pyrolysis of waste cotton

Dried textile spinning cotton waste (20 g per run) was subjected to pyrolysis in a mini pilot-scale pyrolyzer under a nitrogen atmosphere. The pyrolysis experiments were conducted at temperatures of 300°C, 350°C, 400°C, 450°C, and 500°C to investigate the effect of temperature on biochar yield. A constant nitrogen flow rate of 5 $\mathrm{Lmin}^{-1}$ was maintained throughout each run to ensure an inert environment. Pyrolysis of 50 g dried waste cotton under these conditions primarily yielded biochar and some gaseous products, with negligible liquid product collected. Each pyrolysis run was performed in triplicate to ensure reproducibility and allow for determination of the average biochar yield and standard deviation at each temperature.

### 2.5. Characterization processes

#### 2.5.1. Proximate analysis and char yield

Proximate analysis determines the weight percentages of moisture, ash, volatile matter, and fixed carbon in a sample, all of which are essential in evaluating the fuel properties of biochar. The quantities of volatile combustible matter and fixed carbon directly contribute to the heating value of biochar. Fixed carbon serves as the main source of heat during combustion, while a higher volatile matter content indicates easier ignition when used as a fuel source. The ash content is also critical because it impacts furnace design, combustion volume, pollution control equipment, and ash handling processes. Standard methods were followed for proximate analysis:

a) Moisture content of the sample was determined according to ASTM D3173 by drying 1g of the sample at 105°C in a drying oven for 2 h.
b) Ash content of the sample was measured using a muffle furnace at 800°C for 1 h following ASTM D3174.
c) Volatile matter was determined by heating the sample in a crucible covered with a lid in a muffle furnace at 800°C for 7 min, following ASTM D3175. The remaining material is fixed carbon and ash.
d) Fixed carbon content was calculated by the following equation:

$$\text{Fixed carbon}(\%) = 100 - (\%\text{Moisture} + \%\ \text{Volatile matter} + \%\ \text{Ash content}) \quad (1)$$

The solid char products were collected from the pyrolizer, weighed, and stored in airtight containers. The input of biomass was compared to the quantity of outputs. 100 % conversion efficiency was assumed, as well as a conversion efficiency with a gas loss of ……. %. Char yield was calculated with equation (1) in which $M_C$ is the mass of the produced char, $M_{\text{Feed}}$ is the mass of the feedstock, and $Y_{\text{Char}}$ is the calculated percentage yield (Bridgeman et al., 2008):

$$Y_{char}(\%) = (M_C / M_{Feed}) \times 100(2)$$

#### 2.5.2. Fourier transform infrared spectroscopy (FT-IR)

Fourier Transform Infrared Spectroscopy (FTIR) of the samples was performed using a Bruker Alpha ATR-FTIR Spectrometer (Germany) in the spectral range of 4000–600 $\mathrm{cm}^{-1}$. The spectra were acquired in transmission mode, averaging 64 scans, with a spectral resolution of 4 $\mathrm{cm}^{-1}$.

#### 2.5.3. X-Ray diffraction (XRD)

XRD analysis was performed to investigate the crystallographic structure of the collagen samples. The measurements were carried out using a Phillips X-Pert PRO PW3040 X-ray diffractometer operating at 40 kV and 40 mA, with CuKα radiation ($\lambda = 1.54060$ Å). Scans were conducted over a 2θ range of 10° to 70° to determine the crystalline properties of the biochar sample.

#### 2.5.4. Thermogravimetric analysis (TGA)

Thermogravimetric analysis (TGA) of the samples was carried out using a Thermogravimetric Analyzer (Model TGA 8000, PerkinElmer, USA) under a nitrogen atmosphere with a flow rate of 20 mL $\mathrm{min}^{-1}$. The samples were heated at a rate of 10°C $\mathrm{min}^{-1}$, and the measurements were recorded over a temperature range of 50°C to 800°C.

#### 2.5.5. Differential scanning calorimetry (DSC)

Differential Scanning Calorimetry (DSC) analysis was conducted using a NETZSCH STA 449 F5 Jupiter Simultaneous Thermal Analyzer (Germany), which provides a DSC resolution of less than 1 μW (sensor-dependent). The measurements were performed in an inert nitrogen ($N_2$) environment to prevent oxidation. A controlled heating rate of 5°C/min was applied. In the DSC evaluation of copper nanoparticles (Cu NPs), enthalpy changes were observed, which reflect physical or chemical transitions occurring in the material as temperature changes or over time.

#### 2.5.6. Surface morphology

The surface morphology and elemental composition of the samples were analyzed using a Zeiss Sigma VP300 FE-SEM (Germany). The samples were mounted on conductive carbon tape and then sputter-coated with a thin layer of gold (~5 nm) prior to examination to ensure optimal conductivity and imaging quality.

#### 2.5.7. Brunauer-emmet-teller (BET) surface area

To determine the surface area of the biochar samples, the BET method was employed using a BET-201-A sorptometer (PMI, Tampa, FL, USA). Biochar samples were first degassed at 200°C under vacuum to eliminate moisture and any volatile substances. Nitrogen gas adsorption and desorption isotherms were then generated, enabling calculations of surface area, pore volume, and pore size distribution in accordance with BET theory. The Barrett–Joyner–Halenda (BJH) method was applied for pore size distribution analysis, while the t-plot method was used to estimate the micropore surface area.

#### 2.5.8. *Elemental analysis*

Elemental analysis of the waste textile and biochar was conducted using a Vario MICRO CHNS Analyzer, which uses combustion analysis at high temperatures in an oxygen-rich environment. The sample undergoes combustion, and the resulting oxide gases are analyzed using Thermal Conductivity Detectors (TCD) and Infrared Detectors. This method allows for the detection of carbon, hydrogen, nitrogen, and sulfur.

#### 2.5.9. *Determination of calorific value*

The calorific value of the WC and the biochar were determined using an oxygen bomb calorimeter according to the standard method ASTM D2015–96. The test measures the energy released by burning a weighed sample in oxygen under controlled conditions. The calorimeter was calibrated using benzoic acid, and the calorific value was calculated based on temperature measurements taken before, during, and after combustion.

#### 2.5.10. *Gas composition analysis*

The composition of the product gas from the pyrolysis process was analyzed using a biogas analyzer. Gas samples were collected in gas bags 15 min after the pyrolysis reactor reached the desired temperature. The biogas analyzer provided detailed information on the gas composition.

## 3. Results and discussion

### 3.1. *Effects of temperature on pyrolysis of waste cotton*

The pyrolysis temperature plays an important role in determining the product distribution during the pyrolysis of waste cotton, influencing the relative yields of biochar. At lower temperatures, such as 300°C, the pyrolysis process is relatively incomplete, resulting in a higher biochar yield due to limited decomposition of cellulose and other organic components. At this stage, the thermal energy primarily drives dehydration and minor carbonization, with initial aromatic structures forming through the carbonization of reaction intermediates (Bridgwater, 2012).

When the pyrolysis temperature increases to 350°C, significant decomposition of cellulose and hemicellulose occurs, leading to reduction in biochar yield. The temperature facilitates enhanced depolymerization and cleavage of glycosidic bonds, producing liquid intermediates and volatile compounds. Simultaneously, thermal reactions such as aromatization and the breakdown of larger molecules begin to dominate (Yang et al., 2007). As the temperature further rises to 500°C, the pyrolysis process shifts towards increased gasification, evidenced by a progressive decline in biochar yield. For instance, biochar yield was decreased from 37.5 % at 350°C to 26.7 % at 500°C.

This trend is attributed to intensified thermal cracking and secondary decomposition reactions, which convert larger molecular weight compounds into smaller, volatile gaseous products. Such processes also enhance the production of hydrogen, carbon monoxide, carbon dioxide, methane, making the process more favorable for gaseous output at elevated temperatures (Kambo and Dutta, 2015).

### 3.2. *Proximate analysis*

The proximate analysis of biochar derived from waste cotton (WC) at varying pyrolysis temperatures, as summarized in Table 1, reveals significant thermal and compositional transformations. These changes highlight the effects of increasing temperature on moisture content, ash content, volatile matter, and fixed carbon, providing insights into the thermal decomposition mechanisms and potential applications of the biochar.

