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COFFEE-GROUND–DERIVED HYDROTHERMALLY ACTIVATED CARBON: SYNTHESIS, CHARACTERIZATION, AND ADSORPTION PERFORMANCE TOWARD METHYLENE BLUE

Abstract: *Spent coffee grounds (SCGs), an abundant lignocellulosic agro-industrial residue, were valorized into porous carbonaceous adsorbents through hydrothermal carbonization (HTC) followed by alkaline activation, aiming at the efficient removal of methylene blue (MB) from aqueous solutions. HTC was conducted under subcritical water conditions at temperatures of 180-220 °C and residence times of 2-6 h, producing hydrochars with tunable physicochemical properties. The obtained hydrochars were subsequently activated using potassium hydroxide in a microwave reactor to enhance surface functionality and porosity. The structural, textural, and chemical characteristics of the materials were comprehensively analyzed by N_2 physisorption (BET surface area and pore size distribution), FTIR spectroscopy, SEM, XRD/Raman spectroscopy, and elemental analysis (XRF/EDX).*

Batch adsorption experiments were performed to evaluate the adsorption kinetics, equilibrium isotherms, and thermodynamic behavior toward methylene blue. The activated coffee-ground-derived carbons exhibited rapid adsorption kinetics and significantly enhanced adsorption capacities compared to non-activated hydrochars. The improved performance was attributed to the synergistic effects of developed micro- and mesoporous structures and abundant oxygen-containing surface functional groups. Mechanistic analysis indicated that methylene blue uptake was governed by a combination of pore filling, electrostatic attraction, π–π electron donor–acceptor interactions between the aromatic carbon surface and dye molecules, hydrogen bonding, and intraparticle diffusion.

The results demonstrate that hydrothermal carbonization coupled with mild alkaline activation provides an effective and sustainable route for converting spent coffee grounds into high-performance adsorbents. This study elucidates the relationships between synthesis conditions, surface chemistry, textural properties, and adsorption performance, highlighting the potential of SCG-derived activated carbon for practical wastewater treatment applications.

Key words: *Hydrothermal carbonization; Spent coffee grounds; Activated carbon; Methylene blue adsorption; Water purification.*

1. Introduction

Coffee is among the largest commodities in the world, which generates 2 billion tons of waste annually, and most of which remains unutilized [1]. One of the biggest problems facing modern society is the contamination of natural resources, especially water. The anthropogenic discharge of dye-contaminated effluents from textile, printing, leather, and pharmaceutical industries constitutes a significant environmental hazard to aquatic ecosystems and poses substantial risks to public health. Despite being a sign of global economic advancement, the growing demand for industrial processes contributes significantly to the spread of pollutants that endanger human health and the ecosystem by degrading the environment [2]. Synthetic dyes exhibit high chemical stability, complex polycyclic aromatic structures, and recalcitrance to biodegradation, rendering conventional biological treatment processes largely ineffective. Among these contaminants, methylene blue (MB), a thiazine-class cationic dye, is extensively utilized in industrial applications and is frequently detected in wastewater streams at concentrations exceeding regulatory thresholds. At even trace concentrations, MB attenuates photosynthetic light penetration in aquatic environments and demonstrates cytotoxic, mutagenic, and carcinogenic potential, thereby necessitating the development of efficient and sustainable remediation technologies. Inadequate management of pollutants produced by industrial and agricultural processes results in serious water pollution, which damages the ecosystem and has an impact on human and other living things' health [3]. For instance,

dye, once it has been used and discharged into the waterway, not only alters the quality of the environment but also causes the loss of aesthetic value due to the high color content that it has [4]. Over 7×10^5 tons of over 100,000 different kinds of chemical dyes are manufactured annually for commercial use [5].

Globally, both coffee production and consumption are rising. The market for coffee shops has grown significantly during the 2000s due to the popularity of coffee-drinking culture and the rising demand for different kinds of coffee goods [6]. As a result, the quantity of spent coffee grounds (SCGs), which are byproducts produced following the extraction of coffee, has also been steadily rising. Although some SCGs are used as compost, most are disposed of through incineration and landfills [7]. Because of this, there has been an increase in the amount of interest in technology that make use of SCGs as a source of renewable energy [6]. Pent coffee grounds (SCGs) represent an abundant and underutilized lignocellulosic biomass residue, with an estimated global annual production exceeding 6 million metric tons from domestic, commercial, and industrial coffee processing operations. Compositionally, SCGs are rich in cellulose, hemicellulose, lignin, and lipophilic extractives, rendering them a promising carbonaceous precursor for the synthesis of functionalized carbon materials. The valorization of SCGs into activated carbon adsorbents not only mitigates the environmental burden associated with landfill disposal and greenhouse gas emissions but also aligns with circular economy principles by transforming waste biomass into high-value materials for environmental remediation applications [8].

