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Impact of Bagasse Carbonization Temperature on Activated Carbon Properties for Chromium Hexavalent Adsorption and an Environmental Analysis

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Abstract

The electroplating industry discharges Chromium Hexavalent [Cr(VI)] at concentrations as high as 48.7 mg/L, far exceeding the permissible limit of 0.1 mg/L. Adsorption using activated carbon derived from cellulose-rich agro-waste bagasse offers a cost-effective and efficient Cr(VI) removal solution. However, the influence of carbonization temperature (450–600°C) on bagasse-derived activated carbon's properties and adsorption performance remains poorly understood. This study investigates the effect of carbonization temperature on Cr(VI) adsorption efficiency while conducting a life cycle assessment (LCA) to evaluate the environmental implications of production under varying thermal conditions. The research encompasses four key stages: carbonization, activation, adsorption testing, and environmental impact analysis. Results demonstrate that higher carbonization temperatures (up to 600°C) enhance Cr(VI) adsorption removal (up to 72,57%) and improve activated carbon quality. However, LCA reveals that the highest temperature corresponds to the most significant environmental impact, particularly in acidification (10.25%), freshwater aquatic ecotoxicity (15.89%), and human toxicity (16.08%) due to H_2SO_4 and electricity use, and the lowest yield. Balancing performance and sustainability, a carbonization temperature of 550°C is recommended, offering optimal adsorption efficiency, higher yield, and reduced environmental harm. This research significantly progresses agro-waste-derived adsorbent technology for sustainable industrial wastewater treatment by systematically quantifying process efficiency versus environmental sustainability trade-offs.

INTRODUCTION

The rapid expansion of industrial activities, particularly electroplating operations, has led to significant environmental release of chromium, a heavy metal of considerable toxicological concern. Chromium exists in multiple oxidation states, with hexavalent chromium (Cr(VI)) demonstrating approximately 100-fold greater toxicity compared to its trivalent counterpart (Cr(III)) (Sawicka et al., 2021). Chronic exposure to Cr(VI) compounds is associated with numerous adverse health effects, including severe ocular, respiratory, and dermatological irritation (Mohanty et al., 2023). Of particular environmental significance, electroplating effluents frequently contain Cr(VI) concentrations as high as 48.7 mg/L (More & Gupta, 2021), dramatically exceeding the regulatory threshold of 0.1 mg/L established for safe discharge. This substantial discrepancy underscores the critical need for effective treatment technologies to reduce Cr(VI) concentrations to compliant levels in industrial wastewater streams.

Several methods for processing electroplating industrial waste to remove Cr(VI) include precipitation, coagulation, ion exchange, electrolysis, and the application of membrane technology (Irshad et al., 2023). However, these

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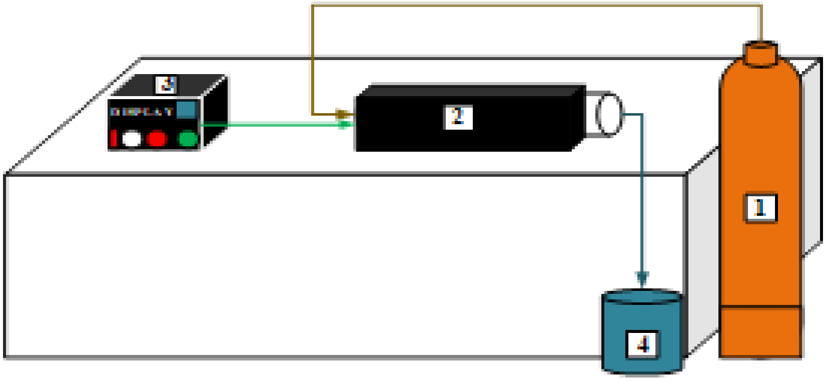

Figure 1. Carbonization reactor apparatus.

various methods require expensive equipment systems, lots of chemicals, and the presence of sludge, which requires further handling (Demiral et al., 2008). As an alternative, the adsorption method has been identified as a relatively economical and simple way to remove chrome from industrial waste (Thallapalli et al., 2015).

The adsorption process involves absorbing adsorbate (absorbed substance) by an adsorbent (solid surface) (Qiu et al., 2022). Activated carbon is the type of adsorbent often used to remove Cr(VI) levels. The activated carbon raw materials come from various sources, such as rice husk (Romero-Hernandez et al., 2024), corn stalk (Zhao et al., 2020), palm leaves (Islam et al., 2024), durian rind (Sulistiyo et al., 2022), cashew nut shell (Fonseca-Bermúdez et al., 2024), and food industry by-products. As one agricultural waste, bagasse is a potential raw material to produce activated carbon because it contains 50% cellulose, 25% hemicellulose and 25% lignin (Pandey et al., 2000).