The moisture content of biochar decreased progressively with increasing temperature, from 6.33 % in raw WC to 2.52 % at 500°C. This reduction is due to the evaporation of free and bound water during pyrolysis, as higher temperatures effectively break hydrogen bonds within the biomass structure. Lower moisture content enhances biochar's hydrophobicity and storage stability, making it suitable for applications where moisture is a limiting factor, such as solid fuels. Yang et al. (Yang et al., 2007) noted that reduced moisture content at higher pyrolysis temperatures improves the energy density of biochar, thereby increasing its combustion efficiency.

The ash content showed a significant increase, rising from 0.01 % in raw WC to 13.13 % at 500°C. This trend reflects the thermal degradation of organic matter, leaving behind mineral-rich residues. At higher temperatures, the decomposition of organic compounds results in the enrichment of inorganic constituents like potassium, calcium, and phosphorus, which contribute to the ash fraction. This is consistent with the findings of Leng et al. (Leng et al., 2019), who demonstrated that increasing pyrolysis temperatures result in higher ash content in biochar, which could enhance its value as a soil amendment. However, higher ash content may slightly reduce the calorific value of biochar when used as a fuel.

The volatile matter content decreased markedly from 34.33 % in raw WC to 15.70 % at 500°C, indicating the release of volatile organic compounds during pyrolysis. The sharp decline in volatile matter, particularly between 350°C and 400°C, corresponds to the major devolatilization phase, during which cellulose and hemicellulose decompose into lighter organic molecules. This reduction in volatile matter content enhances the thermal stability of the biochar. Zhang et al. (Zhang et al., 2010) observed a similar trend in the pyrolysis of lignocellulosic biomass, attributing the decrease in volatile matter to the conversion of labile organic compounds into gases and tar.

On the other hand, the fixed carbon content increased from 59.33 % in raw WC to 68.65 % at 500°C, reflecting the enrichment of thermally stable carbonaceous material as non-carbon elements like hydrogen and oxygen were volatilized. Fixed carbon content is a critical determinant of the energy content and reactivity of biochar, with higher values indicating greater energy density and combustion efficiency. The progressive increase in fixed carbon at higher temperatures aligns with the carbonization process, as reported by Cha et al. (Cha et al., 2016), where the thermal breakdown of biomass polymers concentrates the carbon-rich fraction.

These results demonstrate the influence of pyrolysis temperature on biochar properties, allowing its composition to be tailored for specific applications. Biochar produced at lower temperatures (350°C-400°C), with higher volatile matter content, is more reactive and suitable for

**Table 1**
Proximate analysis and effect of biochar yield with temperature.

| Temperature (°C) | Biochar yield (%) | Feed (g) | Retention time (min) | Proximate analysis | | | |
|---|---|---|---|---|---|---|---|
| | | | | Moisture content (%) | Ash content (%) | Volatile matter (%) | Fixed carbon (%) |
| WC | - | - | - | 6.33 | 0.01 | 34.33 | 59.33 |
| WC-300 | 50.50 | 30 | 60 | 5.46 | 1.94 | 26.68 | 65.92 |
| WC-350 | 37.50 | | | 4.70 | 2.87 | 24.77 | 67.66 |
| WC-400 | 33.80 | | | 3.94 | 5.21 | 22.82 | 68.03 |
| WC-450 | 29.95 | | | 3.20 | 8.33 | 19.95 | 68.52 |
| WC-500 | 26.70 | | | 2.52 | 13.13 | 15.70 | 68.65 |

applications requiring rapid combustion, such as residential heating. In contrast, biochar generated at higher temperatures (450°C-500°C), with reduced volatile matter and increased fixed carbon content, is ideal for slow-burning fuels, industrial furnaces, and long-term carbon sequestration. The ash-rich biochar produced at elevated temperatures may also serve as a nutrient source in agricultural applications. The proximate analysis trends confirm that increasing pyrolysis temperature enhances the carbonization of biochar while concentrating its mineral fraction.

### *3.3. Surface morphology*

The Field Emission Scanning Electron Microscopy (FESEM) analysis of waste cotton (WC) (a) and waste cotton derived biochar produced through pyrolysis at various temperatures reveals key morphological transformations. The SEM images of waste cotton and biochar were given in Fig. 1 A. In the figure a1 and a2 showed long, fibrous structures with diameters ranging from 10 to 30 µm, characteristic of natural cotton fibers (Gao et al., 2021).

The pyrolysis of WC at 350°C (Fig. 1 A b1, b2), the fibers fragmented into slightly smaller, plate-like particles with increased surface roughness, initiating changes that enhance the material's adsorption potential. The fiber diameter of the char remained approximately 10–20 mm which means that the biochar retained a structure closely resembling that of the original WC fibers (Pituello et al., 2015). However, some degradation and fiber shortening occurred due to moisture loss and the breakdown of volatile organic compounds. The thermal treatment at relatively low temperature resulted in increased surface roughness, indicating the beginning of structural changes that would enhance its properties for energy applications (Wang et al., 2024).

The pyrolysis at temperature 400–500°C (Fig. 1 c-d), the biochar undergoes significant degradation, resulting in small, granular aggregates with a compact, layered morphology. This also adopted a highly porous, honeycomb-like structure with irregular particles. Surface roughness increases with fiber diameter ranges from 100–200 nm, and numerous micropores and nanopores form, with pore sizes ranging from 30 to 50 nm. This enhanced porosity facilitated greater accessibility for adsorbates if applied in adsorption, indicating a potential for contaminant adsorption applications, while the substantial increase in surface area promoted catalytic activities (Lehmann and Joseph, 2024).

This increase in surface area also suggested enhanced combustion efficiency indicating potential for renewable energy applications (Szwaja et al., 2019). Overall, the FESEM analysis demonstrated the progressive transformation from fibrous cotton to a highly porous,