Hydrothermal reactions exploit the strong dissolution capability of subcritical water in a high-pressure reactor to produce finer particles by turning organic polymers into low-molecular-weight compounds [9]. Hydrothermal carbonization (HTC) has garnered considerable interest as a thermochemically sustainable conversion pathway for the transformation of wet biomass into carbonaceous materials under subcritical water conditions (typically 180–250°C, autogenous pressure). Unlike conventional pyrolysis, which necessitates elevated temperatures (>400°C) and anhydrous feedstocks, HTC proceeds via dehydration, decarboxylation, and condensation reactions in the aqueous phase, obviating energy-intensive pre-drying requirements and rendering it particularly advantageous for high-moisture-content substrates such as coffee grounds. The resultant hydrochar is characterized by abundant oxygen-containing surface functional groups (carboxyl, hydroxyl, carbonyl), which facilitate electrostatic and hydrogen-bonding interactions with cationic dye molecules. Subsequent physicochemical or chemical activation processes further enhance textural properties through the development of hierarchical micro- and mesoporous networks, thereby substantially augmenting adsorptive capacity and mass transfer kinetics [10].

Despite the proliferation of research on biomass-derived carbonaceous adsorbents, systematic investigations elucidating the structure–property–performance relationships of hydrothermally synthesized coffee-ground-derived activated carbon for methylene blue sequestration remain scarce. Specifically, the correlations between synthesis parameters (temperature, residence time, activation agent), surface chemistry (functional group distribution, surface charge density), textural characteristics (specific surface area, pore size distribution), and adsorption efficacy require comprehensive elucidation. A mechanistic understanding of the governing adsorption phenomena—including electrostatic interactions, π–π electron donor-acceptor complexation, hydrogen bonding, and intraparticle diffusion-is imperative for rational material design and optimization of adsorbent performance in practical wastewater treatment applications [11].

In particular, hydrochar generated from SCGs has demonstrated excellent efficacy in the removal of heavy metals, organic dyes, and medicines from wastewater [12]. Nevertheless, hydrochars often exhibit limited surface areas, laying a key importance on the surface functions to supply adsorption sites for the pollutants. Depending on the HTC temperature and residence time, HTC was found to affect the presence of functional groups on the material surface, such as by causing the loss of oxygen-containing functional groups [13]. Therefore, chemical/physical activation is often needed to change the surface functioning and boost the adsorption capability of the generated hydrochar [14]. Chemical activation entails treating the hydrochar with activating chemicals such as potassium hydroxide or phosphoric acid, which not only enhance the surface area but also introduce additional functional groups on the surface, further improving the material's potential to collect pollutants [13].

The adsorption capability of hydrochars made from HTC of SCGs at various temperatures is examined in this work. The physical/chemical properties and adsorption potential of HTC products

and raw feedstock are examined in order to remove MB from water. The effect of gentle alkaline activation on enhancing the adsorption capacity of the SCG-derived hydrochar is further examined. To the best of our knowledge, dye adsorption on SCG hydrochars was not systematically explored in prior studies; in this investigation, MB is employed as a model dye to elucidate adsorption of raw and minimally activated SCG hydrochars. The effects of initial MB concentration and temperature are explained, along with the process's kinetics, isotherms, and thermodynamics.

2. Experimental part

2.1 Materials and method

Spent coffee grounds (SCGs) were procured from the Satbayev University café facility as post-extraction solid residue. The feedstock originated from Brazil Mogiana (Coffea arabica) beans processed under standardized espresso extraction parameters: water temperature of 90-94 °C and extraction pressure of approximately 9 bar (0.9 MPa), as specified by the manufacturer protocol for the Nuova Simonelli commercial espresso system. Analytical-grade potassium hydroxide (KOH, ≥97% purity, CAS: 1310-58-3) was procured from Sigma-Aldrich Corporation. Deionized water (electrical resistivity up to 18.2 MΩ·cm) was obtained from a laboratory water purification system (Basic-Q15-II, LabSoul, China).

Thermal activation procedures were executed in a programmable microreactor system (PR 250, LabSoul Technology, China) under controlled temperature and atmospheric conditions. Microwave-assisted activation was performed using a multimode microwave reactor (YMW-HP80, LabSoul Technology, China) operating at a frequency of 2.45 GHz with adjustable power output, enabling rapid volumetric heating and enhanced activation kinetics.

