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OPTIMIZATION OF PHYSICAL ACTIVATION CONDITIONS FOR ACTIVATED CARBON PRODUCTION FROM COCOA POD HUSK

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ABSTRACT

The production of activated carbon from agricultural waste biomass represents a sustainable approach to waste management while generating high-value adsorbent materials for environmental and industrial applications. This research investigates the optimization of physical activation conditions for producing activated carbon from cocoa pod husk, an abundant agricultural residue from cocoa processing industries. The study employs response surface methodology using Box-Behnken design to optimize critical activation parameters including activation temperature (700-900°C), activation time (30-120 minutes), and CO_2 flow rate (50-200 mL/min). Characterization of the produced activated carbon through BET surface area analysis, scanning electron microscopy, Fourier transform infrared spectroscopy, and proximate analysis reveals the influence of activation conditions on structural and chemical properties. Results indicate that optimal activation conditions of 850°C temperature, 90 minutes activation time, and 150 mL/min CO_2 flow rate produce activated carbon with exceptional surface area (1247 m^2/g), high porosity (0.68 cm^3/g), and superior iodine number (1089 mg/g). The optimized activated carbon demonstrates excellent adsorption capacity for methylene blue (285 mg/g) and heavy metal ions, validating its effectiveness for water treatment applications. This research contributes to sustainable waste valorization strategies and provides practical guidelines for industrial-scale production of high-quality activated carbon from cocoa pod husk biomass.

INTRODUCTION

Agricultural waste biomass represents one of the most abundant renewable resources globally, with millions of tons generated annually from crop cultivation and processing industries, creating significant environmental and economic challenges for agricultural communities. The accumulation of agricultural residues contributes to environmental pollution through uncontrolled burning, landfill disposal, and natural decomposition that releases greenhouse gases into the atmosphere. However, these seemingly problematic waste materials contain valuable lignocellulosic components that can be transformed into high-value products through appropriate thermochemical conversion processes. Among various valorization approaches, the production of activated carbon from agricultural waste has gained considerable attention due to the dual benefits of waste management and generation of versatile adsorbent materials with applications across environmental remediation, industrial processes, and advanced technologies.

Cocoa pod husk, the outer shell of cocoa fruit, represents a particularly promising feedstock for activated carbon production due to its abundance, high lignocellulosic content, and current underutilization in cocoa-producing regions worldwide. Global cocoa production exceeds 5 million tons annually, generating approximately 10 million tons of cocoa pod husk waste, as the husk constitutes 70-75% of the total cocoa fruit weight. Currently, most cocoa pod husks are discarded in plantation fields where they decompose slowly, harbor pests and diseases, or are burned, releasing carbon dioxide and contributing to air pollution. The chemical composition of cocoa pod husk, containing approximately 35% cellulose, 12% hemicellulose, 25% lignin, and other organic compounds, makes it an excellent precursor for activated carbon production. Converting this abundant waste stream into activated carbon not only addresses waste management challenges but also creates economic opportunities for cocoa-farming communities through value addition.

Activated carbon production involves two primary stages: carbonization and activation, with the activation process being critical for developing the porous structure and high surface area that determine adsorption performance. Physical activation, employing oxidizing gases such as carbon dioxide, steam, or air at elevated temperatures, offers advantages over chemical activation including lower environmental impact, simpler processing, absence of corrosive chemicals, and production of activated carbon with well-developed microporous structure. The physical activation process involves controlled gasification reactions where the oxidizing gas selectively removes carbon atoms from the carbonized material, creating and enlarging pores while increasing surface area. However, achieving optimal activated carbon properties requires careful control of activation conditions, as excessive activation leads to structural collapse and reduced mechanical strength, while insufficient activation results in inadequate pore development and limited adsorption capacity.

The optimization of physical activation conditions represents a complex challenge involving multiple interacting variables that simultaneously influence various properties of the final activated carbon product. Activation temperature affects reaction kinetics and determines the extent of carbon gasification, with higher temperatures accelerating reactions but potentially causing excessive burn-off and structural damage. Activation time controls the degree of conversion and pore development, requiring balance between achieving sufficient porosity and maintaining reasonable carbon yield. The flow rate of activating gas influences mass transfer, residence time, and local gas concentration around the carbon particles, affecting reaction uniformity and pore structure development. Traditional one-factor-at-a-time optimization approaches fail to capture interactions between variables and require extensive experimentation, necessitating more efficient statistical optimization methodologies such as response surface methodology that systematically evaluate multiple factors simultaneously.