Despite growing interest in bagasse-derived activated carbon for heavy metal remediation, critical knowledge gaps persist regarding the temperature-dependent optimization of its production. Current studies have mainly overlooked two fundamental aspects: the systematic correlation between carbonization temperature (450-600°C) and the resulting physicochemical properties governing Cr(VI) adsorption and the environmental consequences of temperature selection across the production lifecycle. This study addresses these dual challenges by innovatively combining materials characterization with life cycle assessment (LCA) to establish temperature-property-performance-environment relationships. Specifically, we investigate how thermal treatment conditions modulate bagasse-derived carbon's carbon and adsorption capacity while quantifying the associated environmental trade-offs. Our findings will provide a science-based framework for selecting carbonization temperatures that maximize Cr(VI) removal efficiency, material yield, and ecological sustainability, a crucial advancement for developing cost-effective and environmentally responsible water treatment solutions.

MATERIALS AND METHOD

Materials

Bagasse used in this study was obtained from PG Kebon Agung Malang. Supporting materials used were Sulfuric Acid (H_2SO_4) 98%, Potassium dichromate ($K_2Cr_2O_7$) 99%, Whatman filter paper grade 42, Phosphoric acid 85%, 1,5-diphenyl carbazide, acetone, and aquadest.

Equipment

The carbonization reactor system, as schematically depicted in Figure 1, consists of four essential components: (1) a high-pressure nitrogen (N_2) cylinder equipped with a precision regulator to maintain an oxygen-free environment, (2) a heat-resistant 316-grade stainless steel reactor chamber (18 cm × 18 cm × 27 cm) designed for operation, (3) a temperature controller to regulate the carbonization process; and (4) a gas trap to capture volatile byproducts generated during carbonization.

Carbon Preparation

The raw bagasse was washed with distilled water to remove surface impurities and cut into approximately 1 cm pieces. The material was oven-dried at 115±5°C for 1 hour to remove moisture content, then cooled in a desiccator for 15 minutes before weighing. For carbonization, the dried bagasse was placed in a reactor and heated to

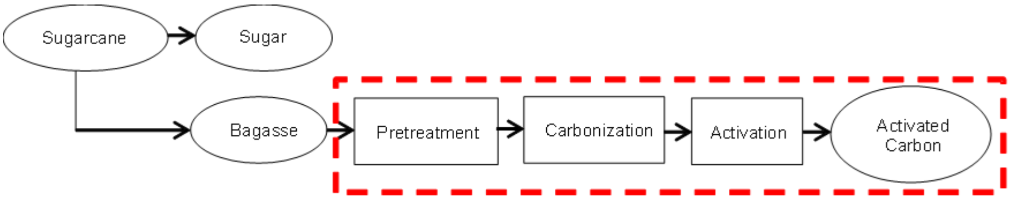

Figure 2. LCA scope for activated carbon production from sugarcane bagasse.

temperatures ranging from 450-600°C for 2 hours under continuous N_2 gas flow to maintain an oxygen-free environment. The resulting carbonized material is mechanically ground using a mortar and pestle to achieve particle sizes of -80+120 mesh (Asrijal et al., 2014). The carbon mass was measured repeatedly until a constant weight, enabling the calculation of the carbonization yield through gravimetric analysis.

Activation Carbon and Characterization

The carbon activation process was performed using 0.3 M H_2SO_4 at an activator-to-carbon ratio of 15:1 (v/w). The mixture was homogenized at 80°C for 1 hour under continuous stirring using a hot plate with a magnetic stirrer. Following activation, the slurry was vacuum-filtered through Whatman No. 42 filter paper to separate the acidic filtrate from the solid-activated carbon. The obtained carbon was thoroughly washed with distilled water until it had a neutral pH. Subsequent drying was conducted in a convection oven at 115±5°C for 30 minutes, then cooling in a desiccator for 15 minutes. Comprehensive characterization included determination of moisture content, volatile matter, ash content, and fixed carbon percentage (Nasional, 1995), complemented by elemental analysis using X-ray fluorescence spectroscopy (XRF).

Adsorption

In each test, 3 g of activated carbon was introduced into 100 mL of Cr(VI) solution and agitated in an orbital shaker at 90 rpm for 75 minutes under controlled room temperature conditions (25±2°C). Following the adsorption process, the filtrate's residual Cr(VI) concentration was quantitatively analyzed using UV-Vis spectrophotometry according to the Indonesian National Standard method (SNI 6989.71-2009). The analytical procedure involved the complexation of Cr(VI) with 1,5-diphenylcarbazide in an acidic medium, which produces a characteristic purplish-red chromogen exhibiting maximum absorbance at 540 nm (Nasional, 2009). The measured absorbance at this wavelength shows direct proportionality to the Cr(VI) concentration, enabling precise quantification of the adsorption efficiency.

