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Converting Polystyrene and Corn Waste into Activated Carbon with High Surface Area

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Abstract

The significant challenges of plastic waste management and agricultural by-product treatment demand innovative and sustainable solutions. Polystyrene (PS) is a widely used synthetic polymer; however, without effective post-use treatment, it can cause significant adverse impacts on both human health and the environment. In recent years, co-pyrolysis technology has emerged as a promising thermochemical approach for converting such materials into value-added products. This work investigates the co-pyrolysis of both PS and CS to produce biochar (BC), followed by chemical activation using 5 M KOH to obtain activated carbon (AC) with high surface area. We found that the optimal conditions for co-pyrolysis were identified at a PS:CS mass ratio of 1:2, a temperature of 500 °C, and a residence time of 1.5 h. The BC obtained under these conditions exhibited a surface area of 58.74 $m^2 g^{-1}$. Subsequent the activation process with KOH at a BC: KOH mass ratio of 1:3, a temperature of 750 °C, and a duration of 3h have synthesized the achieved AC with an excellent surface area of 914.83 $m^2 g^{-1}$.The results of work demonstrate the promising of combining co-pyrolysis with chemical activation as a sustainable strategy for waste valorization that promise for wider applications in environmental energy storage, and other advanced technological fields.

Keyword: Activated Carbon, Co-Pyrolysis, Corn stover, Polystyrene plastic, Synergistic Effects.

1. Introduction

Polystyrene (PS) is among the most prevalent plastic wastes found in the South Atlantic, Indian, and Pacific Oceans, accumulating notably in the Great Pacific Garbage Patch [1-3]. Among major plastic pollutants such as polyethylene and PET, PS degrades most rapidly into microplastics [4], which are linked to oxidative stress, inflammation, and metabolic disorders in humans [5]. Styrene monomers and oligomers, especially carcinogenic compounds, have been detected leaching from polystyrene microplastics [6].

Another issue with polystyrene, as with many conventional plastics, lies in its feedstock sourcing. Polystyrene production is tightly linked to the petrochemical industry, as its two main components—benzene and ethylene—are derived via processes including steam cracking and catalytic reforming [7]. Benzene is alkylated with ethylene in an acid-catalyzed reaction, typically in the liquid phase with catalysts such as $AlCl_3$ or zeolites, producing ethylbenzene. Styrene is then produced from ethylbenzene via catalytic dehydrogenation before being polymerized into polystyrene. Since over 99% of global ethylbenzene is consumed in this process, their productions are closely interdependent [8]. Overall, polystyrene production is inherently unsustainable due to associated greenhouse gas emissions and pollutant release. Most polystyrene exists as expanded polystyrene foam, including Styrofoam, which is notoriously difficult to recycle. A main challenge in polystyrene recycling arises from its lightweight molecular structure, which is not amenable to mechanical recycling methods. Therefore, alternative recycling approaches are necessary for further work to overcome these challenges. Pyrolysis, or thermal decomposition, is the most widely studied plastic degradation method and offers advantages including tolerance of higher impurity levels compared to mechanical recycling Polystyrene pyrolysis is typically conducted at 350–700 °C, with consistent material retention above 90% by weight. [9]

Conversely, maize (corn) is one of the most widely cultivated cereal crops globally. Its processing generates substantial agricultural residues, including husks, cobs, and silks, which hold significant potential for value addition within a circular economy. [10-11] However, these by-products are often underutilized or discarded. Commercial maize cultivation produces vast amounts of biomass, much of which remains undervalued or discarded. Nonetheless, many anatomical components of the maize plant possess potential for conversion into value-added products, offering renewable alternatives to conventional disposal methods. Optimizing the reuse of these maize residues within circular economy frameworks depends on a thorough understanding of their properties with representing the promising sources of bioactive compounds and lignocellulosic material with high value-add potential. Among agricultural products, corn stalks (CS) is one of promising waste to produce the high value products due to the corn stalks, comprising stems and leaves, consist of approximately 15% pitch and 35% rind in the stem, in which leaves account for 40% of the stalk weight and contain about 30% fiber. The stem has a higher bulk density (127.32 kg/m³) and lower porosity (58.71%) than leaves (81.61 kg/m³). Lignocellulosic biomass, including corn stalks, typically contains high cellulose content (35–60 wt%), along with hemicellulose (20–35 wt%) and lignin (15–25 wt%), plus minor amounts of extractives, proteins, and minerals [12-14].