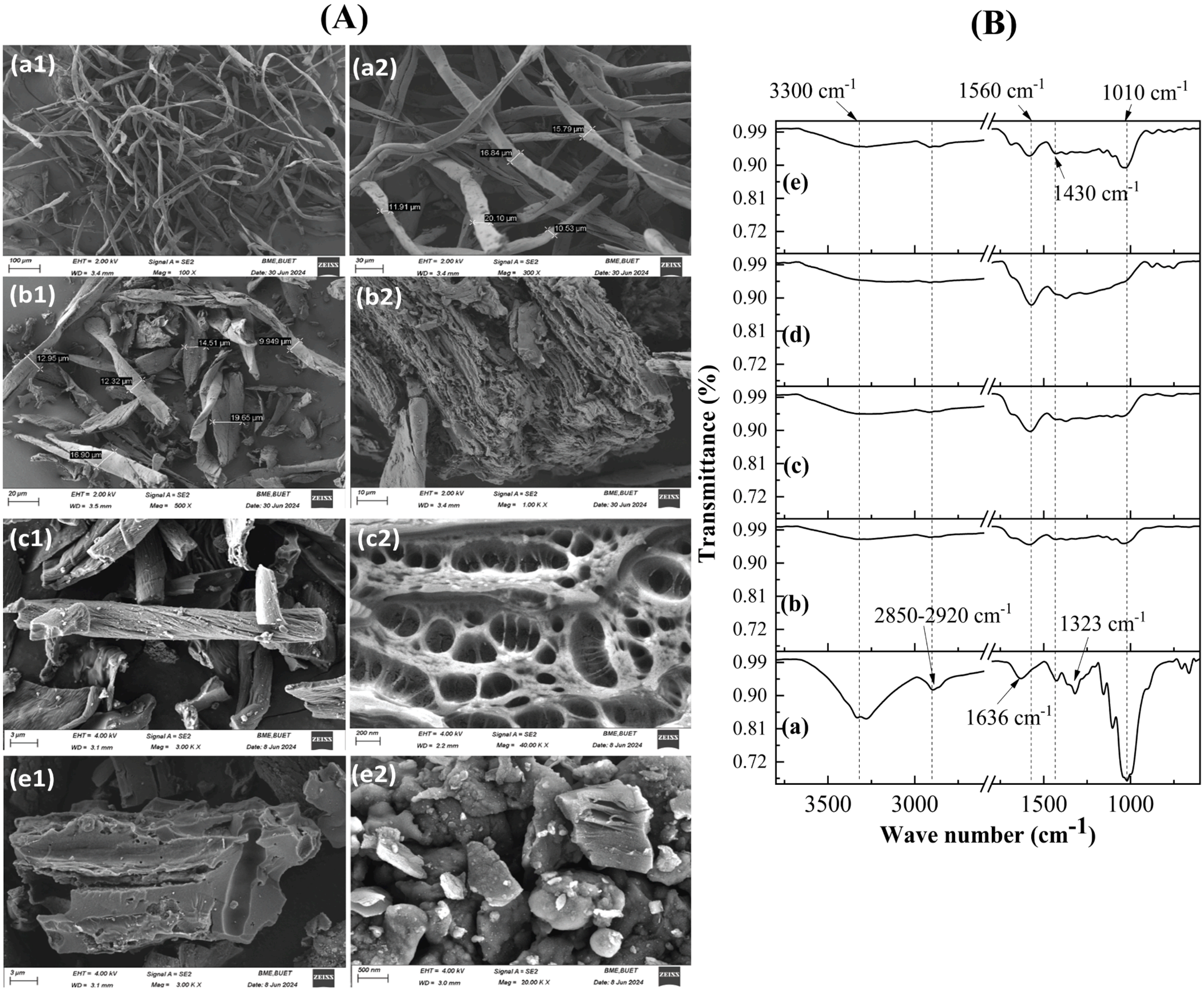

**Fig. 1.** Surface morphology (A) and FTIR spectra (B) of waste cotton and waste cotton pyrolyzed biochar. The labels represent: (a) waste cotton, (b) biochar produced at 350°C, (c) biochar produced at 400°C, (d) biochar produced at 450°C, and (e) biochar produced at 500°C.

carbonized material with increasing surface area and pore size, making the biochar suitable for energy and environmental applications.

### 3.4. FTIR study

Fourier Transform Infrared (FTIR) spectroscopy analysis has been instrumental in elucidating the compositional transformations during the pyrolysis of waste cotton into biochar across various temperatures and is presented in Fig. 1 (B). The initial FTIR spectrum of untreated waste cotton showed characteristic peaks indicative of its cellulosic nature. A broad absorption band around 3300 cm$^{-1}$ corresponded to the stretching vibrations of hydroxyl (-OH) groups, signifying the presence of cellulose and adsorbed moisture (Yang et al., 2007). Peaks in the 2850–2920 cm$^{-1}$ range were attributed to C-H stretching vibrations in aliphatic chains, further confirming the cellulosic structure (Sun et al., 2014). A distinct peak at 1636 cm$^{-1}$ was associated with the bending vibrations of adsorbed water molecules (Das et al., 2015). Additionally, the peak at 1323 cm$^{-1}$ was linked to C-O stretching vibrations in alcohols and carboxylic acids, while the strong absorption at 1010 cm$^{-1}$ corresponded to C-O-C stretching vibrations in the glycosidic linkages of cellulose (Das et al., 2015).

Upon pyrolysis at 350°C, there was a marked reduction in the intensity of the 3300 cm$^{-1}$ peak, indicating a decrease in -OH group content, suggesting partial dehydration and decomposition of cellulosic components. The peaks within the 2850–2920 cm$^{-1}$ region also diminished, reflecting the thermal degradation of aliphatic chains (Kumar and Mishra, 2022). The reduction in the 1636 cm$^{-1}$ peak intensity signifies to decreased adsorbed water content. Similarly, the significant decrease in the 1323 cm$^{-1}$ peak suggested the elimination of C-O containing functional groups, and the attenuation of the 1010 cm$^{-1}$ peak indicated the breakdown of glycosidic linkages (Qian et al., 2023).

As the pyrolysis temperature was elevated to 400°C, further reductions in the intensities of peaks associated with oxygen-containing functional groups were observed in the FTIR spectrum. The near absence of the 3300 cm$^{-1}$ peak implied a substantial loss of -OH groups. The decrease of the intensities of peaks in the 2850–2920 cm$^{-1}$ range indicated ongoing decomposition of aliphatic structures. At 450°C, the FTIR spectrum revealed minimal presence of oxygen-containing functional groups. The almost complete disappearance of the 3300 cm$^{-1}$ peak signified near-total removal of -OH groups (Das et al., 2015). The further reduction of aliphatic C-H stretching vibrations was evident. The peaks at 1636 cm$^{-1}$, 1323 cm$^{-1}$, and 1010 cm$^{-1}$ were barely detectable, suggesting substantial elimination of adsorbed water and C-O containing functional groups. Finally, at 500°C, the FTIR spectrum demonstrated the most pronounced reduction in oxygen-containing functional groups. The complete absence of the 3300 cm$^{-1}$ peak indicated the total removal of -OH groups. Aliphatic C-H stretching vibrations were nearly eradicated. The disappearance of peaks at 1636 cm$^{-1}$, 1323 cm$^{-1}$, and 1010 cm$^{-1}$ confirmed the comprehensive elimination of adsorbed water and C-O containing functional groups (Liu et al., 2019).

During the pyrolysis of cotton, the FTIR spectra showed a decrease in O–H stretching vibrations around 3574 cm$^{-1}$ and C-H stretching