Life Cycle Assessment

Goal and Scope

This study employs a gate-to-gate approach encompassing bagasse preparation, carbonization, and activation processes (Figure 2) while excluding nitrogen production and equipment manufacturing from the system boundaries. We utilized the East Java grid mix from the OpenLCA database for electricity inputs, which incorporates power generation from coal (PLTU Paiton) and hydroelectric sources (PLTA Brantas and PLTA Wlingi). The discussion focuses on the three most significant environmental impacts identified through LCA. Figure 3 shows the Database Element Gate-to-Gate Scope of bagasse-activated Carbon.

Life Cycle Inventory

This study obtained primary data through controlled laboratory experiments, with mass balance calculations adjusted to the functional unit of 20 g activated carbon production. Energy consumption for electrical equipment (carbonization reactor, oven, and magnetic stirrer) was precisely measured using a digital wattmeter to ensure accurate energy input quantification.

Life Cycle Impact Assessment

This study employed OpenLCA software with the CML IA Baseline 2000 methodology, implementing EU 25+3 (2000) normalization references to categorize, characterize, and evaluate the potential environmental impacts identified in the inventory analysis.

Interpretation

The interpretation phase constitutes the critical evaluation stage where LCI and LCIA

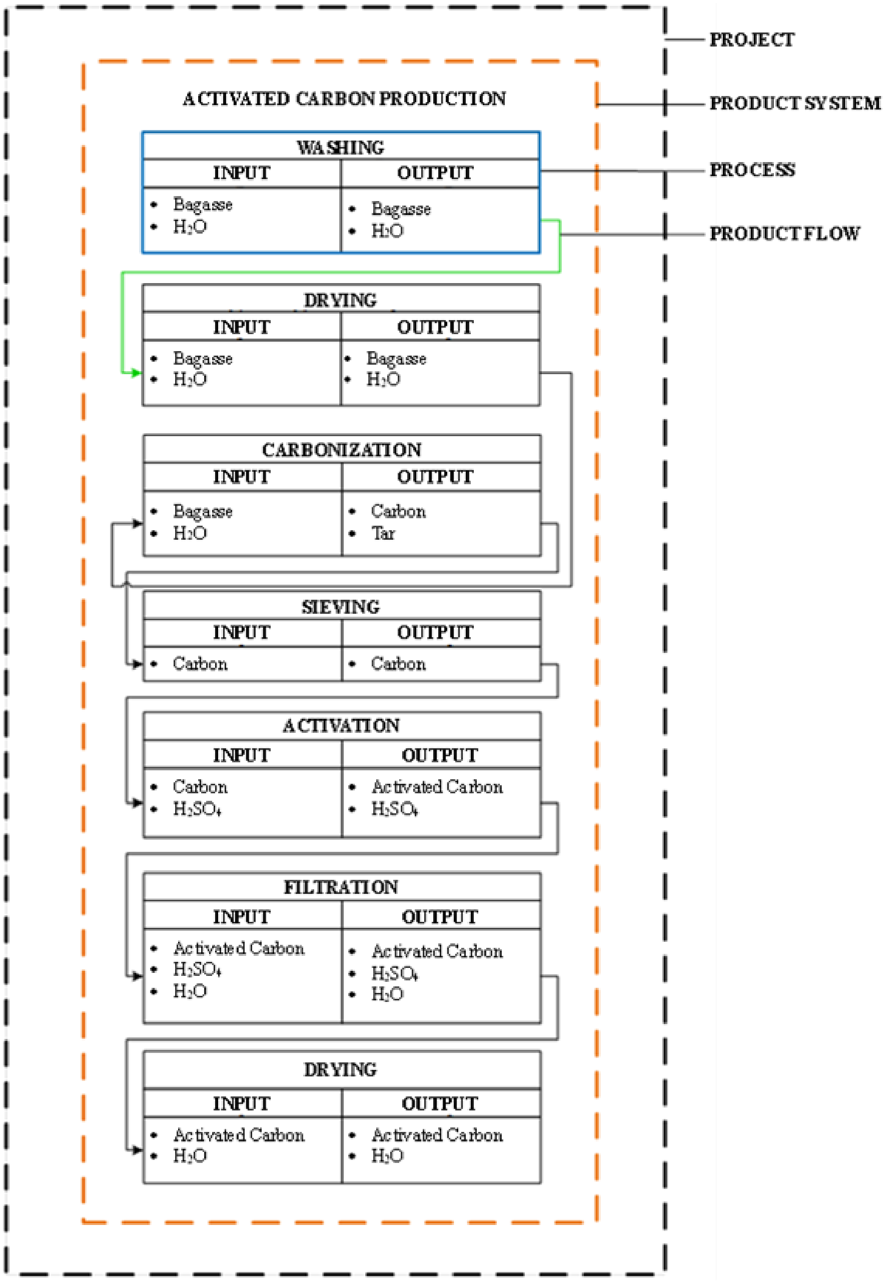

Figure 3. Database element gate-to-gate scope of bagasse activated carbon.

results are analyzed to: (1) derive scientifically valid conclusions, (2) identify significant environmental hotspots, and (3) inform decision-making by the study's predefined goals and scope. This systematic approach ensures robust and actionable findings from the life cycle assessment.