2.2 Synthesis of coffee hydrochar

Spent coffee grounds were dried at 110°C in a drying oven for 24 h. Subsequently, 50 g of the dried material was mixed with 150 mL of deionized water and loaded into a high-pressure microreactor (PR-250, LabSoul, China). Hydrothermal carbonization was carried out at 180, 200, and 220 °C with residence times of 2 and 6 h.

The optimal mass ratio of coffee grounds to water was determined experimentally. In total, six biochar samples were obtained under different reaction conditions, as summarized in Table 1. The biochar yield ranged from 62 to 73 wt%.

Table 1. Hydrothermal carbonization conditions and yields of biochar samples derived from spent coffee grounds.

№	Sample	Time (h)	Temperature (°C)	Ration (mass of raw coffee to DI)	Steering	Pressure, MPa	Yield (%)	Mass, g	Surface area, m^2/g
1	HTK180/2	2	180	(50:150)	300	1.17	73.2	36.60	0,80
2	HTK180/6	6	180	(50:150)	300	1.16	70.56	35.28	2,6
3	HTK200/2	2	200	(50:150)	300	2.19	69.7	34.85	2,4
4	HTK200/6	6	200	(50:150)	300	2.43	68.34	34.17	3,2
5	HTK220/2	2	220	(50:150)	300	2.23	61.6	30.80	3,9
6	HTK220/6	6	220	(50:150)	300	3.86	62.92	31.46	5,9

The change in the ratio in the microreactor is shown using the example of HTK 220/6 in Figure 1, and the maximum value produced in the reactor is shown in Figure 1.

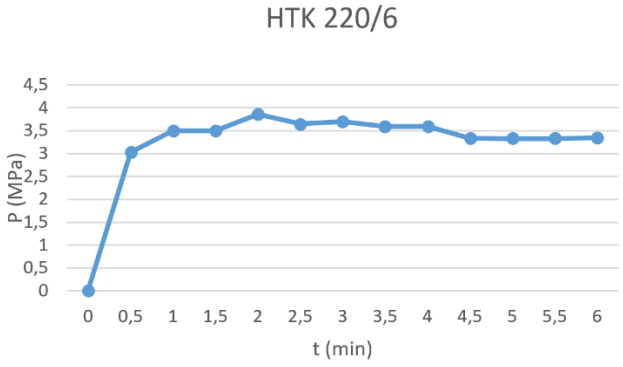

Figure 1 – Pressure–time profile for HTK 220/6 in the microreactor

The activated samples obtained in the microreactor were thoroughly washed with 100 mL of deionized water, subsequently filtered using a Büchner funnel, and dried at 110°C in a laboratory drying oven (DHG-9145A, LabSoul, China).

Subsequently, microwave-assisted activation of the HTK 220/6 sample was carried out using potassium hydroxide (KOH) in an aqueous solution with a concentration of 2 M, as HTK 220/6 exhibited the most optimal specific surface area among the obtained samples. The activation temperature was varied within the range of 80-160 °C in order to investigate the effect of KOH on the composition and structure of the material.

For this purpose, after hydrothermal carbonization of the coffee residue, the samples were additionally treated with a 2 M KOH solution (Figure 2) in a microwave reactor, which was expected to promote surface modification, chemical activation of the carbon matrix, and partial pore development, leading to further enhancement of textural properties.