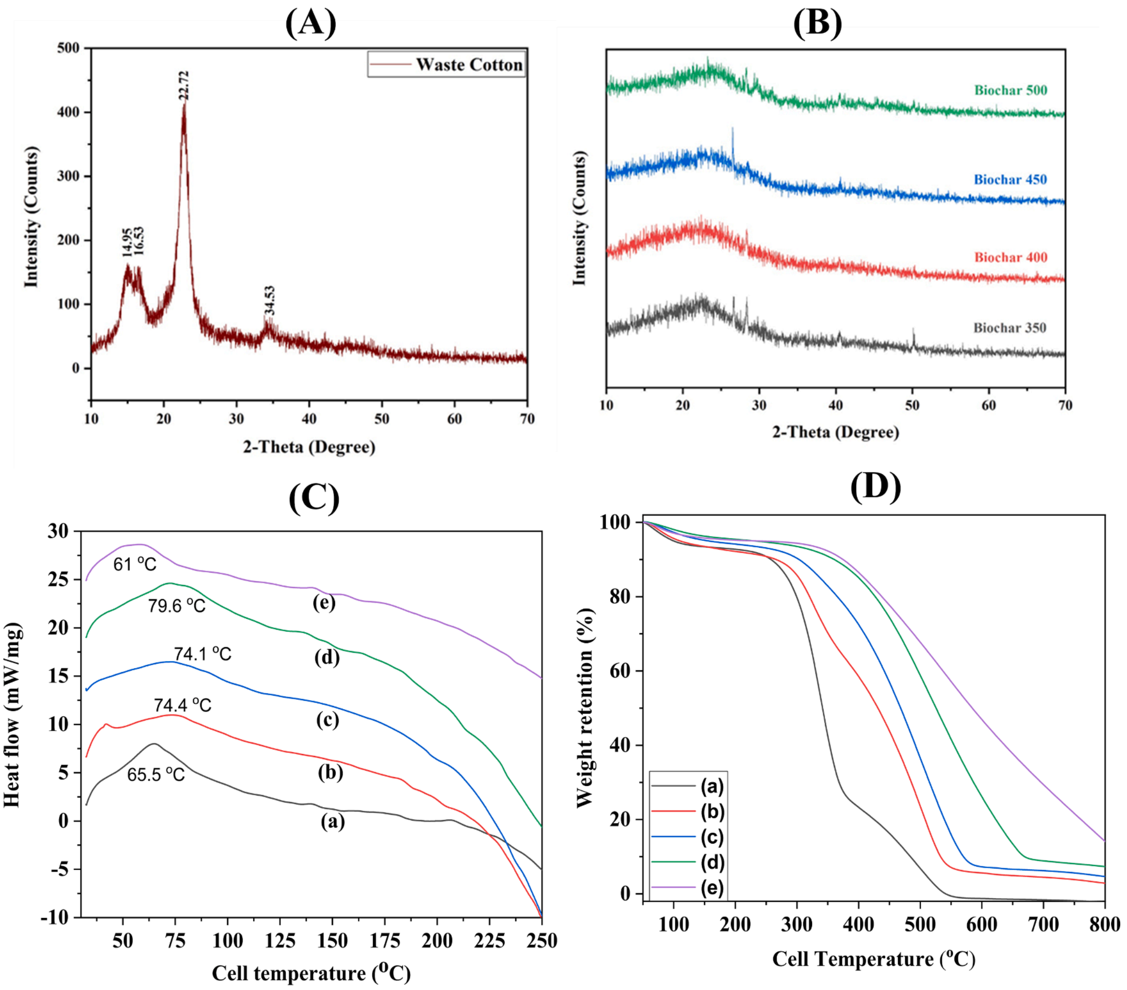

**Fig. 2.** Physicochemical Properties of Biochar Derived from Waste Cotton (A) XRD pattern of waste cotton; (B) XRD pattern of biochar derived from waste cotton at different pyrolysis temperatures; (C) DSC thermograms; and (D) TGA thermograms of waste cotton and its derived biochar. The labels represent: (a) waste cotton, (b) biochar produced at 350°C, (c) at 400°C, (d) at 450°C, and (e) at 500°C.

vibrations near 2919 $\mathrm{cm}^{-1}$, indicating the degradation of hydroxyl and aliphatic groups, respectively (Sun et al., 2014). The removal of specific oxygen-containing functional groups, such as hydroxyl (-OH), carboxyl (C=O), and ether (C-O-C) groups, during pyrolysis significantly influences the biochar's adsorptive properties and reactivity. The loss of hydrophilic -OH groups reduce the biochar's affinity for polar molecules, potentially diminishing its capacity to adsorb water and other polar substances (Islam et al., 2021). Conversely, the elimination of these oxygen-containing groups increases the biochar's hydrophobicity and surface area, which can enhance its adsorption potential for non-polar molecules (Islam et al., 2021).

### 3.5. *XRD analysis*

The X-ray diffraction (XRD) analysis of waste cotton and biochar produced at different pyrolysis temperatures reveals critical insights into the structural changes during the pyrolysis process and is shown in Fig. 2 (A-B). The X-ray Diffraction (XRD) pattern of the waste cotton initially revealed a semi-crystalline structure, characteristic of cellulose I. The diffractogram showed a prominent peak at approximately $2\theta = 22.72^\circ$, serving as an assay mark for the crystalline form of cellulose, along with minor peaks at around 14.95° and 16.53°, further confirming the presence of cellulose I. The broadness of these peaks indicated that the crystalline domains within the waste cotton were relatively small and imperfect, a common trait for natural cellulosic materials.

The XRD of biochar produced from waste cotton (WC) pyrolyzed at temperatures ranging from 350°C to 500°C revealed notable structural transformations. At 350°C, the biochar exhibits a broad, low-intensity peak in the 20–30° 2θ range, indicative of a predominantly amorphous carbon structure. This suggests that initial carbonization at this temperature results in a disordered carbon matrix with minimal crystalline domains (Khalid and Inam, 2024).

As the pyrolysis temperature increases to 400°C and 450°C, there is a noticeable enhancement in peak intensity within the same 20–30° 2θ region. This trend implies a progressive increase in structural ordering, with the development of more organized carbon arrangements (Dobariya et al., 2022). However, the persistence of broad peaks indicates that the material retains a significant degree of amorphousness.

At 500°C, the XRD pattern showed a further intensified peak around 20–30° 2θ, suggesting the formation of larger or more numerous graphitic-like structures. Despite this increased ordering, the biochar does not achieve the sharp, well-defined peaks characteristic of highly crystalline graphite, indicating that the material remains largely amorphous with some semi-crystalline regions. These structural evolutions are consistent with findings from other studies (Tomczyk et al., 2020). For instance, research has demonstrated that pyrolysis at higher temperatures leads to increased ordering within the carbon matrix, yet the biochar remains predominantly amorphous even at elevated temperatures. Additionally, studies have shown that biochars produced at temperatures up to 500°C exhibit broad XRD peaks, reflecting a disordered carbon structure.

The observed increase in structural ordering with rising pyrolysis temperatures has significant implications for the biochar's properties and potential applications. Enhanced ordering can improve electrical conductivity, making the biochar more suitable for applications in energy storage devices, such as supercapacitors and batteries, where efficient charge transport is essential (Liu et al., 2019). Moreover, the combination of a porous structure, surface functional groups, and improved conductivity renders the biochar a promising candidate for electrocatalysis in reactions like oxygen reduction and hydrogen evolution. Therefore, tailoring the pyrolysis temperature allows for the optimization of biochar properties to meet specific requirements in renewable energy applications.

### 3.6. *Thermal properties of biochar*

#### 3.6.1. *Thermogravimetric analysis (TGA)*

According to the TGA in Fig. 2(C), WC loses its 100 % weight at about 550°C, while the TGA curves clearly demonstrate that the biochar exhibits significantly higher thermal stability compared to waste cotton. This increased thermal stability can be attributed to the carbonization process during pyrolysis, which leads to the formation of aromatic carbon structures and elemental carbon (Leng and Huang, 2018). The formation of these stable structures imparts greater resistance to thermal degradation, resulting in a reduced mass loss during heating. The biochar produced at 350°C (b) showed a moderate increase in thermal stability compared to (a). It retained 3.1 % of its mass after heating to 800°C, indicated a significant reduction in mass loss compared to WC. This suggests that the carbonization process at this temperature has begun to influence the thermal properties of the material (Kambo and Dutta, 2015). As the pyrolysis temperature increases, the thermal stability of the biochar further improves.

The biochar produced at 400°C (c) and 450°C (d) exhibit even lower mass loss at 800°C, retaining 4.9 % and 10.2 % of their initial mass, respectively. This indicated a more extensive formation of aromatic carbon structures and elemental carbon, leading to enhanced thermal resistance. The biochar produced at 500°C (e) showed the highest thermal stability among all samples. It retains 14.7 % of its mass after heating to 800°C, demonstrating significant resistance to thermal degradation. This high thermal stability can be attributed to the formation of highly stable aromatic carbon structures and the presence of inorganic matter, which acts as a thermal barrier. The increased thermal stability and reduced mass loss of the biochar have significant implications for their potential applications.

### 3.7. *Differential scanning calorimetric (DSC) analysis*

The Differential Scanning Calorimetry (DSC) analysis of waste cotton and its derived biochar at varying temperatures (as shown in Fig. 2 (C)) revealed distinct thermal transitions, providing insights into their structural and chemical transformations. The DSC curve of waste cotton exhibited a broad endothermic peak centered around 65.5°C, which was attributed to the dehydration of hydrophilic components, primarily due to the evaporation of absorbed moisture and the release of bound water from the amorphous regions of cellulose (Liu et al., 2019). Upon pyrolysis at 350°C and 400°C (Fig 2(C) b and c), the resulting biochar showed a similar but less pronounced endothermic peak shifted to 74.4°C, the endothermic peak shifted to 74.4°C and became more defined, indicating a change in the nature of the remaining volatile components or a more uniform thermal transition within the biochar structure, possibly related to the release of low molecular weight organic compounds (Zhang et al., 2023).

Further increasing the pyrolysis temperature to 450°C resulted in a continued shift of the endothermic peak to 74.1°C with similar sharpness. This shift suggested the stabilization of the biochar structure, possibly due to the removal of less thermally stable oxygen-containing functional groups, such as hydroxyl (-OH) and carboxyl (-COOH) groups, which decompose at moderate temperatures (Tomczyk et al., 2020). At 500°C, the endothermic peak further shifted to 79.6°C and became broader, with a noticeable increase in heat flow. This indicated a more complex thermal transition, likely involving the structural rearrangement of the carbonaceous matrix and the decomposition of thermally stable functional groups, such as lactones and carbonyl groups (Usevičiūtė and Baltrėnaitė-Gedienė, 2021). The higher temperature required for this transition suggested that biochar produced at 500°C had a more thermally stable structure compared to those produced at lower temperatures.