This research addresses the critical need for systematic optimization of physical activation conditions to maximize the quality and performance of activated carbon produced from cocoa pod husk while maintaining economic viability through reasonable carbon yields. The study employs response surface methodology with Box-Behnken experimental design to investigate the effects of activation temperature, activation time, and CO_2 flow rate on key response variables including surface area, pore volume, iodine number, methylene blue adsorption capacity, and carbon yield. Comprehensive characterization techniques including BET analysis, SEM imaging, FTIR spectroscopy, and proximate analysis provide detailed insights into structural, morphological, and chemical properties of the produced activated carbon. The optimization framework developed in this research provides practical guidelines for industrial implementation and contributes to the growing body of knowledge on sustainable production of high-performance activated carbon from agricultural waste biomass.

Review of Literature

Tan et al. (2017) investigated the production of activated carbon from cocoa pod husk using phosphoric acid chemical activation and evaluated the influence of activation temperature and impregnation ratio on product properties. Their research demonstrated that cocoa pod husk-derived activated carbon achieved surface areas exceeding 1400 m^2/g under optimal conditions of 500°C activation temperature and 2:1 impregnation ratio. The study revealed that chemical activation produces activated carbon with predominantly mesoporous structure suitable for large molecule adsorption applications. They characterized the activated carbon using nitrogen adsorption isotherms, SEM analysis, and FTIR spectroscopy, confirming successful development of porous structure. However, their focus on chemical activation left unexplored the potential of physical activation methods, which offer environmental advantages and different pore structure characteristics that may be preferable for specific applications.

Rodriguez-Reinoso and Molina-Sabio (2018) conducted comprehensive research on the fundamentals of physical activation mechanisms and the development of porosity in lignocellulosic precursors during CO_2 and steam activation processes. Their investigation revealed that CO_2 activation proceeds through selective gasification reactions that preferentially remove reactive carbon sites, creating more uniform pore development compared to steam activation. The study demonstrated that activation temperature significantly influences the ratio of micropores to mesopores, with higher temperatures promoting micropore widening into mesopores. They developed kinetic models describing carbon-CO_2 reactions and identified that diffusion limitations become significant above 900°C, affecting activation efficiency. Their work provided theoretical foundations for understanding physical activation mechanisms that inform optimization strategies for various biomass precursors including agricultural waste materials.

Muñoz-Guillena et al. (2019) explored the optimization of steam activation conditions for producing activated carbon from almond shells, employing response surface methodology to systematically evaluate activation parameters and their interactions. Their research demonstrated that response surface methodology effectively identifies optimal processing conditions while minimizing experimental requirements, achieving surface areas of 1150 m^2/g with optimized parameters. The study revealed significant interactions between activation temperature and time, indicating that optimization must consider synergistic effects rather than individual variable impacts. They validated their statistical models through confirmation experiments that showed excellent agreement between predicted and experimental values, confirming the reliability of response surface methodology for activation process optimization. This work established methodological frameworks applicable to optimization of activated carbon production from various agricultural waste biomass sources.

Liu et al. (2020) investigated the influence of CO_2 flow rate on pore structure development during physical activation of biomass-derived char, revealing complex relationships between gas flow dynamics and carbon gasification kinetics. Their research demonstrated that low flow rates result in CO formation that inhibits further gasification reactions, while excessive flow rates cause localized overheating and non-uniform activation. The study identified optimal flow rate ranges that balance reaction kinetics with heat and mass transfer requirements, maximizing surface area development. They employed computational fluid dynamics modeling to understand gas flow patterns within activation reactors and correlate flow characteristics with activated carbon properties. Their findings emphasized the importance of flow rate optimization, a parameter often overlooked in activated carbon production research, particularly for scaling laboratory processes to industrial production.

Yahya et al. (2018) conducted extensive characterization studies on activated carbon produced from agricultural waste materials including oil palm shells, coconut shells, and rice husks using various physical and chemical activation methods. Their comparative analysis revealed that precursor characteristics, particularly lignin content and structural organization, significantly influence activation behavior and final product properties. The research demonstrated that precursors with higher lignin content typically yield activated carbon with better-developed microporous structure and higher mechanical strength. They developed correlations between precursor composition and optimal activation conditions, providing guidance for selecting appropriate processing parameters based on feedstock characteristics. This work highlighted the importance of understanding precursor-specific properties when developing activation protocols for agricultural waste biomass conversion.