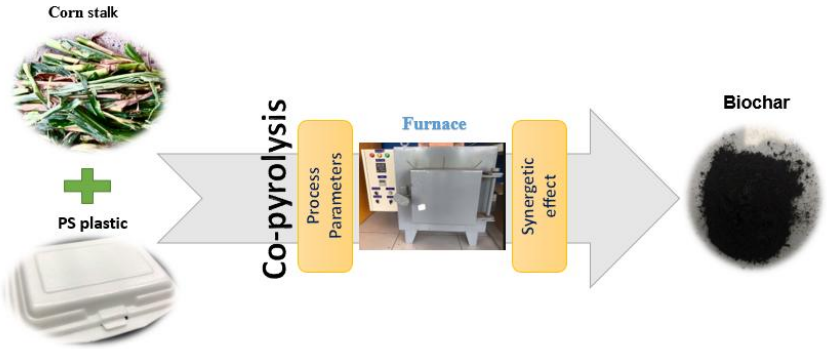
Interestingly, the high cellulose content of corn stalks renders them suitable for conversion into biochar, fiber-reinforced composites, and bioplastics [15].
Co-pyrolysis of biomass and plastic waste has recently studied as main direction for circular economy via sustainable development representing a key step in thermochemical conversion [16]. Pyrolysis is a thermally driven decomposition process that converts waste materials into energy and value-added products under oxygen-free conditions [17]. Especially, parameters of process and properties of product can be significantly influenced by the physicochemical properties, yield, and quality of pyrolysis products [18-19].
In recent years, some works have investigated the co-pyrolysis of plastic waste and biomass such as Rumaihi et al. [20] have studied blending biomass with plastic waste to optimize biochar production. Zulkafli et al. [21] have evaluated the function of plastics and catalysts in co-pyrolyzing biomass and plastic waste to generate renewable fuels. Chen et al. [22] conducted co-pyrolysis of carbonaceous materials and biomass, while Adeniyi et al. [23] have studied the co-pyrolyzing biomass and plastic waste into biochar. Collectively, these studies addressed co-pyrolysis technologies for biomass and plastic waste, providing an overview of recent advancements, synergistic effects, and potential of the co-pyrolysis process without focusing the optimized process to synthesis the higher-value products post-pyrolysis.
Herein, the present study aims to develop a co-pyrolysis process for polystyrene (PS)-a recalcitrant and non-recyclable plastic, together with corn stalk, an agricultural by-product, to obtain the optimized process which produces activated carbon with a higher specific surface area than that obtained from other agricultural residues. The as-synthesized achieved carbon obtained is promising for wide applications in environmental remediation and energy storage.

2. Materials and Methods

2.1. Materials

Polystyrene (PS) waste and corn stalk (CS) agricultural residues used in this study were collected in Ho Chi Minh City, Vietnam. Potassium hydroxide (KOH, 85%) was used as the activating agent, hydrochloric acid (HCl, 36–38%) and acetone (C_3H_6O, 99.0%) were purchased from Xilong, China. Co-pyrolysis and activation were carried out under nitrogen gas (N_2, 99.99% purity) environment that purchased from company in Vietnam. All chemicals were used as received without further purification.