RESULTS AND DISCUSSION

The compositional analysis of bagasse (Table 1) revealed cellulose, hemicellulose, and lignin as the primary structural components, serving as the fundamental carbon sources for activated carbon production. These three biopolymers accounted for most biomass composition, consistent with typical lignocellulosic material characteristics. Notably, silicate compounds were also detected, which undergo transformation into ash residues during carbonization (Hamidu et al., 2025). This compositional profile confirms the suitability of bagasse as a precursor material for activated carbon synthesis, while the silicate content explains the observed ash formation during thermal processing.

Figure 4 shows the effect of Temperature on Sugarcane Bagasse Carbonization Yield. The experimental results demonstrate an inverse correlation between processing temperature and

Table 1. Bagasse content.

Component	Percentage (%)
Cellulose	35.22
Hemicellulose	22.18
Lignin	19.04
Silicate	3.04

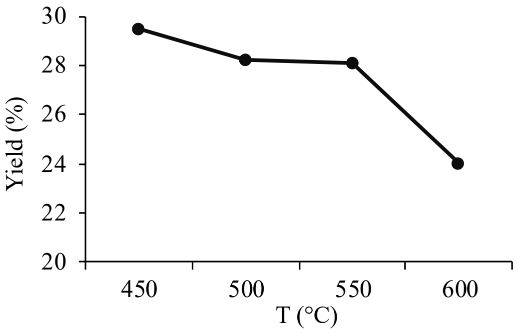

Figure 4. Effect of temperature on sugarcane bagasse carbonization yield.

product yield, aligning with fundamental pyrolysis mechanisms. The carbonization process involves complex thermochemical transformations comprising four concurrent pathways: (1) dehydration, (2) depolymerization, (3) covalent bond scission, and (4) structural rearrangement of hydrocarbon matrices (Ge et al., 2022). These reactions promote carbon enrichment primarily through moisture elimination and the evolution of volatile compounds (CO_2, CH_4, and CO), with reaction kinetics becoming more pronounced at elevated temperatures, accounting for the progressive yield reduction observed across the experimental temperature spectrum. From an industrial standpoint, moderate carbonization temperatures (450-550°C) present significant practical benefits by preserving higher mass yields. This improved mass retention efficiency directly correlates with lower feedstock consumption per unit output of activated carbon.

Following carbonization, the next step involved chemical activation using 0.3 M H_2SO_4 to enhance the properties of the activated carbon. The characteristics of activated carbon results (Table 2) indicate that the product met the requirements for technical-grade activated carbon according to SNI 06-3730-1995 (Nasional, 1995). The study revealed that a lower carbonization temperature (450°C) yielded activated carbon with higher moisture content (1.7%), whereas a higher temperature (600°C) produced a sample with lower moisture content (0.21%). Thus, based on these findings, a higher carbonization temperature is preferable for producing high-quality activated carbon.

Based on the volatile substance content, a higher carbonization temperature also positively impacts the product. A higher carbonization temperature (600^{0}C) gives the lowest volatile matter concentration with only 16.33%, while a lower temperature(450^{0}C) leaves 24.3% of volatile substance. A higher carbonization temperature vaporizes volatile substances such as CO, CO_2, CH_4, and H_2 more effectively than a lower temperature. Even if activated carbon products in all temperature variables met the criteria for technical activated carbon (less than 25%), a higher temperature is more favorable since it produces a lower volatile content. The process of pore formation generally occurs due to volatile molecules from biomass waste and water molecules during carbonization, resulting in an opening in the carbon structure (Mathangi et al., 2021).

A fixed carbon test also shows that a higher carbonization temperature is more beneficial than a lower one, even though all the different temperatures in carbonization result in a product that meets the technical activated carbon criteria (minimum 65%). A higher operating condition of 600^{0}C gives 73.71% of fixed carbon, while it was only 67.27% for 450^{0}C. Fixed carbon content is important in adsorption because it influences the carbon material's surface area and structure, directly impacting its ability to adsorb substances.

Table 2. Quality of activated carbon produced at different temperature variations.