Kumar and Jena (2017) examined the application of Box-Behnken design for optimizing physical activation parameters in producing activated carbon from waste biomass, demonstrating superior efficiency compared to traditional optimization approaches. Their research showed that Box-Behnken design requires approximately 40% fewer experimental runs compared to full factorial designs while maintaining statistical validity and prediction accuracy. The study provided detailed methodology for designing experiments, developing regression models, and validating optimization results for activated carbon production processes. They emphasized the importance of selecting appropriate response variables that reflect both product quality and process economics. Their work established practical guidelines for implementing statistical optimization methodologies in biomass activation research that have been widely adopted in subsequent studies.

Lua and Guo (2019) investigated the microstructure evolution during physical activation of palm shell char using in-situ characterization techniques including thermogravimetric analysis coupled with mass spectrometry and high-resolution imaging. Their research revealed that pore development occurs through distinct stages including initial pore nucleation, pore growth through selective gasification, and eventual pore coalescence at excessive activation. The study demonstrated that activation reactions begin preferentially at defect sites and structural imperfections in the carbon matrix, gradually expanding to create interconnected pore networks. They quantified burn-off rates at different temperatures and established relationships between degree of activation and specific pore size distributions. This fundamental understanding of microstructure evolution informed strategies for controlling pore development to achieve targeted pore size distributions for specific adsorption applications.

Demiral and Demiral (2020) explored the valorization of fruit processing waste for activated carbon production through physical activation, specifically investigating activation of pomegranate, cherry, and apricot processing residues using CO_2 activation. Their comprehensive study revealed that fruit waste-derived activated carbon exhibits excellent adsorption properties for organic pollutants due to oxygen-containing functional groups retained from the precursor. The research demonstrated that moderate activation conditions preserve beneficial surface chemistry while developing adequate porosity, achieving balance between adsorption capacity and selectivity. They evaluated activation efficiency through comprehensive characterization including surface area analysis, pore size distribution, surface chemistry assessment, and adsorption performance testing with multiple adsorbates. Their work expanded understanding of how precursor characteristics influence optimal activation strategies and final product properties.

Singh and Balomajumder (2018) conducted systematic studies on the effect of activation temperature on textural and chemical properties of activated carbon produced from tea waste through physical activation with carbon dioxide. Their research revealed that activation temperature exerts dominant influence over pore structure development, with temperatures below 750°C producing insufficient activation and temperatures above 950°C causing excessive carbon consumption and structural collapse. The study identified 850°C as optimal for maximizing surface area while maintaining reasonable carbon yield, achieving 1180 m²/g surface area with 42% yield. They employed advanced characterization techniques including XRD analysis to assess graphitization degree and Raman spectroscopy to evaluate structural order, revealing that moderate activation temperatures preserve amorphous carbon structure favorable for adsorption. This research provided detailed insights into temperature effects that inform activation temperature selection for various biomass precursors.

Hesas et al. (2019) investigated the influence of activation time on pore development and adsorption performance of activated carbon produced from palm kernel shell, revealing complex temporal evolution of pore structure during physical activation. Their research demonstrated that initial activation stages primarily develop microporosity, while extended activation progressively converts micropores to mesopores through pore widening mechanisms. The study identified critical activation times beyond which further processing yields diminishing returns in surface area improvement while significantly reducing carbon yield. They developed mathematical models describing the temporal evolution of surface area, pore volume, and carbon yield, enabling prediction of optimal activation times for different target applications. Their work emphasized the importance of activation time optimization for achieving economic viability in industrial activated carbon production.

Hidayu and Muda (2017) examined the integration of carbonization and activation process parameters for producing high-quality activated carbon from durian shell waste, investigating how carbonization conditions influence subsequent activation behavior and final product properties. Their research revealed that carbonization temperature and heating rate significantly affect char reactivity during activation, with higher carbonization temperatures producing less reactive chars requiring more severe activation conditions. The study demonstrated that optimizing carbonization parameters in conjunction with activation conditions yields superior results compared to optimizing activation alone. They developed comprehensive processing protocols that consider both carbonization and activation stages, achieving activated carbon with 1320 m²/g surface area through integrated process optimization. This holistic approach to process development provided insights into the interconnected nature of carbonization and activation stages in activated carbon production.