In addition to the endothermic peaks, all biochar samples exhibited a gradual exothermic trend starting around 225°C, which was attributed to the oxidative decomposition of the remaining carbonaceous material in the presence of air. The onset of this exotherm indicated the thermal stability limit of the biochar in an oxidizing environment. The biochar produced at 500°C showed the highest exothermic heat flow, suggesting a higher degree of carbonization and a larger amount of oxidizable carbon present (Chen et al., 2020). This exothermic behavior corresponded to the combustion of more graphitic and thermally stable carbon structures, which is crucial for applications in thermochemical energy conversion, such as combustion and gasification (Jagnade et al., 2023).

### 3.8. BET analysis

The Brunauer-Emmett-Teller (BET) analysis of biochar produced from co-pyrolysis of sludge and cotton stalk at 400°C and 500°C revealed significant differences in surface area and porosity, which are key factors in determining its suitability as a solid fuel. The BET surface area, pore structures, and pore size results are presented in Table 2. At 400°C, the BET surface area was 156.25 $m^2/g$, while at 500°C, it increased to 225.24 $m^2/g$. This increase is attributed to enhanced biomass decomposition at higher temperatures, which promotes the formation of a more porous structure through the release of volatile gases, creating both micropores (<2 nm) and mesopores (2–50 nm) (Kambo and Dutta, 2015).

The pore size distribution showed a clear trend: biochar produced at 400°C had pores in the range of 1.0–2.5 nm, whereas at 500°C, the range expanded to 1.1–2.7 nm, indicating a more developed and interconnected pore network. This increased porosity improves the biochar's combustion efficiency, as higher surface area provides more active sites for reactions, facilitating better oxygen diffusion and reactivity, which are critical for solid fuel performance (Chen et al., 2014).

The addition of sludge further enhances the pore structure, particularly in the 3–80 nm range, compared to the non-porous cotton stalk biochar, contributing to a more porous and reactive biochar at higher pyrolysis temperatures (Wang et al., 2024). This improved porosity and surface area make biochar from 500°C particularly suitable for high-performance energy production systems.

### 3.9. Elemental analysis

The elemental analysis data in Table 3 revealed significant shifts in the elemental composition of waste cotton (WC) after pyrolysis, with changes becoming more pronounced at higher pyrolysis temperatures. These shifts highlighted the transformation of WC to WCB, with an increase in carbon content and a reduction in other elements such as oxygen, hydrogen, sulfur, and nitrogen. WC initially has a carbon content of 41.95 %. However, after pyrolysis, the carbon percentage in biochar increases significantly with temperature, reaching a high of 73.62 % at 500°C. This increase indicated that pyrolysis, especially at elevated temperatures, promotes carbonization, concentrating carbon while eliminating more volatile elements (Liu et al., 2017).

Oxygen content in waste cotton begins at 46.7 %, a relatively high level due to organic matter and moisture. During pyrolysis, oxygen levels decrease sharply, with biochar at 500°C containing only 13.27 % oxygen. This reduction is a result of deoxygenation as volatile compounds are released, yielding a more stable biochar with a lower moisture affinity, which is favorable for use as a solid fuel (Lee et al., 2023). Hydrogen content also decreased notably, from 6.06 % in WC to 2.79 % in WCB-500 pyrolyzed at 500°C. The decrease of both hydrogen and oxygen suggests less oxygen-containing functional groups at high-temperature biochar, with enhanced stability and calorific value, making it a better energy source (Li et al., 2023).

**Table 2**

BET surface area and porosity of biochar.

| Name | Method & Temp | Surface area $m^2/g$ | Pore structure | Pore size nm | References |
|---|---|---|---|---|---|
| WC-400 | Pyrolysis (400°C) | 156.25 | Micro & mesopores | 1.0–2.5 | This work |
| WC-500 | Pyrolysis (500°C) | 225.24 | | 1.1–2.7 | |
| GSC-400 | Co-pyrolysis (400°C) | 1.58 | Micro & mesopores | 28.58 | (Wang et al., 2024) |
| GSC-500 | Co-pyrolysis (400°C) | 5.49 | | 13.69 | |

Sulfur content reduced from 0.80 % in waste cotton to 0.29 % in WCB-500 pyrolyzed at 500°C. This decrease in sulfur indicates that pyrolysis can reduce sulfur emissions, an environmental benefit that makes high-temperature biochar an environmentally friendly fuel. The sulfur content of biochar at 350°C and above is well below the typical 5 % threshold, supporting its suitability as a solid fuel alternative that meets environmental standards (Goswami et al., 2021).

Nitrogen content slightly varies across the temperatures, with the N/C ratio peaking at 0.0466 in biochar produced at 400°C. This indicated that biochar produced at this temperature could retain nitrogen more effectively, which can be beneficial for applications in soil amendment and environmental remediation. The H/C and O/C ratios both decrease as pyrolysis temperature rises, indicating a progression toward more stable, aromatic biochar. Lower H/C ratios suggest increased aromaticity, which improves the biochar's resistance to microbial degradation. Lower O/C ratios imply a more carbon-rich, stable structure, further enhancing the biochar's durability and energy density (Goswami et al., 2021).

Biochar produced at different temperatures can be compared with coal types. For instance, biochar from lower pyrolysis temperatures (e.g., 300°C) has characteristics like lignite coal, with relatively high oxygen content and moderate carbon. In contrast, biochar produced at 400–500°C resembles bituminous coal, showing high carbon and low sulfur levels. These characteristics make high-temperature biochar a viable, sustainable alternative to bituminous coal as a solid fuel (Babin et al., 2021). The results revealed that increasing the pyrolysis temperature results in a biochar with higher carbon content, lower H/C and O/C ratios, and reduced sulfur, positioning it as a more stable, energy-dense, and environmentally friendly fuel option.

### 3.10. Calorific value

The calorific value of biochar, a measure of its energy potential, is profoundly influenced by the pyrolysis temperature due to changes in its chemical composition and structural properties (Yang et al., 2007). The calorific value of biochar produced from raw cotton waste in the spinning industry by pyrolysis was a critical factor in determining its potential as a solid fuel. The values provided for different pyrolysis temperatures (WC-300, WC-350, WC-400, WC-450, and WC-500) reflected the impact of temperature on the energy content of the resulting biochar. The results clearly showed that the calorific value of the biochar increased with the pyrolysis temperature, peaking at 400°C. This trend was consistent with the general understanding of pyrolysis chemistry and its influence on biochar characteristics (Zhang et al., 2020).

Pyrolysis is a thermochemical process where organic materials are heated in the absence of oxygen, leading to the breakdown of complex molecules into simpler compounds. During pyrolysis, the temperature plays a significant role in determining the composition and structure of the resulting biochar. At low pyrolysis temperatures, around 300°C, pyrolysis primarily drove off volatile components such as water, $CO_2$, and organic volatiles, but the carbon content of the biochar remained relatively low. As a result, the calorific value was moderate (22.0 MJ/kg). The biochar at this temperature tended to have a higher oxygen content and lower carbon content, which limited its energy density compared to biochar produced at higher temperatures (Tomczyk et al., 2020, Amalina et al., 2022).