Parameter	Temperature (°C)				Standard
	450	500	550	600	(SNI 06-3730-1995)
Water content (%)	1.7	0.61	0.52	0.21	≤ 25
Ash content (%)	8.43	8.87	9.36	9.96	≤ 10
Volatile matter (%)	24.3	18.47	17.37	16.33	≤ 25
Fixed carbon (%)	67.27	72.79	73.40	73.71	≥ 65

Table 3. Carbon and activated carbon compounds reduction.

Variable (°C)	Material	Compounds (%)			
		SiO_2	K_2O	CaO	Fe_2O_3
450	Carbon	33.20	4.70	29.50	8.11
	Activated Carbon	32.30	2.00	28.10	7.29
	Reduction	**0.90**	**2.70**	**1.40**	**0.82**
500	Carbon	35.40	6.74	34.50	12.10
	Activated Carbon	33.10	2.20	28.00	8.33
	Reduction	**2.30**	**4.54**	**6.50**	**3.77**
550	Carbon	38.20	7.19	38.80	12.00
	Activated Carbon	35.90	1.80	27.80	7.34
	Reduction	**2.30**	**5.39**	**11.00**	**4.66**
600	Carbon	33.90	7.84	36.70	12.10
	Activated Carbon	31.30	1.60	21.20	5.32
	Reduction	**2.60**	**6.24**	**15.50**	**6.78**

In contrast to water content, volatile matter, and fixed carbon, a higher temperature negatively affects the product on ash content parameter. At a temperature variable of 450^{0}C, the lowest percentage of ash is about 8.43%, and the highest is 600^{0}C at 9.96%. It shows that a higher carbonization temperature increases non-volatilized inorganic compounds, including silicates and minerals contained in activated carbon, as the temperature increases. However, all the variables show that the ash content meets the technical activated carbon criteria (under 25%). The activation process using H_2SO_4 effectively reduces the content of non-volatile inorganic compounds because these contents will dissolve in H_2SO_4.

The XRF analysis results presented in Table 3 indicate the compositional distribution of carbon and activated carbon compounds. Consistent with prior studies on ash content, the combustion of sugarcane bagasse primarily yields inorganic constituents such as SiO_2, Al_2O_3, Fe_2O_3, and K_2O (Singh et al., 2021). As evidenced in Table 3, the carbon content exhibits a progressive decline with increasing carbonization temperature. This trend can be attributed to the dissolution of pore-blocking inorganic compounds in H_2SO_4, which subsequently enhances the surface area of the activated carbon.

Figure 5. demonstrates that activated carbon produced at higher carbonization temperatures exhibits superior Cr(VI) removal efficiency compared to those carbonized at lower temperatures. The results indicate a progressive increase in Cr(VI) removal percentage from 450°C to 600°C, reaching a maximum removal efficiency of 72.57%. This trend suggests an inverse relationship between Cr(VI) concentration and carbonization temperature. The enhanced performance can be attributed to the increased surface area of activated carbon generated at elevated temperatures. A greater surface area provides additional active sites for adsorption, thereby improving the material's capacity to retain adsorbate molecules (Liu et al., 2024).

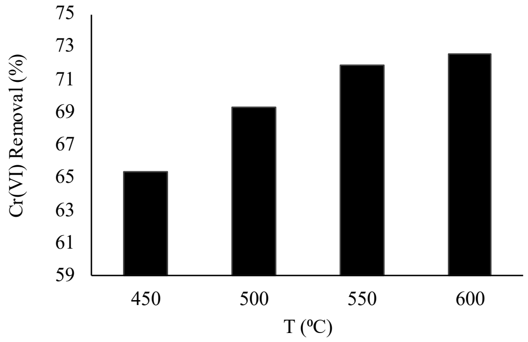

Figure 5. Cr(VI) removal.

The characterization and Cr(VI) removal show that a higher temperature of 600°C is more favorable than a lower temperature. However, higher temperatures potentially increase the environmental impact. Therefore, a life cycle assessment was performed to evaluate the environmental impact of different temperature operating conditions on the production process of activated carbon. In addition, the environmental impact assessment is also beneficial in identifying hotspots of the overall process. Hotspot analysis can be a reference for considering future improvements to develop processes with a lower environmental impact. The mass balance of activated carbon based on the laboratory experiment shown in Table 4.

Table 4. Mass balance of sugarcane bagasse-derived activated carbon across varied carbonization temperatures.