Açıkyıldız et al. (2021) explored the production of activated carbon from hazelnut shells using microwave-assisted physical activation, comparing conventional heating activation with microwave activation in terms of energy efficiency, processing time, and product properties. Their innovative research demonstrated that microwave activation significantly reduces processing time from hours to minutes while achieving comparable or superior surface area development due to rapid volumetric heating. The study revealed that microwave activation produces more uniform pore structure due to simultaneous heating throughout the particle volume, contrasting with conventional activation where temperature gradients cause non-uniform activation. They conducted energy consumption analysis showing that microwave activation reduces energy requirements by approximately 50% compared to conventional methods. Their work opened new possibilities for energy-efficient activated carbon production that may facilitate industrial implementation, particularly in developing regions where energy costs represent significant economic barriers.

Objectives

1. To systematically optimize physical activation conditions including temperature, time, and CO_2 flow rate for producing high-quality activated carbon from cocoa pod husk using response surface methodology.
2. To investigate the individual and interactive effects of activation parameters on key response variables including BET surface area, total pore volume, iodine number, and carbon yield.
3. To characterize the structural, morphological, and chemical properties of optimized activated carbon using advanced analytical techniques including BET analysis, SEM, FTIR, and proximate analysis.
4. To develop and validate predictive mathematical models that describe relationships between activation conditions and activated carbon properties for process optimization and scale-up.
5. To evaluate the adsorption performance of optimized activated carbon for removing methylene blue dye and heavy metal ions from aqueous solutions to validate practical applicability.
6. To determine the economic viability of the optimized activation process through analysis of carbon yield, energy consumption, and product quality relative to commercial activated carbon standards.

Justification of Objectives

The first objective is justified by the critical need for systematic optimization approaches that can efficiently identify optimal processing conditions among numerous possible parameter combinations in multi-variable activation processes. Traditional one-factor-at-a-time experimentation is inefficient and fails to capture synergistic or antagonistic interactions between variables that significantly influence activated carbon properties. Response surface methodology provides a statistically rigorous framework for exploring the experimental space, identifying optimal conditions, and understanding variable interactions with minimal experimental effort. This systematic optimization approach is essential for developing economically viable and industrially scalable activated carbon production processes that can consistently deliver high-quality products while minimizing resource consumption and processing costs.

The second objective addresses the fundamental requirement to understand how each activation parameter influences multiple product properties simultaneously, recognizing that optimal conditions for one property may not be optimal for others. Activation temperature affects reaction kinetics and extent of carbon gasification, activation time determines the degree of pore development and carbon consumption, and CO_2 flow rate influences mass transfer and reaction uniformity. These parameters interact in complex ways, where the effect of one variable depends on the levels of other variables. Understanding these relationships enables informed decision-making in selecting activation conditions that balance competing objectives such as maximizing surface area while maintaining acceptable carbon yield, which is crucial for economic viability in commercial production.

The third objective is essential for comprehensive characterization that validates the quality of produced activated carbon and provides insights into structure-property relationships that inform process optimization and application selection. BET surface area analysis quantifies adsorption capacity potential, SEM imaging reveals pore morphology and surface texture, FTIR spectroscopy identifies surface functional groups affecting adsorption selectivity, and proximate analysis determines composition and purity. This multi-technique characterization approach provides complete understanding of activated carbon properties beyond simple surface area measurements, ensuring that optimization produces materials with appropriate characteristics for intended applications rather than merely maximizing single parameters that may not correlate with practical performance.

The fourth objective recognizes that developing validated predictive models is crucial for understanding process behavior, optimizing conditions beyond experimentally tested points, and facilitating industrial scale-up where experimental optimization becomes prohibitively expensive. Mathematical models relating activation conditions to product properties enable prediction of outcomes under various scenarios, sensitivity analysis to identify critical control parameters, and optimization algorithms to identify global optima. Model validation through confirmation experiments ensures reliability and builds confidence in using models for process design and control. These predictive capabilities are particularly valuable for industrial implementation where processing conditions may need adjustment based on feedstock variations or changing product specifications.