At medium pyrolysis temperatures, between 350°C and 400°C, the

**Table 3**
Elemental compositions of waste cotton, biochar, and comparison with coal.

| Sample name | C (%) | N (%) | H (%) | O (%) | S (%) | N/C | H/C | O/C |
|---|---|---|---|---|---|---|---|---|
| WC | 41.95 | 2.19 | 6.06 | 46.70 | 0.80 | 0.0522 | 0.1445 | 1.1132 |
| WCB (300°C) | 53.13 | 2.30 | 5.93 | 34.18 | 0.58 | 0.0433 | 0.1116 | 0.6433 |
| WCB (350°C) | 66.32 | 2.24 | 5.44 | 21.22 | 0.39 | 0.0338 | 0.0820 | 0.3200 |
| WCB (400°C) | 67.63 | 3.15 | 4.35 | 18.2 | 0.35 | 0.0466 | 0.0643 | 0.2691 |
| WCB (450°C) | 70.78 | 2.53 | 3.49 | 15.95 | 0.34 | 0.0357 | 0.0493 | 0.2253 |
| WCB (500°C) | 73.62 | 2.83 | 2.79 | 13.27 | 0.29 | 0.0384 | 0.0379 | 0.1802 |
| Lignite coal (Ghetti, 1986) | 61.30 | 1.10 | 5.40 | 30.80 | 1.40 | 0.0179 | 0.0881 | 0.5024 |
| Bituminous coal (Ghetti, 1986) | 75.90 | 1.50 | 5.30 | 12.60 | 4.70 | 0.0198 | 0.0698 | 0.1660 |

conversion of cellulose, hemicellulose, and lignin into more stable carbon structures was more complete. This led to a biochar with a higher carbon content, fewer volatiles, and lower oxygen content, significantly enhancing its calorific value. The calorific value peaked at 400°C (27.31 MJ/kg), reflecting an optimal balance between carbonization and the structural integrity of the biochar. The biochar produced at this temperature was highly suitable for use as a solid fuel due to its relatively high energy content (Shen et al., 2019).

At high pyrolysis temperatures, above 450°C, the biochar continued to undergo further carbonization, and the structural integrity of the carbon matrix improved. However, higher temperatures could lead to the formation of graphite-like structures, which might reduce the biochar's reactivity and energy release potential when combusted. As observed, the calorific value at 450°C (27.02 MJ/kg) and 500°C (27.29 MJ/kg) was slightly lower than at 400°C, possibly due to the reduced reactivity of the biochar at these higher temperatures (Selvarajoo and Oochit, 2020).

The calorific value of biochar was an essential parameter for its potential use as a solid fuel. Biochar with a high calorific value indicated a higher energy content per unit mass, making it a more effective fuel for combustion. The values presented suggested that biochar produced at 300°C had a moderate calorific value but was still suitable for some energy applications. The 350°C-400°C range produced biochar with an excellent calorific value, making it highly suitable as a solid fuel for combustion. This biochar had a good balance of energy content and carbon structure. Biochar produced at 450°C-500°C still retained a relatively high calorific value, but its structural properties may have made it less reactive as a fuel, reducing its efficiency compared to the biochar from the 350°C-400°C range (Pariyar et al., 2020).

The relationship between pyrolysis temperature and biochar characteristics has been well documented in various studies. The calorific value of biochar increased as the pyrolysis temperature rose due to increased carbon content and decreased oxygenated functional groups. The higher pyrolysis temperatures led to a greater degree of carbonization, resulting in biochar with higher calorific values, making it a better fuel source (Pariyar et al., 2020). The calorific value of biochar produced from raw cotton waste increased with temperature, with the highest values achieved at 350–400°C. This temperature range provided biochar with an optimal carbon content and energy density, making it suitable as a solid fuel. The slightly lower calorific values at 450°C and 500°C suggested that although the biochar remained energy-dense, its suitability as a fuel might be reduced due to lower reactivity. Therefore, pyrolysis at 400°C was considered the most efficient for producing biochar with the best balance of energy content and fuel properties (Tomczyk et al., 2020).

**Table 4**
Composition of pyrolysis product gas.

| Pyrolysis Temperature (°C) | $N_2$ (%) | $CH_4$ (%) | $CO_2$ (%) | CO (%) |
|---|---|---|---|---|
| 300°C | 98.55 | 0.7 | 0.70 | 0.05 |
| 350°C | 98.94 | 0.8 | 0.18 | 0.08 |
| 400°C | 97.37 | 2.4 | 0.14 | 0.09 |
| 450°C | 95.47 | 4.2 | 0.10 | 0.23 |
| 500°C | 94.15 | 5.1 | 0.10 | 0.65 |

### *3.11. Gas composition analysis*

The analysis of the product gas composition from the pyrolysis of waste cotton, as presented in Table 4, revealed a clear relationship between pyrolysis temperature and the composition of the gaseous products. Notably, nitrogen ($N_2$) constituted most of the gas at all temperatures, decreasing only slightly as the temperature increased from 300°C to 500°C. At 500°C, $N_2$ accounted for 94.15 % of the product gas, compared to 98.55 % at 300°C. This high proportion of nitrogen, which originated from the inert atmosphere maintained during the pyrolysis process, significantly diluted the combustible gas fraction, reducing the potential of the gas for energy recovery. The inert nitrogen atmosphere prevented complete oxidation and facilitated the thermal degradation of the biomass, yet it limited the presence of oxidizing agents necessary for more efficient gas production (Rajendiran et al., 2023).

The methane ($CH_4$) content showed a marked increase as the pyrolysis temperature rose, from 0.7 % at 300°C to 5.1 % at 500°C. This rise in methane production was attributed to the thermal degradation of cellulose, hemicellulose, and lignin in the waste cotton, as well as methanation reactions favored by the higher pyrolysis temperatures. Methane is a key component of syngas and contributes to the calorific value of the gaseous product, making it crucial for solid fuel applications (Zhang et al., 2015). Although the overall methane concentration remained relatively low, its increase at elevated temperatures indicated that optimizing the pyrolysis process could improve the energy yield of the product gas.

Carbon monoxide (CO) also exhibited a notable rise, increasing from 0.05 % at 300°C to 0.65 % at 500°C. Carbon monoxide is another significant energy carrier in the product gas and its increased presence with rising temperature suggested enhanced potential for syngas production. However, the low CO concentration overall indicated that additional modifications, such as introducing air or oxygen, might be necessary to increase CO production and improve the gas's utility as a fuel (Jayakumar et al., 2023). Conversely, the carbon dioxide ($CO_2$) content in the product gas decreased as the temperature increased, dropping from 0.70 % at 300°C to 0.10 % at 500°C.

This reduction was likely due to the consumption of available oxygen in the system and the dominance of CO formation reactions at higher temperatures. The lower $CO_2$ concentration is favorable from an energy perspective, as it indicates a higher proportion of combustible gases in the product gas at elevated temperatures (Jayakumar et al., 2023). $CO_2$ does not contribute to the calorific value of the gas, and its reduction improves the overall energy potential of the product gas. Despite these changes in gas composition, the dominant presence of nitrogen, which remained above 94 % even at 500°C, limited the energy recovery potential of the product gas. As a result, the gaseous products from the pyrolysis of waste cotton under nitrogen-rich conditions were not particularly conducive to energy recovery or syngas production (Lehmann and Joseph, 2015).

While the increased production of methane and carbon monoxide at higher temperatures is promising for energy recovery, the high nitrogen content significantly limits the overall energy potential of the product gas. To improve the energy yield, strategies such as optimizing the pyrolysis process, introducing oxidizing agents, or separating the valuable components from the nitrogen-rich gas stream could be considered.

The analysis of the product gas composition reveals that while pyrolysis of waste cotton can produce valuable gaseous products, the high nitrogen content limits their energy recovery potential. To enhance the energy yield, future research should focus on optimizing the pyrolysis conditions, exploring alternative gasification techniques, and developing efficient gas separation and purification technologies.

## 4. Conclusion

This study demonstrated the efficient conversion of waste cotton (WC) into biochar through pyrolysis and the results showed that higher pyrolysis temperatures enhanced biochar's fixed carbon content and calorific value while reducing volatile matter and moisture content. The calorific value peaked at 400°C (27.31 MJ/kg), making it a viable alternative to conventional solid fuels. Despite these promising findings, some limitations remain. The biochar yield decreased with temperature, which may impact large-scale applications. Additionally, the high ash content at elevated temperatures could affect fuel efficiency. Future research should focus on optimizing pyrolysis parameters to maximize biochar yield while maintaining desirable properties. Further studies on biochar functionalization for environmental applications, such as wastewater treatment and soil amendment, could expand its utility. Integrating this approach into industrial-scale textile cotton waste management can contribute to sustainable waste valorization, carbon sequestration, and renewable energy development, aligning with circular economy goals and climate change mitigation strategies.