2.2. Co-pyrolysis process of PS and CS

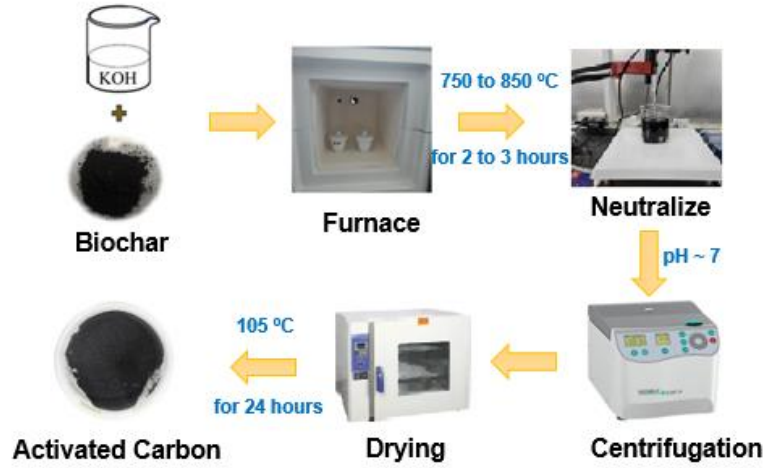


Scheme 1. The co-pyrolysis process of PS và CS.

The PS and CS were pre-treated before carrying the co-pyrolysis process following as the collected PS waste was washed in water to remove dust and air-dried under sunlight for 24 h, then cut into uniform pieces with size 0.5 × 0.5 cm. For CS, leaves, flowers, and roots were removed, retaining only the stalks, which were washed with water to remove impurities, chopped, oven-dried at 80 °C for 24 h, and sieved to a particle size of 0.4 × 0.4 cm. The prepared PS and CS samples were stored in a desiccator prior to use.

The co-pyrolysis procedure for PS and CS is illustrated in Scheme 1. The PS and CS mixtures were prepared at mass ratios of 1:1, 1:2, and 1:3 (PS:CS), placed into ceramic crucible, and put into a muffle furnace. The mixtures were pyrolyzed at various temperatures of 450 °C, 500 °C, and 550 °C for 1, 2 and 3 hours under an inert nitrogen atmosphere. After pyrolysis, the ceramic crucible was left to cool naturally to room temperature. The as-synthesized biochar (BC) was designated as C_1:2_500_1.5 and analysis the properties and continued for the activated chemical process.

2.3. Activation process of PS and CS



Scheme 2. Schematic of activated carbon synthesis from Biochar.

Scheme 2 shows the process of activated carbon (AC) from biochar (BC) that obtained via co-pyrolysis of PS and CS from the co-pyrolysis process of PS and CS. The BC was mixed with KOH solution of a specified concentration with mass ratio. The mixture was placed into ceramic crucibles and put into a muffle furnace, then heated at 750–850 °C for 2–3 h with a heating rate of 16.5 °C/min under a nitrogen atmosphere. After activation, the crucibles were left in the furnace to cool naturally to room temperature. The resulting AC was neutralized with 1 M HCl to pH 7, centrifuged at 6000 rpm with four washes times using deionized water and acetone before drying it in the oven-dried at 105 °C for 24 h.

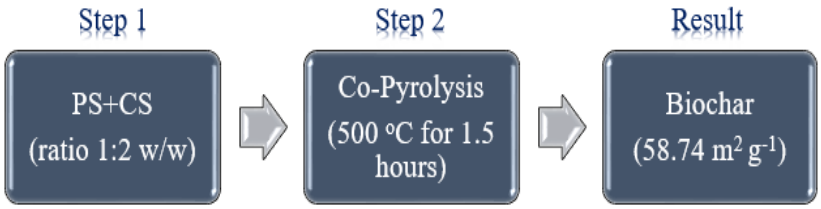
2.4. Characterization of biochar and activated carbon

The specific surface areas of C_1:2_500_1.5 and AC_1:3_750_3 were determined from nitrogen adsorption–desorption isotherms using the Brunauer–Emmett–Teller (BET) method. Pore volume and pore diameter were calculated from the desorption isotherms using the Barrett–Joyner–Halenda (BJH) method. Surface morphology and structure were examined by scanning electron microscopy (SEM, HITACHI S-4800, Japan). Surface functional groups were analyzed by Fourier transform infrared spectroscopy (FTIR, PerkinElmer Frontier FT-IR/NIR, USA) coupled with attenuated total reflectance (ATR). FTIR spectra were recorded in the range of 3500–500 cm^{-1}.