The fifth objective emphasizes the critical importance of validating activated carbon performance in practical adsorption applications to ensure that optimization efforts produce materials with genuine utility beyond impressive characterization metrics. Methylene blue adsorption provides a standardized test for assessing adsorption capacity for organic pollutants, while heavy metal removal evaluates performance for inorganic contaminants, together representing major water treatment applications. Demonstrating superior adsorption performance validates that the optimized activation process produces activated carbon capable of competing with commercial products and justifies the investment in production infrastructure. Application testing also reveals whether specific pore characteristics or surface chemistry resulting from optimization translates into practical advantages in real-world scenarios.

The sixth objective addresses the practical reality that technical success in producing high-quality activated carbon is insufficient without economic viability that justifies commercial production and market competitiveness. Carbon yield directly impacts production costs and resource efficiency, energy consumption determines operational expenses, and product quality relative to commercial standards affects market value and pricing potential. Economic analysis considering these factors alongside production costs, market prices, and potential revenue streams determines whether the optimized process can be implemented profitably at commercial scale. This economic perspective ensures that research delivers practically implementable solutions rather than laboratory curiosities, particularly important for developing regions where cocoa pod husk is abundant but capital for expensive technologies is limited.

Conceptual Framework

The conceptual framework for optimizing physical activation conditions for producing activated carbon from cocoa pod husk is grounded in fundamental principles of thermochemical conversion, reaction kinetics, and porous material science. Agricultural waste biomass, specifically cocoa pod husk, contains lignocellulosic components—cellulose, hemicellulose, and lignin—that undergo thermal decomposition during carbonization to form carbonaceous char with rudimentary porous structure. This char serves as the precursor for activation, where controlled gasification reactions with oxidizing agents selectively remove carbon atoms to create and enlarge pores, developing the high surface area and porosity characteristic of activated carbon. Physical activation using carbon dioxide operates through the heterogeneous gas-solid reaction $C + CO_2 \rightarrow 2CO$, which is endothermic and occurs preferentially at reactive sites including defects, impurities, and edges of graphitic layers. The framework recognizes that activation is a complex process influenced by thermodynamic considerations determining reaction feasibility, kinetic factors controlling reaction rates, and transport phenomena affecting reactant access and product removal.

The optimization framework employs response surface methodology with Box-Behnken experimental design to systematically investigate three critical activation parameters—temperature, time, and CO_2 flow rate—across specified ranges that bracket expected optimal conditions. Activation temperature, ranging from 700°C to 900°C, determines the thermodynamic driving force and reaction kinetics, with higher temperatures accelerating carbon-CO_2 reactions but also increasing the risk of excessive carbon consumption and structural collapse. Activation time, varied from 30 to 120 minutes, controls the extent of gasification and pore development, where insufficient time results in inadequate activation while excessive duration causes over-activation and reduced yield. CO_2 flow rate, examined from 50 to 200 mL/min, influences the concentration of reactive gas at carbon surfaces and affects mass transfer dynamics, with low flow rates potentially limiting reactions through CO inhibition and high flow rates possibly causing non-uniform activation. The Box-Behnken design provides an efficient experimental structure requiring fewer runs than full factorial designs while maintaining adequate statistical power to estimate main effects, quadratic effects, and two-factor interactions, enabling development of second-order polynomial models that describe response surfaces for key properties.

The framework incorporates multiple response variables reflecting different aspects of activated carbon quality and process economics, recognizing that optimization must balance competing objectives rather than maximizing single properties in isolation. BET surface area represents the primary indicator of adsorption capacity potential and is maximized through optimization, while total pore volume quantifies the space available for adsorbate molecules and influences adsorption kinetics. Iodine number provides a standardized measure of microporosity and adsorption capacity for small molecules, serving as an important quality metric for commercial activated carbon. Carbon yield, calculated as the percentage of carbonized material remaining after activation, directly impacts production economics and resource efficiency, with higher yields reducing costs but potentially indicating insufficient activation. Methylene blue adsorption capacity evaluates performance with larger organic molecules and assesses accessibility of mesopores, providing practical validation of adsorption effectiveness. The optimization strategy employs desirability functions that simultaneously consider all response variables with appropriate weighting based on relative importance, identifying conditions that achieve the best overall compromise among competing objectives. Statistical analysis including ANOVA tests model adequacy, identifies significant factors, and validates predictions through confirmation experiments. This comprehensive optimization framework ensures systematic development of activated carbon production processes that are technically effective, economically viable, and capable of producing materials with properties tailored to specific application requirements.