## CRediT authorship contribution statement

**Fatema Tujjohra:** Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Md. Ehsanul Haque:** Writing – original draft, Software, Resources, Methodology, Investigation, Funding acquisition, Data curation. **Md. Abdul Kader:** Writing – review & editing, Supervision, Resources, Data curation. **Mohammed Mizanur Rahman:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.clce.2025.100161.

## Data availability

No data was used for the research described in the article.

## References

Amalina, F., Abd Razak, A.S., Krishnan, S., Sulaiman, H., Zularisam, A., Nasrullah, M., 2022. Biochar production techniques utilizing biomass waste-derived materials and environmental applications–A review. J. Hazard. Mater. Adv. 7, 100134.

Babin, A., Vaneeckhaute, C., Iliuta, M.C., 2021. Potential and challenges of bioenergy with carbon capture and storage as a carbon-negative energy source: A review. Biomass Bioenergy 146, 105968.

Basu, A., 2003. Intermill study of quality of cotton yarns. Asian Textile J.-Bombay- 12 (7), 63–68.

Brassard, P., Godbout, S., Lévesque, V., Palacios, J.H., Raghavan, V., Ahmed, A., Hogue, R., Jeanne, T., Verma, M., 2019. Biochar for soil amendment, char and carbon materials derived from biomass. Elsevier 109–146.

Bridgeman, T., Jones, J., Shield, I., Williams, P., 2008. Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties. Fuel 87 (6), 844–856.

Bridgwater, A.V., 2012. Review of fast pyrolysis of biomass and product upgrading. Biomass Bioenergy 38, 68–94.

Cha, J.S., Park, S.H., Jung, S.-C., Ryu, C., Jeon, J.-K., Shin, M.-C., Park, Y.-K., 2016. Production and utilization of biochar: A review. J. Industr. Eng. Chem. 40, 1–15.

Chen, T., Zhang, Y., Wang, H., Lu, W., Zhou, Z., Zhang, Y., Ren, L., 2014. Influence of pyrolysis temperature on characteristics and heavy metal adsorptive performance of biochar derived from municipal sewage sludge. Bioresour. Technol. 164, 47–54.

Chen, Q., Tan, X., Liu, Y., Liu, S., Li, M., Gu, Y., Zhang, P., Ye, S., Yang, Z., Yang, Y., 2020. Biomass-derived porous graphitic carbon materials for energy and environmental applications. J. Mater. Chem. A 8 (12), 5773–5811.

Das, O., Sarmah, A.K., Bhattacharyya, D., 2015. A novel approach in organic waste utilization through biochar addition in wood/polypropylene composites. Waste Manag. 38, 132–140.

Dobariya, U., Gojiya, D., Makavana, J., Kelaiya, S., Gadhiya, G., Dulawat, M., Vaja, K., Chauhan, P., 2022. Influence of temperature on the production of biochar from cotton and Castor feed stalk in a pyrolysis process. Curr. World Environ. 17 (3), 634.

Esteve-Turrillas, F.A., de La Guardia, M., 2017. Environmental impact of Recover cotton in textile industry. Res., Conserv. Recycl. 116, 107–115.

Gao, L., Li, Z., Yi, W., Li, Y., Zhang, P., Zhang, A., Wang, L., 2021. Impacts of pyrolysis temperature on lead adsorption by cotton stalk-derived biochar and related mechanisms. J. Environ. Chem. Eng. 9 (4), 105602.

Ghetti, P., 1986. DTG combustion behaviour of coal: correlations with proximate and ultimate analysis data. Fuel 65 (5), 636–639.

Goswami, M., Pant, G., Mansotra, D.K., Sharma, S., Joshi, P., 2021. Biochar: a carbon negative technology for combating climate change. Adv. Carbon Capture Utiliz. 251–272.

Hamawand, I., Sandell, G., Pittaway, P., Chakrabarty, S., Yusaf, T., Chen, G., Seneweera, S., Al-Lwayzy, S., Bennett, J., Hopf, J., 2016. Bioenergy from cotton industry wastes: a review and potential. Renew. Sustain. Energy Rev. 66, 435–448.

Haslinger, S., Hummel, M., Anghelescu-Hakala, A., Määttänen, M., Sixta, H., 2019. Upcycling of cotton polyester blended textile waste to new man-made cellulose fibers. Waste Manag. 97, 88–96.

Hoang, A.T., Ong, H.C., Fattah, I.R., Chong, C.T., Cheng, C.K., Sakthivel, R., Ok, Y.S., 2021. Progress on the lignocellulosic biomass pyrolysis for biofuel production toward environmental sustainability. Fuel Process. Technol. 223, 106997.

Islam, M.S., Kwak, J.-H., Nzediegwu, C., Wang, S., Palansuriya, K., Kwon, E.E., Naeth, M. A., El-Din, M.G., Ok, Y.S., Chang, S.X., 2021. Biochar heavy metal removal in aqueous solution depends on feedstock type and pyrolysis purging gas. Environ. Pollut. 281, 117094.

Jagnade, P., Panwar, N.L., Agarwal, C., 2023. Experimental investigation of kinetic parameters of bamboo and bamboo biochar using thermogravimetric analysis under non-isothermal conditions. BioEnergy Res. 16 (2), 1143–1155.

Jayakumar, M., Hamda, A.S., Abo, L.D., Daba, B.J., Prabhu, S.V., Rangaraju, M., Jabesa, A., Periyasamy, S., Suresh, S., Baskar, G., 2023. Comprehensive review on lignocellulosic biomass derived biochar production, characterization, utilization and applications. Chemosphere, 140515.

Kambo, H.S., Dutta, A., 2015. A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. Renew. Sustain. Energy Rev. 45, 359–378.

Khalid, U., Inam, M.A., 2024. The influence of pyrolysis temperature on the performance of cotton stalk biochar for hexavalent chromium removal from wastewater. Water, Air, Soil Pollut. 235 (2), 114.

Koszewska, M., 2019. Circular economy in textiles and fashion-the role of a consumer, Circular economy in textiles and apparel. Elsevier 183–206.

Kumar, A., Mishra, R.K., 2022. Pyrolysis of low-value waste miscanthus grass: physicochemical characterization, pyrolysis kinetics, and characterization of pyrolytic end products. Process Safet. Environ. Protect. 163, 68–81.

Lee, J., Kim, S., You, S., Park, Y.-K., 2023. Bioenergy generation from thermochemical conversion of lignocellulosic biomass-based integrated renewable energy systems. Renew. Sustain. Energy Rev. 178, 113240.

Lehmann, J., Joseph, S., 2015. Biochar for environmental management: an introduction, Biochar for environmental management. Routledge 1–13.

Lehmann, J., Joseph, S., 2024. Biochar for environmental management: science, technology and implementation. Taylor & Francis.

Leng, L., Huang, H., 2018. An overview of the effect of pyrolysis process parameters on biochar stability. Bioresour. Technol. 270, 627–642.

Leng, L., Huang, H., Li, H., Li, J., Zhou, W., 2019. Biochar stability assessment methods: a review. Sci. Total Environ. 647, 210–222.

Li, Y., Gupta, R., Zhang, Q., You, S., 2023. Review of biochar production via crop residue pyrolysis: development and perspectives. Bioresour. Technol. 369, 128423.

Li, Z., Shi, L., Liang, D., Li, F., Wei, L., Li, W., Zha, X., 2025. Study on the hydrocarbon-rich bio-oil from catalytic fast co-pyrolysis cotton stalk and polypropylene over alkali-modified HZSM-5. Ind. Crops. Prod. 224, 120352.

Liu, W.-J., Li, W.-W., Jiang, H., Yu, H.-Q., 2017. Fates of chemical elements in biomass during its pyrolysis. Chem. Rev. 117 (9), 6367–6398.

Liu, W., Liu, S., Liu, T., Liu, T., Zhang, J., Liu, H., 2019. Eco-friendly post-consumer cotton waste recycling for regenerated cellulose fibers. Carbohydr. Polym. 206, 141–148.