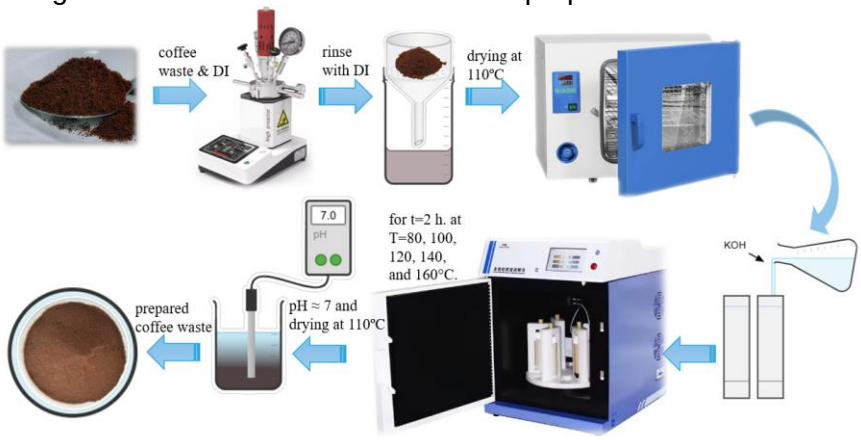

Figure 2 – Schematic illustration of carbon material synthesis from coffee waste

The evolution of temperature and pressure as a function of reaction time during microwave-assisted hydrothermal carbonization of spent coffee grounds is illustrated in Figure 3. As can be observed, both temperature and pressure increased with increasing residence time, reflecting the progressive heating of the reaction medium and the corresponding build-up of autogenous pressure inside the sealed reactor. The pressure development is attributed to water vapor generation and the formation of gaseous decomposition products during hydrothermal reactions. The simultaneous increase in temperature and pressure confirms stable operation of the microwave reactor under subcritical water conditions throughout the experiment.

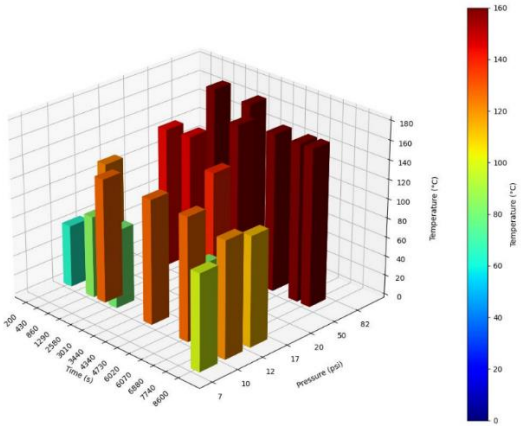

Figure 3 – Time–pressure–temperature profiles during microwave-assisted hydrothermal carbonization of spent coffee grounds

2.3 pH analysis of carbon samples

pH analysis is used to evaluate the acid-base properties of carbon materials and to characterize the nature of their surface functional groups. The pH value reflects the presence of

acidic (e.g., carboxylic, phenolic) or basic sites on the carbon surface, which play a key role in adsorption processes. This parameter is particularly important for understanding the interaction between adsorbents and aqueous pollutants, as it influences surface charge, ion exchange behavior, and overall adsorption efficiency.

The pH measurements were carried out by contacting 50 mg of carbon samples with 50 mL of 0.1 M KCl solution for 72 h at 20 °C under static conditions. After equilibration, the pH of the suspensions was measured.

2.4 Infrared spectroscopy (FTIR) and interpretation of the obtained spectra

Fourier-Transform Infrared (FTIR) spectroscopy is a widely used analytical technique based on the absorption of infrared radiation by molecules at specific frequencies corresponding to the vibrations of chemical bonds. The technique gives a substance's "molecular fingerprint" and makes it possible to identify functional groups. By examining the location, strength, and form of distinctive absorption bands in relation to wavenumber, the spectra can be interpreted to determine the sample's molecular makeup and structure.

2.5 Scanning Electron Microscopy (SEM) analysis and interpretation of the obtained images

Scanning Electron Microscopy (SEM) analysis provides high-resolution imaging of a sample's surface by scanning it with a focused electron beam and detecting the emitted secondary or backscattered electrons. When using backscattered electron detection, compositional differences are frequently revealed through variations in brightness. The resulting grayscale images, where contrast arises from surface topography and material composition, allow for the interpretation of morphological features such as grain structure, particle size, surface roughness, and defect distribution.

2.6 Ultraviolet–visible spectroscopy (UV–Vis) technique for studying adsorption kinetics and isotherms

UV–visible spectrophotometry (UV–Vis) was used to measure the amount of methylene blue in aqueous solutions (λ = 664 nm) both before and after adsorption. The residual adsorbate concentration in the solution can be quantitatively determined using this method, which is based on measuring the optical density of the solution at the dye's distinctive absorption wavelength.

Solution samples were collected during the adsorption process at predetermined intervals in order to conduct kinetic tests. Under controlled experimental settings, a series of solutions with varying initial methylene blue concentrations were utilized to create adsorption isotherms. The samples were extracted from the solid phase and subjected to spectrophotometric analysis prior to measurement.

The adsorption capacity of the sorbent at time t was calculated using the material balance equation:

$$q_t = \frac{(C_0 - C_t)V}{m} \quad (1)$$

where, q_t – adsorption capacity at time t (mg·g⁻¹), C_0 and C_t – initial and current adsorbate concentrations (mg·L⁻¹), V – solution volume (L), m – adsorbent mass (g).