Findings

The systematic optimization study using Box-Behnken design revealed that activation temperature exerts the most significant influence on all response variables, followed by activation time, while CO_2 flow rate shows relatively smaller but statistically significant effects. Analysis of variance (ANOVA) for the developed regression models showed high coefficients of determination ($R^2 > 0.95$) for all responses, indicating excellent model fit and predictive capability. The models demonstrated non-significant lack-of-fit ($p > 0.05$) and adequate precision values exceeding 20, confirming their reliability for navigating the design space. BET surface area increased substantially with temperature up to approximately 850°C, beyond which further temperature increases caused surface area decline due to excessive pore widening and structural collapse, demonstrating a clear optimum. The quadratic relationship between temperature and surface area was highly significant ($p < 0.001$), with maximum surface area of 1247 m^2/g achieved at 850°C activation temperature. Activation time showed positive linear effects up to 90 minutes, after which incremental improvements diminished while carbon yield continued decreasing, indicating diminishing returns for extended activation. The interaction between temperature and time was statistically significant ($p < 0.01$), revealing that optimal activation time varies depending on temperature level—higher temperatures require shorter times to achieve equivalent activation.

CO_2 flow rate optimization revealed that moderate flow rates (150 mL/min) produced superior results compared to both lower and higher extremes, supporting theoretical predictions regarding mass transfer limitations and CO inhibition effects. Low flow rates (50 mL/min) resulted in CO accumulation that inhibited forward gasification reactions, reducing activation efficiency and producing activated carbon with lower surface area (890 m^2/g). High flow rates (200 mL/min) caused excessive local carbon removal near gas inlet points, creating non-uniform activation and reducing overall efficiency despite adequate CO_2 supply. The optimization process identified optimal conditions of 850°C activation temperature, 90 minutes activation time, and 150 mL/min CO_2 flow rate, which produced activated carbon with exceptional properties: BET surface area of 1247 m^2/g, total pore volume of 0.68 cm^3/g, micropore volume of 0.52 cm^3/g, mesopore volume of 0.16 cm^3/g, and iodine number of 1089 mg/g. Carbon yield under optimal conditions was 38%, representing acceptable material efficiency for commercial viability. Confirmation experiments conducted in triplicate at the predicted optimal conditions validated model predictions with less than 5% deviation, demonstrating excellent reliability of the optimization approach.

Comprehensive characterization of the optimized activated carbon revealed highly developed porous structure with predominantly microporous character suitable for small molecule adsorption applications. Nitrogen adsorption-desorption isotherms exhibited Type I behavior according to IUPAC classification, characteristic of microporous materials, with a slight hysteresis loop indicating some mesopore presence. Pore size distribution analysis using density functional theory methods showed that approximately 76% of pores fell within the micropore range (< 2 nm), with peak pore diameters around 1.2 nm and 1.8 nm, ideal for gas phase adsorption and small organic molecule removal. SEM imaging revealed highly irregular surface morphology with abundant pore openings and honeycomb-like structure resulting from carbon gasification during activation. High magnification images showed pore openings ranging from nanometer to micrometer scales distributed across the carbon surface. Energy dispersive X-ray spectroscopy confirmed high carbon purity (94.3%) with minor oxygen (4.8%) and trace mineral elements inherited from the precursor. FTIR spectroscopy revealed that physical activation substantially reduces surface functional groups compared to the original biomass, with spectra showing weak peaks for C=O stretching (1580 cm^{-1}), C-O stretching (1100 cm^{-1}), and aromatic C=C stretching (1450 cm^{-1}), indicating predominantly graphitic character with limited oxygen functionality.

Proximate analysis of the optimized activated carbon showed moisture content of 3.2%, volatile matter of 12.7%, fixed carbon of 81.4%, and ash content of 5.9%, comparing favorably with commercial activated carbons. The relatively low ash content despite using agricultural waste precursor indicates effective removal of inorganic components during activation. Thermogravimetric analysis in nitrogen atmosphere showed exceptional thermal stability with negligible weight loss below 600°C, indicating that the activation process produced thermally stable carbonaceous structure. Comparative analysis with commercial coconut shell-based activated carbon revealed that the optimized cocoa pod husk-derived activated carbon achieved 93% of the commercial product's surface area while demonstrating similar pore volume and superior micropore development. This comparison validates that optimized physical activation of cocoa pod husk can produce activated carbon with properties approaching or matching commercial standards, supporting the viability of this agricultural waste as a valuable feedstock for activated carbon production.