Process Stage	**Input/Output**	**Mass (g)**			
		450°C	**500°C**	**550°C**	**600°C**
1. Bagasse Pre-treatment	**Input**				
- Washing	- Bagasse (s)	92.89	97.44	97.24	112.80
	- H_2O (l)	8,917.57	9,354.22	9,335.47	10,829.14
	Output				
	- Bagasse (s)	92.89	97.44	97.24	112.80
	- H_2O (l)	8,917.57	9,354.22	9,335.47	10,829.14
- Drying	**Input**				
	- Bagasse (s)	92.89	97.44	97.24	112.80
	- H_2O (l)	3.72	3.90	3.89	4.51
	Output				
	- Bagasse (s)	89.18	93.54	93.35	108.29
	- H_2O (g)	3.72	3.90	3.89	4.51
2. Production					
- Carbonization	**Input**				
	- Bagasse (s)	89.18	93.54	93.35	108.29
	Output				
	- Carbon (s)	26.28	26.41	26.23	26.00
	- Tar (aq)	62.89	67.14	67.13	82.29
- Sieving	**Input**				
	- Carbon (s)	26.28	26.41	26.23	26.00
	Output				
	- Carbon (s) (+80-120 mesh)	21.03	21.12	20.98	20.80
	- Carbon (s) (+120 mesh)	5.26	5.28	5.25	5.20
3. Activation Process	**Input**				
- Activation	- Carbon (s)	21.03	21.12	20.98	20.80
	- H_2SO_4 (l)	8.82	8.82	8.82	8.82
	Output				
	- Activated Carbon (s)	21.03	21.12	20.98	20.80
	- H_2SO_4 (l)	8.82	8.82	8.82	8.82
- Filtration	**Input**				
	- Activated Carbon (s)	21.03	21.12	20.98	20.80
	- H_2SO_4 (l)	8.82	8.82	8.82	8.82
	- H_2O (l)	2,966.67	2,966.67	2,966.67	2,966.67
	Output				
	- Activated Carbon (s)	20	20	20	20
	- H_2O in Activated Carbon (l)	14.83	14.83	14.83	14.83
	- Activated Carbon loss (s)	1.25	1.34	1.20	1.02
	- H_2SO_4 (l)	8.60	8.60	8.60	8,60
	- H_2O (l)	2,951.83	2,951.83	2,951.83	2,951.83
- Drying	**Input**				
	- Activated Carbon (s)	20	20	20	20
	- H_2O (l)	14.83	14.83	14.83	14.83
	Output				
	- Activated Carbon (s)	20	20	20	20
	- H_2O (l)	14.83	14.83	14.83	14.83

The Indonesian electricity grid supplied the electrical energy requirements for the activated carbon production system. Electricity consumption was measured using a wattmeter for all energy-intensive processes, including drying (using an oven), carbonization (in the reactor), activation (stirring and heating), and the final drying of the activated carbon (Table 5). A Life Cycle Impact

Table 5. Electrical energy consumption in activated carbon production from sugarcane bagasse across different carbonization temperatures.

Temperature (°C)	Drying (bagasse)		Carbonization			Activation		Drying (activated carbon)	
	KWh	Time (h)	KWh	Time (h)	Temperature rise (°C)	KWh	Time (h)	KWh	Time (h)
450	2	4	3.5	2	2	1	1	2	1
500	2	4	3.5	2	2.5	1	1	2	1
550	2	4	4	2	3	1	1	2	1
600	2	4	4	2	4	1	1	2	1

Table 6. Life cycle impact assessment results of activated carbon production across all temperature variables using OpenLCA.

No.	Impact categories	Unit	Activated Carbon ($\times 10^{-4}$)			
			450°C	500°C	550°C	600°C
1	Abiotic depletion	MJ	0	0	0	0
2	Abiotic depletion	kg Sb eq	0	0	0	0
3	Acidification	kg SO_2 eq	1.499	1.544	1.542	1.700
4	Eutrophication	kg PO_4- eq	0.689	0.723	0.721	0.837
5	Freshwater aquatic ecotox	kg 1,4-DB eq	34.8	36.5	36.5	42.3
6	Global warming	kg CO_2 eq	66.0	69.2	69.0	80.1
7	Human toxicity	kg 1,4-DB eq	36.85	38.65	38.55	44.75
8	Marine aquatic ecotoxicity	kg 1,4-DB eq	463.9	486.7	485.7	563.4
9	Ozone layer depletion	kg CFC-11 eq	0	0	0	0
10	Photochemical oxidation	kg C_2H_4 eq	0.022	0.022	0.022	0.022
11	Terrestrial ecotoxicity	kg 1,4-DB eq	0.878	0.921	0.919	1.10

Assessment (LCIA) was conducted using OpenLCA software with the CML-IA Baseline method to evaluate the environmental impacts of bagasse-derived activated carbon production. The assessment began with the characterization phase, which facilitates the comparison of Life Cycle Inventory (LCI) results across different impact categories. Table 6 presents the results for 11 environmental impact categories obtained through this methodology. Normalization was performed to standardize the disparate units of measurement across impact categories and evaluate their relative contributions. The normalization results (Table 7) revealed three dominant environmental impacts, listed in descending order of significance: Freshwater aquatic ecotoxicity, Acidification and Human toxicity. Consequently, the subsequent analysis focuses on these three critical impact categories, representing the most significant environmental burdens associated with the production process.