3 RESULTS

3.1 pH analysis of carbon samples

The initial 0.1 M KCl solution showed a slightly acidic pH of 5.96. After interaction with pristine HTK 220/6, the pH slightly increased to 6.02, indicating weakly basic surface properties.

Further treatment was applied to the HTK 220/6 sample under different conditions. As shown in Table X, the sample obtained at 80°C exhibited the highest pH (7.80), while increasing the treatment temperature (100-160°C) resulted in lower pH values (6.79-7.02), approaching neutral conditions. This trend indicates changes in surface functional groups of the carbon material.

Table 1 – Effect of treatment conditions on pH of HTK 220/6 carbon samples

Sample	pH	Mass of carbon, mg
MilliQ water	5,53	
0,1 M KCl	5,96	
0,1 M KCl and HTK 220/6	6,02	50,3
0,1 M KCl and HTK 220/6 MV 80/2	7,80	50,2
0,1 M KCl and HTK 220/6 MV 100/2	6,79	50,2
0,1 M KCl and HTK 220/6 MV 120/2	7,02	50,2

0,1 M KCl and HTK 220/6 MV 140/2	6,91	50,3
0,1 M KCl and HTK 220/6 MV 160/2	6,93	50,0

3.2 Results of Infrared Spectroscopy (FTIR)

The infrared spectra of HTK samples obtained at temperatures of 80-160°C are shown in the figure. Spectral analysis allows the identification of the main functional groups present on the surface of the carbon materials obtained.

The spectra of all samples show a band in the 3000-2900 cm^{-1} range, which corresponds to the valence vibrations of (CH) bonds in aliphatic structures. These bands are characteristic of carbon materials obtained from biomass and are associated with residual organic components of the raw material.

The absorption band in the range of 1700-1600 cm^{-1} refers to carbonyl groups (C=O). The presence of these bands indicates the formation of an aromatic carbon structure and the presence of oxygen-containing functional groups on the surface of the material.

In the 1500-1400 cm^{-1} range, bands are observed that are caused by C–H deformation vibrations in aromatic structures. These peaks confirm the formation of condensed carbon fragments during the thermal treatment of coffee residues.

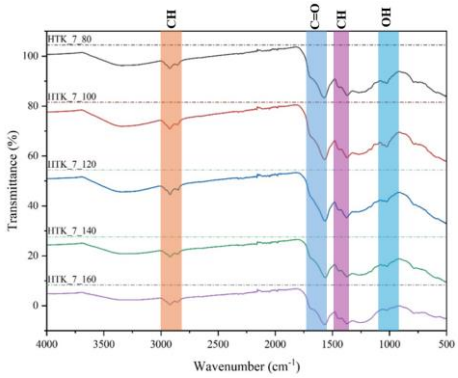

Figure 4 – FT-IR functional group analysis

Also, in the range of 1100-1000 cm^{-1}, there are bands associated with the vibrations of C–O and O–H groups, which are characteristic of phenolic, alcohol, and ether compounds. The presence of these functional groups indicates the presence of active centers on the surface of the carbon material.

The results of FTIR analysis show that as the processing temperature increases, the chemical structure of the material changes and a functionalized carbon surface is formed. Such surface groups can play an important role in the adsorption of pollutants.

3.3 Scanning Electron Microscopy (SEM) results

The morphology of the hydrothermally carbonized and KOH-activated carbon materials derived from spent coffee grounds was examined by scanning electron microscopy (SEM) (Fig. 5 a-e). The micrographs reveal a clear evolution of surface structure as a function of hydrothermal carbonization (HTC) severity and subsequent microwave-assisted activation.

For the HTK220/6 sample, the effect of microwave-assisted activation temperature (80-160 °C) on surface morphology was systematically evaluated. At 80°C (Fig. 5a), a relatively compact surface with poorly developed porosity is observed. Increasing the temperature to 100 °C (Fig. 5b) results in slight surface roughening and the appearance of initial structural heterogeneities.

At 120°C (Fig. 5c), partial fragmentation of the carbon matrix and the formation of irregular voids are detected, indicating the onset of effective activation. A further increase to 140 °C (Fig. 5d) leads to the development of a more open structure with visible cavities and increased surface roughness. At 160°C (Fig. 5e), a highly porous, sponge-like morphology with an interconnected framework is formed. This structural evolution is attributed to enhanced KOH-induced activation under microwave irradiation, resulting in progressive carbon matrix etching and pore development. Increasing activation temperature is therefore directly associated with the formation of a more accessible porous structure.