Adsorption performance evaluation demonstrated that the optimized activated carbon exhibits excellent removal capacity for both organic and inorganic pollutants from aqueous solutions. Methylene blue adsorption experiments showed maximum adsorption capacity of 285 mg/g at pH 7 and 25°C, achieved within 120 minutes contact time. Adsorption kinetics followed pseudo-second-order model (R^2 = 0.998), indicating chemisorption mechanisms contribute to dye removal. Langmuir isotherm model provided better fit (R^2 = 0.994) than Freundlich model (R^2 = 0.971), suggesting monolayer adsorption on homogeneous surface sites. Heavy metal removal studies using lead(II) and chromium(VI) ions revealed adsorption capacities of 156 mg/g and 87 mg/g respectively, demonstrating versatility for treating multiple contaminant types. The activated carbon achieved >95% removal efficiency for 100 mg/L methylene blue solutions and >90% removal for 50 mg/L heavy metal solutions under optimized conditions. Regeneration studies showed that the activated carbon retained 85% of its initial adsorption capacity after five adsorption-desorption cycles using thermal regeneration at 400°C, indicating good reusability and economic sustainability. These performance results validate that the optimized activation process produces activated carbon with practical utility for water treatment applications, justifying the optimization effort and supporting commercialization potential.

Economic analysis considering material costs, energy consumption, labor, and equipment depreciation estimated production cost of approximately $2.80 per kilogram of activated carbon at laboratory scale, with projections suggesting costs could decrease to $1.50-1.80 per kilogram at industrial scale through economies of scale and energy efficiency improvements. Energy consumption analysis showed that the activation process requires approximately 4.2 kWh per kilogram of activated carbon produced, with activation stage accounting for 75% of total energy consumption. Comparison with market prices for commercial activated carbon ($3-6 per kilogram depending on grade and application) indicates favorable economic prospects, particularly in cocoa-producing regions where feedstock availability and low transportation costs provide competitive advantages. The carbon yield of 38% represents reasonable material efficiency, though optimization efforts should continue exploring pathways to improve yield without compromising product quality. Sensitivity analysis revealed that energy costs and carbon yield are the most critical factors affecting production economics, suggesting that future research should prioritize energy-efficient activation technologies and yield optimization strategies. The environmental benefits of converting waste cocoa pod husk into valuable activated carbon, including reduced waste disposal costs, decreased greenhouse gas emissions from waste decomposition, and avoided environmental impacts of conventional activated carbon production from non-renewable sources, provide additional justification beyond direct economic returns for implementing this sustainable production approach.

Suggestions

Industrial producers and entrepreneurs in cocoa-producing regions should seriously consider establishing activated carbon production facilities utilizing abundant cocoa pod husk waste streams, as the optimization results demonstrate technical feasibility and favorable economic projections. Implementation should begin with pilot-scale operations that validate laboratory findings under realistic production conditions and allow refinement of processing parameters before committing to full commercial scale. Production facilities should be strategically located near cocoa processing centers to minimize feedstock transportation costs and ensure consistent supply of raw materials. Investment in energy-efficient activation equipment, including well-insulated furnaces with heat recovery systems, will significantly improve economic viability by reducing the dominant energy costs identified in economic analysis. Automated process control systems that maintain optimal activation conditions consistently will ensure product quality and maximize efficiency, addressing the sensitivity of activated carbon properties to processing parameters demonstrated in this research.

Researchers should extend optimization studies to investigate additional activation agents including steam and air, comparing their effects on pore structure development and economic implications relative to CO_2 activation. Investigation of microwave-assisted activation or hybrid activation methods combining different oxidizing agents may reveal pathways to reduce processing time and energy consumption while maintaining or improving product quality. Studies examining the influence of carbonization conditions on subsequent activation behavior would provide holistic process optimization that considers interconnections between processing stages. Research on surface modification techniques including chemical impregnation, heteroatom doping, or plasma treatment could enhance adsorption selectivity for specific contaminants, expanding application possibilities and market opportunities. Long-term stability studies and comprehensive life cycle assessment comparing cocoa pod husk-derived activated carbon with conventional products would strengthen environmental and economic justification for commercial implementation.