The freshwater aquatic ecotoxicity potential, which quantifies the harmful effects of toxic substances on freshwater ecosystems, demonstrates a temperature-dependent trend in the carbonization process. As illustrated in Figure 6, the environmental impacts for temperatures of 450°C, 500°C, and 550°C remain comparable (36.5 $\times 10^{-4}$ kg 1,4-DB eq) while increasing significantly by 15.89% at 600°C (42.30 $\times 10^{-4}$ kg 1,4-DB eq). This elevated impact primarily stems from using of H_2SO_4 in the activation process, a highly corrosive and toxic substance known for its detrimental effects on aquatic ecosystems. Furthermore, the cumulative electricity consumption throughout the production chain - including biomass drying (8-9 kWh), carbonization (10-12 hours), and product drying- contributes substantially to the environmental burden. The indirect impacts are exacerbated by East Java's coal-fired power plants (e.g., Paiton PLTU), which generate wastewater containing persistent heavy metals like lead (Pb) that bioaccumulate in aquatic organisms (Raj & Das, 2023). Additionally, the carbonization process yields liquid tar byproducts, with the 600°C condition producing the highest quantity (Table 4), further compounding the ecological risks through potential water contamination.

Table 7. Comparison of impact category values in OpenLCA.

Impact categories	**Activated Carbon ($\times 10^{-9}$)**			
	450°C	**500°C**	**550°C**	**600°C**
🟩 Abiotic depletion	0	0	0	0
🟩 Abiotic depletion	0	0	0	0
🟩 Ozone layer depletion	0	0	0	0
🟨 Terrestrial ecotoxicity	0.076	0.079	0.079	0.092
🟧 Marine aquatic ecotoxicity	0.104	0.110	0.109	0.127
🟧 Global warming	0.127	0.133	0.133	0.154
🟧 Photochemical oxidation	0.129	0.129	0.129	0.129
🟧 Eutrophication	0.372	0.390	0.389	0.452
🟥 Human toxicity	0.736	0.772	0.771	0.894
🟥 Acidification	0.890	0.917	0.916	1.007
🟫 Fresh water aquatic ecotox	1.668	1.750	1.746	2.026

Note:

🟩 : Very low
🟨 : Low
🟧 : Medium
🟥 : High
🟫 : Very High

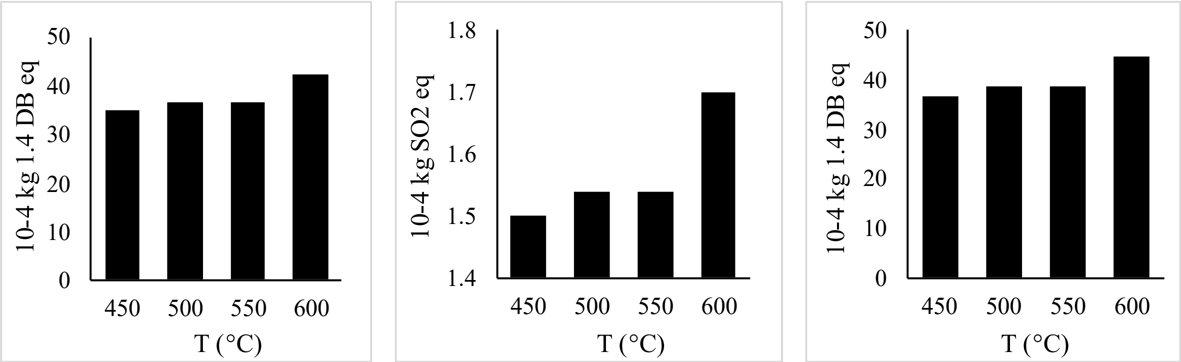

Figure 6. Environmental impact for impact category (a) Freshwater aquatic ecotoxicity, (b) Acidification, and (c) Human toxicity.