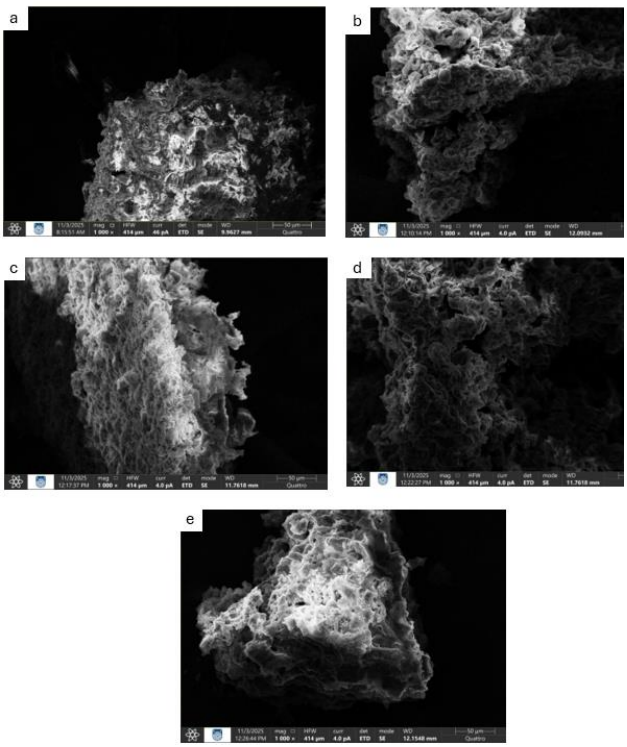

Figure 5 – SEM images of HTK220/6 at different activation temperatures:
(a) 80 °C, (b) 100 °C, (c) 120 °C, (d) 140 °C, (e) 160 °C.

In summary, SEM analysis demonstrates that increasing the microwave-assisted activation temperature from 80 to 160°C leads to a progressive transformation of the HTK220/6 morphology from a compact structure to a highly porous, interconnected framework. This evolution confirms the critical role of activation temperature in governing pore development and structural accessibility, which is expected to enhance the material's adsorption performance.

3.4 Sorption study

The adsorption behavior of methylene blue on the synthesized sorbents is presented as a function of equilibrium concentration. The results demonstrate a typical increase in the adsorbed amount with increasing equilibrium concentration, indicating progressive occupation of available active sites on the sorbent surface.

At lower concentrations, a sharp increase in adsorption capacity is observed, suggesting a high affinity between MB molecules and the sorbent surface, likely driven by electrostatic interactions and π–π stacking. As the concentration increases, the adsorption tends to approach a plateau, indicating partial saturation of active sites.

The differences between the two datasets (blue and orange points) suggest variations in sorption performance, which may be attributed to differences in surface functional groups, porosity, or modification of the sorbents. The higher adsorption capacity observed for the modified samples indicates enhanced interaction mechanisms, possibly due to increased surface heterogeneity and the presence of additional binding sites.

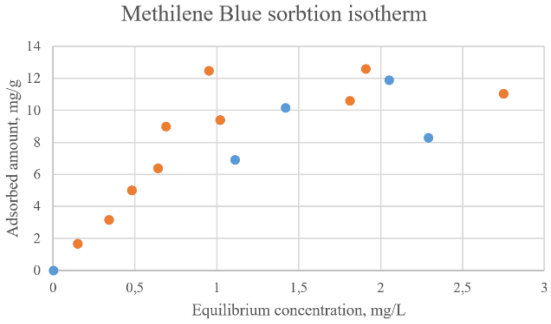

Figure 6 – Adsorption isotherms of methylene blue onto the prepared sorbents

Overall, the obtained isotherm profiles are consistent with Langmuir- or Freundlich-type adsorption behavior, confirming the suitability of the developed materials for dye removal applications.

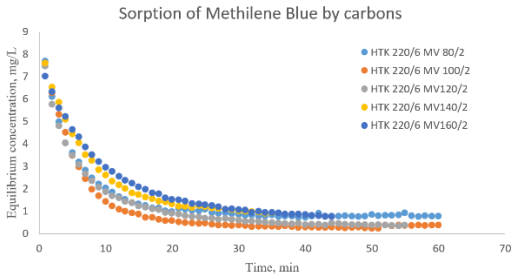

Figure 7 – Adsorption kinetics of methylene blue onto activated carbon samples under different modification conditions

The adsorption kinetics of methylene blue on the synthesized carbon materials are presented as the variation of residual concentration with contact time. A rapid decrease in MB concentration is observed during the initial stage (0-10 min), indicating fast adsorption driven by the abundance of available active sites on the sorbent surface.