3. Results and discussion

3.1. The optimized co-pyrolysis process of PS and CS and property of biochar

3.1.1 The optimized co-pyrolysis process of PS and CS



Scheme 3. Optimization process of the co-pyrolysis technology for PS and CS.

3.1.2 Properties of as-synthesized biochar after co-pyrolysis

Following the co-pyrolysis of PS waste and CS, the properties of as-sythesized biochar (BC) were measured. BET surface area and pore size are key indicators in the conversion of biomass into carbon materials. The surface area and pore size of the activated carbon were determined by nitrogen adsorption–desorption experiments using the Brunauer–Emmett–Teller (BET) method [24]. Figure 1 presents the nitrogen adsorption–desorption isotherms of the synthesized biochar.

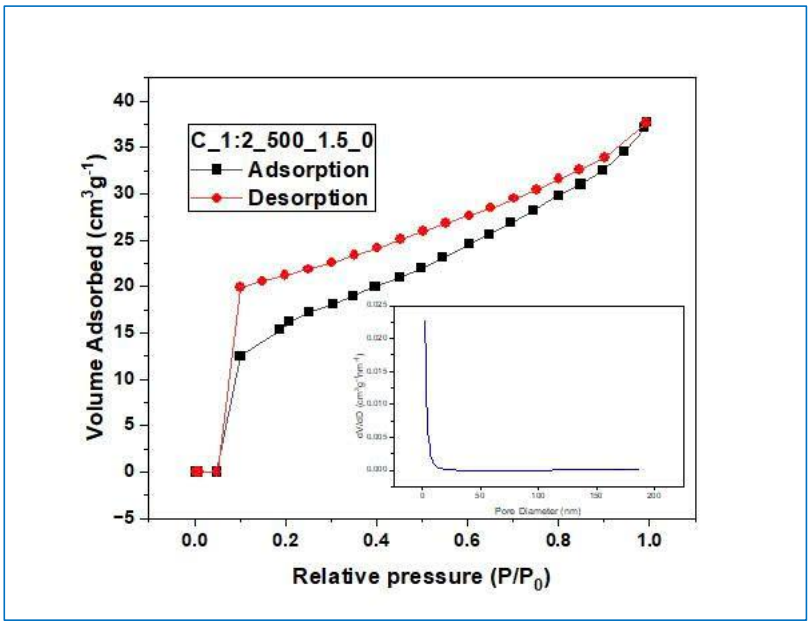


Figure 1. The BET surface area and pore size of optimized biochar products after co-pyrolysis of PS and CS.

BET analysis showed that the as-synthesized biochar (BC) has a specific surface area of 58.74 $m^2 \cdot g^{-1}$ and good morphology with uniform the structure and pore size. Furthermore, Figure 1 indicates that the biochar exhibits predominantly mesoporous characteristics, with pore diameters ranging from ~5 to 180 nm. At low relative pressures ($P/P_0 < 0.1$), an initial steep increase is observed, indicating the presence of a significant amount of micropores in resulting the BET surface area of as synthesized biochar that obtained from the co-pyrolysis process.