The second significant environmental impact is acidification, primarily from deposition inorganic compounds, including sulfates, nitrates, and phosphates, in aquatic and terrestrial ecosystems. Our analysis reveals a clear temperature-dependent trend in acidification potential, with the 450°C carbonization temperature demonstrating the lowest impact. While 500°C and 550°C show marginally higher effects, the 600°C condition exhibits the most substantial acidification impact (1.7×10^{-4} kg SO_2 eq), representing a 10.25-fold increase compared to the 550°C condition. This pronounced effect stems primarily from the 0.3 M H_2SO_4 activation process, where residual acid discharged into water systems contributes directly to aquatic acidification, potentially disrupting delicate ecosystems. Furthermore, the combustion process releases sulfur dioxide (SO_2), a known precursor to acid rain. At the same time, the liquid tar byproduct - particularly abundant at 600°C, appears to be a critical factor in the observed impact escalation. Notably, while H_2SO_4 and electricity inputs remain constant between 550°C and 600°C treatments, the dramatic increase in tar production at the higher temperature (as evidenced in Table 4) suggests tar composition may play a pivotal role in enhancing acidification potential.

The third significant impact is human toxicity, primarily caused by emissions of hazardous substances, including heavy metals, which pose considerable risks to human health (Mitra et al., 2022). This impact stems largely from electricity consumption during the carbonization process, where electrical energy is converted into thermal energy at temperatures ranging from 450–600°C. The high-temperature reactor poses direct risks, such as severe skin burns upon contact. Additionally, using H_2SO_4 during activation introduces further hazards, as sulfuric acid is highly corrosive and can cause extensive damage to the respiratory and digestive systems if inhaled or ingested (Benomran et al., 2008). The human toxicity impact follows a trend similar to acidification, with 450°C, 500°C, and 550°C exhibiting comparable effects, while 600°C demonstrates the highest impact 44.75×10^{-4} kg 1,4-DB eq, representing a 16.08% increase over 550°C.

Although higher carbonization temperatures enhance Cr(VI) adsorption performance, they reduce yield and amplify environmental impacts concurrently. Thus, selecting optimal operating conditions requires balancing multiple factors: adsorption efficiency, product yield, and environmental sustainability. Our findings highlight 550°C as the most favourable compromise, delivering high-quality activated carbon with competitive performance while minimizing adverse ecological and health effects.

As illustrated in Figure 4, the carbon yield significantly declines at 600°C, while environmental impacts sharply increase at this temperature. Although carbonization at 600°C yields superior product quality and performance (Figure 5), the marginal improvement in Cr(VI) removal efficiency and fixed carbon content must be weighed against substantial trade-offs. Notably, operating at 600°C reduces the carbon yield by 4% while significantly exacerbating three key environmental impacts: acidification (10.25%), freshwater aquatic ecotoxicity (15.89%), and human toxicity (16.08%). Furthermore, the 550°C process offers an additional practical advantage, requiring one hour less processing time due to faster reactor heating. These findings demonstrate that 550°C represents the optimal balance between performance efficiency and sustainability, delivering comparable adsorption capacity while maximizing yield and minimizing environmental burdens.

The life cycle impact assessment (LCIA) revealed three dominant environmental impact categories: freshwater aquatic ecotoxicity, acidification, and human toxicity. These impacts primarily originate from two key processes: the chemical activation and electricity consumption throughout the production chain. The acidic nature of H_2SO_4 poses direct environmental risks, including aquatic toxicity through pH alteration and potential human health hazards during handling (da Silva-Rêgo et al., 2022). Furthermore, the indirect impacts stem from electricity generation, which in this study derives from coal-fired power plants. Such energy sources contribute substantially to acid deposition through SOx/NOx emissions and climate-altering greenhouse gases, ultimately affecting aquatic ecosystems and human populations through environmental degradation and associated health consequences (Aakko-Saksa et al., 2023). Electricity-intensive processes, particularly biomass drying, carbonization, and final product drying account for most of these secondary impacts.

Several potential improvements can be explored to enhance the environmental sustainability of bagasse-activated carbon production. The current manufacturing process relies on grid electricity, a significant environmental impact factor. While the present study utilized conventional grid electricity, future implementations could substantially reduce this impact by transitioning to renewable energy sources. Additionally, environmental performance could be further improved by optimizing the activation process through reduced H_2SO_4 concentrations (below 0.3 M), and investigating alternative, more environmentally benign activating agents. These modifications would maintain production efficiency while minimizing the ecological footprint of the activation process, thereby advancing toward greener manufacturing practices for activated carbon.

CONCLUSION

This study identifies 550°C as the optimal carbonization temperature for sugarcane bagasse-derived activated carbon, achieving an exceptional balance between Cr(VI) removal efficiency (71.88%), production yield (28.1%), and environmental sustainability. Contrary to conventional practice favoring higher temperatures (600°C) that reach the highest Cr(VI) removal (72,57%), our results demonstrate that 550°C provides comparable adsorption performance while offering three significant advantages: (1) reduced energy consumption, (2) higher production yield, and (3) substantially lower environmental impacts - particularly in freshwater ecotoxicity, acidification, and human toxicity. These findings challenge existing production paradigms and establish new benchmarks for sustainable adsorbent manufacturing.

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