As the contact time increases, the rate of adsorption gradually slows down, approaching equilibrium after approximately 30-40 min. This behavior suggests a transition from external surface adsorption to intraparticle diffusion and pore filling mechanisms.

Among the studied samples, noticeable differences in adsorption rates and equilibrium concentrations are observed. Samples treated under different modification conditions (e.g., varying MV ratios) exhibit distinct kinetic profiles, reflecting the influence of surface chemistry and pore structure on adsorption performance. The sample HTK 220/6 MV 100/2 demonstrates the fastest removal and lowest residual concentration, indicating superior adsorption efficiency, while other samples show slightly slower kinetics and higher equilibrium concentrations.

The overall kinetic behavior is consistent with pseudo-second-order kinetics, suggesting that chemisorption plays a dominant role in the adsorption process. These results confirm that the modification conditions significantly affect both the adsorption rate and capacity of the carbon materials.

Conclusion

The present study successfully demonstrates the valorization of spent coffee grounds (SCGs) into high-performance activated carbon adsorbents via hydrothermal carbonization followed by microwave-assisted alkaline activation. The developed materials exhibited a hierarchical porous structure and a rich surface chemistry, which were critical for the efficient removal of methylene blue from aqueous solutions.

From the perspective of water purification, the findings highlight the potential of SCG-derived carbons as a sustainable and cost-effective alternative to commercial activated carbon. The synergistic effect of pore filling, electrostatic attraction, and π–π interactions enabled rapid adsorption kinetics and high uptake capacity, making the process viable for treating dye-laden wastewater. Furthermore, the mild activation conditions employed in this work offer an energy-efficient route for scaling up production, aligning with the principles of the circular economy by transforming an abundant agro-industrial waste stream into a functional material for environmental remediation.

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КОФЕ ҚАЛДЫҚТАРЫНАН АЛЫНҒАН ГИДРОТЕРМИЯЛЫҚ АКТИВТЕЛГЕН КӨМІР: СИНТЕЗІ, СИПАТТАМАСЫ ЖӘНЕ МЕТИЛЕН КӨГІНЕ ҚАТЫСТЫ АДСОРБЦИЯЛЫҚ ҚАСИЕТТЕРІ

Пайдаланылған кофе ұнтағы (WCG), мол лигноцеллюлозалық агроөнеркәсіптік қалдық, гидротермиялық көміртек адсорбенттеріне айналдырылды, содан кейін сілтілі активация арқылы су ерітінділерінен метилен көкті (MB) тиімді түрде кетіру үшін. Гидротермиялық көміртектеу (HTC) 180-220°C температурада және 2-6 сағат тұру уақытында судың аса маңызды емес жағдайында жүргізілді, нәтижесінде реттелетін физика-химиялық қасиеттері бар көмірсутектер алынды. Алынған гидрокарбондар кейіннен беттік функционалдылық пен кеуектілікті жақсарту үшін микротолқынды реакторда калий гидроксидін пайдаланып белсендірілді. Материалдардың құрылымдық, текстуралық және химиялық сипаттамалары N_2 физисорбциясын (BET беттік ауданы және кеуек өлшемінің таралуы), Фурье түрлендіру инфрақызылын (FTIR), сканерлеуші электронды микроскопияны (SEM), рентгендік дифракция/Раман спектроскопиясын және элементтік талдауды (XRF/EDX) қолдану арқылы жан-жақты талданды.

Метилен көкке қатысты адсорбция кинетикасын, тепе-теңдік изотермаларын және термодинамикалық мінез-құлықты бағалау үшін партиялық адсорбция тәжірибелері жүргізілді. Кофе ұнтағынан алынған белсендірілген көміртектер белсендірілмеген көмірсутектермен салыстырғанда жылдам адсорбция кинетикасын және адсорбция сыйымдылығын айтарлықтай арттырды. Бұл жақсартылған өнімділік дамыған микро- және мезокеуекті құрылымдардың синергетикалық әсерлеріне және бетіндегі оттегі бар функционалды топтардың көптігіне байланысты болды. Механикалық талдау метилен көк адсорбциясының кеуектерді толтыру,

электростатикалық тартылыс, хош иісті көміртек беті мен боялыш молекулалары арасындағы π–π донор-акцепторлық өзара әрекеттесулер, сутектік байланыс және кеуекішілік диффузияның үйлесімі арқылы жүзеге асатынын көрсетті.