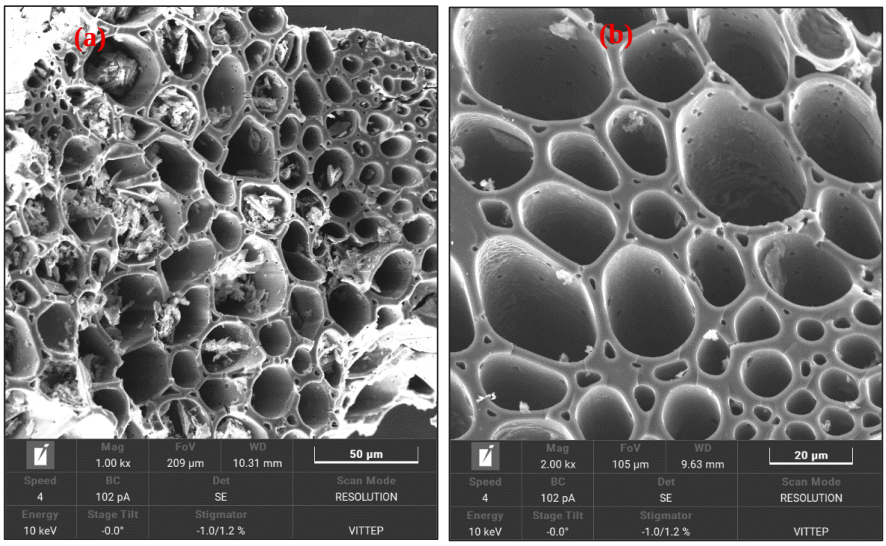


Figure 2. SEM of optimized biochar products after co-pyrolysis of PS and CS with different scale bars (a) 50 µm and (b) 20 µm.

Figure 2a clearly shows large macropores with diameters ranging from approximately 20 to 50 µm for optimized biochar products after co-pyrolysis of PS and CS. Interestingly, these pores are nearly circular to oval in morphology and are arranged in a relatively orderly manner. As the higher magnification (scale bar 20 µm) in Figure 2 (right) finer details are visible. It can be found that the pore walls exhibit a relatively smooth surface, suggesting efficient co-pyrolysis process that applied I this work. Besides, we can observe that at 20 µm scale bar, the large pores appear interconnected through numerous smaller pores on the walls, forming a dense porous network essential for applications such as adsorption and energy storage [25].

The adsorption properties of biochar synthesized from PS and CS co-pyrolysis could be found that it's dependent on surface functional groups. FT-IR analysis was employed to characterize the surface groups of sample C_1:2_500_1.5. As shown in Figure 3, a broad and rounded peak appears around 3300–3500 cm^{-1}, characteristic of the O–H stretching vibration [26].

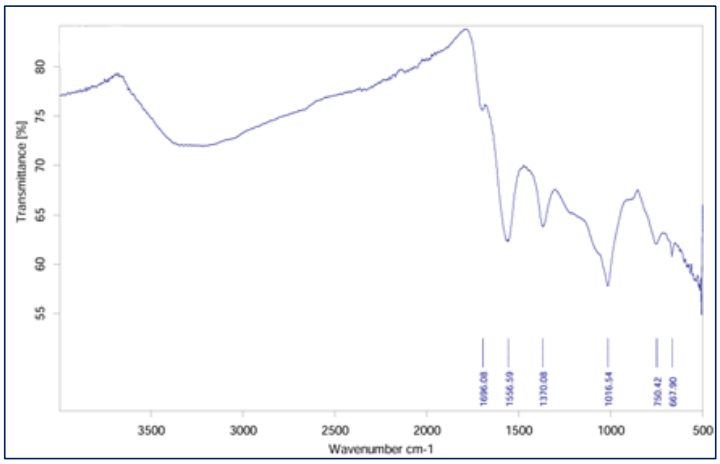


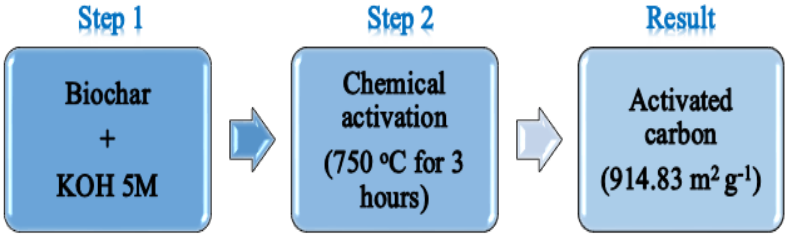
Figure 3. Fourier transform infrared (FTIR) spectrum of optimized biochar products after co-pyrolysis of PS and CS.

From the Figure 3, it can be indicated that at the peak of 1696.08 cm^{-1}, the signal corresponds to the C=O double bond stretching vibration, confirming the presence of a small amount of carboxyl groups in the sample [27]. The peak at 1556 cm^{-1} is typically attributed to the C=C stretching vibration within aromatic rings, enhanced by polar functional groups [27]. The band at 1370 cm^{-1} corresponds to O–H or C–H bending vibrations. The peak at 1016 cm^{-1} is characteristic of C–O single bond stretching and may originate from various functional groups such as carboxylic acids (-COOH), esters, ethers, and phenols. Peaks below 1000 cm^{-1} (e.g., at 750 cm^{-1} and 667 cm^{-1}) are often complex but provide information about out-of-plane bending vibrations of C–H bonds on aromatic rings [27].