Liu, W.-J., Jiang, H., Yu, H.-Q., 2019. Emerging applications of biochar-based materials for energy storage and conversion. Energy Environ. Sci. 12 (6), 1751–1779.

Lord, P.R., 2003. Handbook of yarn production: Technology, science and economics. Elsevier.

Luo, L., Wang, J., Lv, J., Liu, Z., Sun, T., Yang, Y., Zhu, Y.-G., 2023. Carbon sequestration strategies in soil using biochar: advances, challenges, and opportunities. Environ. Sci. Technol. 57 (31), 11357–11372.

Nanda, S., Berruti, F., 2021. Thermochemical conversion of plastic waste to fuels: a review. Environ. Chem. Lett. 19 (1), 123–148.

Negm, M., Sanad, S., 2020. Cotton fibres, picking, ginning, spinning and weaving, Handbook of Natural Fibres. Elsevier, pp. 3–48.

Niinimäki, K., Peters, G., Dahlbo, H., Perry, P., Rissanen, T., Gwilt, A., 2020. The environmental price of fast fashion. Nat. Rev. Earth Environ. 1 (4), 189–200.

Pariyar, P., Kumari, K., Jain, M.K., Jadhao, P.S., 2020. Evaluation of change in biochar properties derived from different feedstock and pyrolysis temperature for environmental and agricultural application. Sci. Total Environ. 713, 136433.

Parthasarathy, P., Al-Ansari, T., Mackey, H.R., Narayanan, K.S., McKay, G., 2022. A review on prominent animal and municipal wastes as potential feedstocks for solar pyrolysis for biochar production. Fuel 316, 123378.

Peighambardoust, S.J., Hamdi, A., Pakdel, P.M., Peighambardoust, N.S., 2025. Elimination of Cu2+ ions from aqueous solutions utilizing a walnut shell biochar/CoFe2O4/ZIF-7 nanocomposite adsorbent. Inorg. Chem. Commun. 173, 113797.

Peighambardoust, S.J., Mahdavi, Z., Gholizadeh, M., Foroutan, R., Ramavandi, B., 2025. Pyrolytic carbon/cloisite 30B/ZnFe2O4 as reclaimable magnetic nanocomposite for methylene blue decontamination. Colloid. Surf. A 704, 135543.

Pensupa, N., Leu, S.-Y., Hu, Y., Du, C., Liu, H., Jing, H., Wang, H., Lin, C.S.K., 2018. Recent trends in sustainable textile waste recycling methods: current situation and future prospects. Chem. Chem. Technol. Waste Valoriz. 189–228.

Pituello, C., Francioso, O., Simonetti, G., Pisi, A., Torreggiani, A., Berti, A., Morari, F., 2015. Characterization of chemical–physical, structural and morphological properties of biochars from biowastes produced at different temperatures. J. Soils. Sediments. 15, 792–804.

Qian, S., Zhou, X., Fu, Y., Song, B., Yan, H., Chen, Z., Sun, Q., Ye, H., Qin, L., Lai, C., 2023. Biochar-compost as a new option for soil improvement: application in various problem soils. Sci. Total Environ. 870, 162024.

Rachiq, T., Abrouki, Y., Mabrouki, J., Samghouli, N., Fersi, C., Rahal, S., El Hajjaji, S., 2021. Evaluation of the efficiency of different materials to remove specific pollutants from landfill leachate. Desalination Water Treat 238, 240–250.

Rajendiran, N., Ganesan, S., Weichgrebe, D., Venkatachalam, S.S., 2023. Optimization of pyrolysis process parameters for the production of biochar from banana peduncle fibrous waste and its characterization. Clean. Technol. Environ. Policy. 25 (10), 3189–3201.

Ranjithkumar, M., Rajarathinam, R., Kumar, P.S., Rangasamy, G., Gurunathan, B., Ethiraj, B., Thanabal, V., 2022. Insight into the effective utilization of cotton spinning wastes from textile mills for the production of bioethanol. Sustain. Energy Technol. Assess. 53, 102770.

Rubi, R.V.C., Allayban, J.P.O., Deduque, D.A.B., Mena, J.A.B., Robles, N.M.D., Rubio, B. D., Roque, E.C., Janaban, P.J., Olay, J.G., 2023. Production and characterization of activated carbon from pyrolysis biochar of cellulosic cotton-based textile wastes. Mater. Today.

Selvarajoo, A., Oochit, D., 2020. Effect of pyrolysis temperature on product yields of palm fibre and its biochar characteristics. Mater. Sci. Energy Technol. 3, 575–583.

Senthil, C., Lee, C.W., 2021. Biomass-derived biochar materials as sustainable energy sources for electrochemical energy storage devices. Renew. Sustain. Energy Rev. 137, 110464.

Seow, Y.X., Tan, Y.H., Mubarak, N., Kansedo, J., Khalid, M., Ibrahim, M.L., Ghasemi, M., 2022. A review on biochar production from different biomass wastes by recent carbonization technologies and its sustainable applications. J. Environ. Chem. Eng. 10 (1), 107017.

Sharma, A., Pareek, V., Zhang, D., 2015. Biomass pyrolysis—A review of modelling, process parameters and catalytic studies. Renew. Sustain. Energy Rev. 50, 1081–1096.

Shen, Z., Hou, D., Jin, F., Shi, J., Fan, X., Tsang, D.C., Alessi, D.S., 2019. Effect of production temperature on lead removal mechanisms by rice straw biochars. Sci. Total Environ. 655, 751–758.

Sun, J., Lian, F., Liu, Z., Zhu, L., Song, Z., 2014. Biochars derived from various crop straws: characterization and Cd (II) removal potential. Ecotoxicol. Environ. Saf. 106, 226–231.

Szwaja, S., Poskart, A., Zajemska, M., 2019. A new approach for evaluating biochar quality from Virginia Mallow biomass thermal processing. J. Clean. Prod. 214, 356–364.

Tomczyk, A., Sokołowska, Z., Boguta, P., 2020. Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Rev. Environ. Sci. Bio/Technol. 19 (1), 191–215.

Usevičiūtė, L., Baltrėnaitė-Gedienė, E., 2021. Dependence of pyrolysis temperature and lignocellulosic physical-chemical properties of biochar on its wettability. BioMass Convers. Biorefin. 11 (6), 2775–2793.

Wang, Y., Liu, Z., Deng, H., Cao, P., Tan, T., Wang, D., Liu, G., 2024. Study on the properties and components of solid-liquid products by co-pyrolysis of sludge and cotton stalk. J. Anal. Appl. Pyrolysis. 182, 106712.

Wang, Y., 2010. Fiber and textile waste utilization. Waste BioMass Valorization. 1, 135–143.

Wu, J., Zhang, J., Yi, W., Cai, H., Li, Y., Su, Z., 2022. Agri-biomass supply chain optimization in north China: model development and application. Energy 239, 122374.

Yang, H., Yan, R., Chen, H., Lee, D.H., Zheng, C., 2007. Characteristics of hemicellulose, cellulose and lignin pyrolysis. Fuel 86 (12-13), 1781–1788.

Yu, X., Wang, S., Zhang, J., 2018. Preparation of high adsorption performance activated carbon by pyrolysis of waste polyester fabric. J. Mater. Sci. 53, 5458–5466.

Zhang, L., Xu, C.C., Champagne, P., 2010. Overview of recent advances in thermo-chemical conversion of biomass. Energy Convers. Manage 51 (5), 969–982.

Zhang, J., Liu, J., Liu, R., 2015. Effects of pyrolysis temperature and heating time on biochar obtained from the pyrolysis of straw and lignosulfonate. Bioresour. Technol. 176, 288–291.

Zhang, X., Zhang, P., Yuan, X., Li, Y., Han, L., 2020. Effect of pyrolysis temperature and correlation analysis on the yield and physicochemical properties of crop residue biochar. Bioresour. Technol. 296, 122318.

Zhang, K., Zhang, K., Li, Y., Kang, Q., Wang, Y., Wang, J., Yang, K., Mao, J., 2023. Easily pyrolyzable biomass components significantly affect the physicochemical properties and water-holding capacity of the pyrolyzed biochar. Agriculture 13 (11), 2053.