Нәтижелер гидротермиялық көміртектенудің жұмсақ сілтілі активациямен біріктірілуі пайдаланылған кофе ұнтағын жоғары тиімді адсорбенттерге айналдырудың тиімді және тұрақты жолын қамтамасыз ететінін көрсетеді. Бұл зерттеу синтез жағдайлары, беттік химия, текстуралық қасиеттер және адсорбция тиімділігі арасындағы байланысты анықтайды, пайдаланылған кофе ұнтағынан алынған белсендірілген көмірдің ағынды суларды тазартуда практикалық қолдану әлеуетін көрсетеді.

Түйін сөздер: *Гидротермиялық көміртектену; Пайдаланылған кофе ұнтағы; Белсендірілген көміртек; Метилен көк адсорбциясы; Суды тазарту.*

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ГИДРОТЕРМАЛЬНО АКТИВИРОВАННЫЙ УГЛЕРОД ИЗ КОФЕЙНОЙ ГУЩИ: СИНТЕЗ, ХАРАКТЕРИСТИКА И АДСОРБЦИОННАЯ СПОСОБНОСТЬ ПО ОТНОШЕНИЮ К МЕТИЛЕНОВОМУ СИНЕМУ

Использованные кофейные гущи (УКГ), обильный лигноцеллюлозный агро-промышленный остаток, были превращены в пористые углеродные адсорбенты через гидротермальную карбонизацию (ГТК), за которой следовала щелочная активация, с целью эффективного удаления метиленового синего (МС) из водных растворов. Гидротермальная карбонизация (ГТК) проводилась в условиях подсуперкритической воды при температурах 180–220 °C и времени пребывания 2–6 ч, что привело к получению гидрокарбонов с настраиваемыми физико-химическими свойствами. Полученные гидрочар были впоследствии активированы с использованием гидроксида калия в микроволновом реакторе для улучшения поверхностной функциональности и пористости. Структурные, текстурные и химические характеристики материалов были всесторонне проанализированы с помощью физисорбции N_2 (площадь поверхности BET и распределение размеров пор), Фурье-спектроскопии ИК (FTIR), сканирующей электронной микроскопии (SEM), рентгеновской дифракции/Раман-спектроскопии и элементного анализа (XRF/EDX).

Пакетные эксперименты по адсорбции были проведены для оценки кинетики адсорбции, равновесных изотерм и термодинамического поведения по отношению к метиленовому синему. Активированные углероды, полученные из кофейной гущи, продемонстрировали быструю кинетику адсорбции и значительно повышенные адсорбционные способности по сравнению с неактивированными гидрокарбонами. Улучшенная производительность была обусловлена синергетическими эффектами развитых микро- и мезопористых структур и обилием кислородсодержащих функциональных групп на поверхности. Механистический анализ показал, что поглощение метиленового синего было обусловлено сочетанием заполнения пор, электростатического притяжения, π–π донорно-акцепторных взаимодействий между ароматической углеродной поверхностью и молекулами красителя, водородных связей и внутрипористой диффузии.

Результаты показывают, что гидротермальная карбонизация в сочетании с мягкой щелочной активацией обеспечивает эффективный и устойчивый путь для преобразования использованной кофейной гущи в высокоэффективные адсорбенты. Это исследование разъясняет взаимосвязи между условиями синтеза, поверхностной химией, текстурными свойствами и адсорбционной эффективностью, подчеркивая потенциал активированного угля, полученного из использованной кофейной гущи, для практических приложений в очистке сточных вод.

Ключевые слова: *Гидротермальная карбонизация; использованная кофейная гуща; активированный уголь; адсорбция метиленового синего; очистка воды.*

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СУДАҒЫ АУЫР МЕТАЛЛ ИОНДАРЫН ТАЗАЛАУҒА АРНАЙЫ MXENE ВАКАНСИЯЛЫҚ ИНЖЕНЕРИЯСЫ: МЕХАНИЗМ, СИНТЕЗ ЖӘНЕ ҚОЛДАНЫСЫ

Аңдапа: *Ауыр металдардан ластанған су ресурстары қазіргі замандағы ең ауқымды мәселесіне айналған, сол үшін ауыр металдарды судан тазартуға арналған жаңа және эффективті материалдарды ойлап табу керек болады. Ғалымдар екі өлшемді өтпелі металл карбидтері мен нитридтерін (MXenes) жақсы адсорбент санағанымен, бұл материалдың бастапқы үлгілерінде табиғи құрылымдық дефектілер жиі кездеседі. Материалдың толық потенциалын ашуға кедергі жасап отыған – нанопарақтардың бір-біріне жақын орналасып қабаттасуы және бетіндегі активті*