Based on the Fourier transform infrared (FTIR) spectrum of optimized biochar products after co-pyrolysis of PS and CS (denote sample C_1:2_500_1.5), it can be concluded that these hydrophilic functional groups are present on the biochar surface structure, enhancing chemical interactions and playing a crucial role in applications such as adsorption and catalysis.

3.2. The optimized activated carbon process of PS and CS and its properties.

3.2.1 The optimized activated carbon process of PS and CS



Scheme 4. The optimized activated carbon process of PS and CS.

3.2.2. Properties of as-synthesized activated carbon

Following the activation of biochar (BC) to synthesis the activated carbon (AC), the physicochemical properties of AC were investigated in Figure 4 and 5. Figure 4 shows the results presents the nitrogen adsorption–desorption isotherms of the synthesized AC to determine surface area and pore size of the activated carbon by nitrogen adsorption–desorption experiments using the Brunauer–Emmett–Teller (BET) method [24].

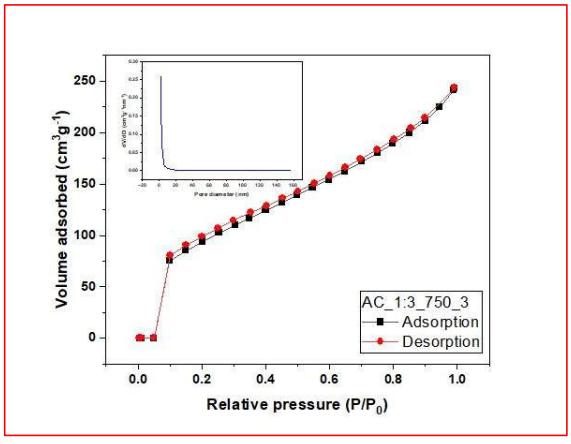


Figure 4. The BET surface area and pore size of optimized as-synthesized activated carbon products after co-pyrolysis of PS and CS.

The BET surface area analysis revealed that the resulting activated carbon (AC) possesses an excellent specific surface area up to 914.83 $m^2 g^{-1}$. The most promising feature is the sharp, nearly vertical increase in nitrogen adsorption at very low relative pressures ($P/P_0 < 0.1$), suggesting nitrogen filling micropores smaller than ~3 nm. These results can understand that an extensively developed microporous network. Furthermore, following this initial steep rise, the isotherm levels off and continues to much increase with a slight hysteresis loop, indicating the presence of mesopores, though they constitute only a minor fraction relative to the micropores. Moreover, a pronounced, sharp peak below 3 nm pore diameter confirms that the material's structure is dominated by uniform micropores [28]. These results can indicate that the co-pyrolysis of PS and CS process that discovered in this works is significant process with high BET surface area and uniform pore side of as-synthesized activated carbon compared to other previous works. Its results could be contributed due to developed technological process is appropriate and promising, successfully synthesizing activated carbon with superior properties from two materials with distinct characteristics, namely PS plastic and CS biomass that can be produced the value products and applied to wide applications.

4. Conclusions

This study studies an effective and sustainable approach for converting solid waste—specifically polystyrene (PS) plastic and corn stalk (CS) agricultural residues—into activated carbon with excellent surface area and pore size. The process involves two main stages including co-pyrolysis and chemical activation. The works found that the optimal co-pyrolysis conditions were a PS:CS mass ratio of 1:2 at 500 °C for 1.5 hours, producing biochar with a surface area of 58.74 $m^2 \cdot g^{-1}$. Subsequent activation of the biochar with KOH at a 1:3 ratio at 750 °C for 3 hours significantly increased the surface area to 914.83 $m^2 \cdot g^{-1}$. This work not only demonstrates the potential of combined co-pyrolysis and chemical activation as an environmentally friendly waste management strategy but also produces activated carbon with superior adsorption properties and pore structure, suitable for practical applications.

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