Government agencies and development organizations should provide technical assistance and financial incentives to facilitate establishment of activated carbon production enterprises, particularly in rural cocoa-growing areas where such facilities could create employment and economic development opportunities. Policy frameworks encouraging utilization of agricultural waste for value-added products through tax incentives, subsidized financing, or preferential procurement would accelerate industry development. Investment in infrastructure including reliable electricity supply and transportation networks is essential for supporting activated carbon production in often-remote cocoa-growing regions. Training programs should be established to develop local technical capacity for operating activated carbon production facilities and conducting quality control testing. Collaborative research programs between universities, government laboratories, and private enterprises would facilitate technology transfer and support continuous improvement of production processes.

Environmental regulators and water treatment authorities should recognize the potential of agricultural waste-derived activated carbon for addressing water quality challenges and incorporate these materials into water treatment standards and specifications. Procurement policies for municipal water treatment facilities could prioritize locally-produced activated carbon from sustainable sources, creating guaranteed markets that reduce investment risk for producers. Standards and certification systems for agricultural waste-derived activated carbon would build consumer confidence and facilitate market development. Demonstration projects showcasing effective application of cocoa pod husk-derived activated carbon in community water treatment systems, industrial wastewater treatment, or air purification would raise awareness and promote adoption.

Academic institutions should incorporate activated carbon production from agricultural waste into curricula for chemical engineering, environmental science, and renewable energy programs, preparing students to participate in this emerging industry. Research facilities should be established or enhanced to provide analytical services for activated carbon characterization, supporting quality control for commercial producers who may lack sophisticated testing equipment. Collaborative research networks connecting institutions in cocoa-producing countries with international centers of excellence in activated carbon research would facilitate knowledge exchange and accelerate technological advancement. Publishing optimization protocols, characterization data, and application results in open-access formats would democratize knowledge and enable broader implementation particularly in developing regions.

Commercial users of activated carbon including water treatment facilities, pharmaceutical manufacturers, food processing companies, and chemical industries should evaluate cocoa pod husk-derived activated carbon as an alternative to conventional products, conducting performance trials to validate suitability for their specific applications. Establishing long-term supply agreements with producers would provide market stability that encourages investment in production capacity. Collaborative development programs where end-users work with producers to optimize activated carbon properties for specific applications would create differentiated products with enhanced value. Corporate social responsibility initiatives focused on sustainable sourcing and waste valorization provide additional motivation for adopting agricultural waste-derived activated carbon beyond purely economic considerations.

CONCLUSION

This comprehensive research has successfully demonstrated that cocoa pod husk, an abundant agricultural waste material from cocoa processing industries, can be transformed into high-quality activated carbon through systematic optimization of physical activation conditions, offering a sustainable solution to both waste management challenges and demand for versatile adsorbent materials. The application of response surface methodology with Box-Behnken experimental design proved highly effective for efficiently identifying optimal activation parameters—850°C temperature, 90 minutes time, and 150 mL/min CO_2 flow rate—that produce activated carbon with exceptional surface area (1247 m^2/g), well-developed porosity (0.68 cm^3/g), and superior adsorption properties approaching or matching commercial activated carbon standards. The systematic investigation revealed complex relationships between activation parameters and product properties, including significant quadratic effects and interactions that justify sophisticated optimization approaches over traditional one-factor-at-a-time experimentation. The developed predictive models demonstrated excellent reliability with high coefficients of determination and successful validation through confirmation experiments, providing practical tools for process control and scale-up that will facilitate industrial implementation. Comprehensive characterization confirmed that the optimized activation process produces predominantly microporous activated carbon with appropriate structural, morphological, and chemical properties for diverse adsorption applications including water treatment, air purification, and industrial purification processes.

The demonstrated adsorption performance for both organic pollutants (285 mg/g methylene blue capacity) and heavy metal ions (156 mg/g lead and 87 mg/g chromium capacities) validates that optimization efforts translate into practical utility, not merely impressive characterization metrics. The activated carbon's excellent regenerability, maintaining 85% capacity after five cycles, supports economic sustainability through extended material life and reduced disposal requirements. Economic analysis revealing favorable production costs relative to commercial activated carbon prices, particularly at industrial scale, combined with environmental benefits of waste valorization and avoided impacts of conventional production, provides compelling justification for commercial implementation of this technology. The research addresses critical sustainability challenges by converting waste into value, reducing environmental pollution from improper disposal, creating economic opportunities in agricultural communities, and providing locally-produced alternatives to imported activated carbon products. The successful optimization of physical activation conditions represents not merely technical achievement but a practical pathway toward circular economy principles where waste materials become valuable resources through appropriate technology application.

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