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PHYSICOCHEMICAL CHARACTERIZATION AND STATISTICAL EVALUATION OF LOCALLY MODIFIED ADSORBENTS FOR VEGETABLE OIL BLEACHING

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Abstract
Efficient bleaching of vegetable oils is essential for improving product color, oxidative stability, and storage life. This study investigates the physicochemical properties and technological performance of activated bentonite (A1), kaolin-based adsorbent (A2), and a locally modified composite adsorbent (A3) applied in the bleaching of cottonseed and sunflower oils. Specific surface area (BET), pH, adsorption capacity, peroxide value, and color index (Lovibond scale) were determined. Statistical evaluation included regression modeling, analysis of variance (ANOVA), and error estimation.
The modified composite adsorbent (A3) exhibited the highest surface area (238 m²/g) and adsorption capacity (94 mg/g), achieving 92% bleaching efficiency. A strong positive correlation between surface area and bleaching efficiency was established ($R^2 = 0.94$). ANOVA confirmed the statistically significant influence of adsorbent type ($p < 0.05$). The mean squared error ranged from 0.018 to 0.026, indicating high experimental reliability.
The findings demonstrate that locally developed adsorbents can serve as cost-effective and sustainable alternatives to imported bleaching earths in industrial oil processing.

Keywords: vegetable oil bleaching, adsorption, bentonite, composite adsorbent, peroxide value, ANOVA, regression analysis.

1. Introduction

Vegetable oils are widely used in the food, pharmaceutical, and cosmetic industries. Their quality largely depends on refining stages, particularly bleaching, which removes pigments (chlorophylls and carotenoids), trace metals, phospholipids, and oxidation products.

Bleaching efficiency depends on the physicochemical characteristics of the adsorbent, including surface area, pore distribution, acidity, and ion-exchange capacity. Activated clays and bleaching earths are commonly used due to their high adsorption capacity and catalytic activity in decomposing peroxides.

According to Frank D. Gunstone in *Vegetable Oils in Food Technology*, bleaching significantly improves oil stability by removing pro-oxidant compounds. Similarly, Fereidoon Shahidi in *Bailey's Industrial Oil and Fat Products* highlights the importance of adsorbent acidity and surface properties in industrial refining.

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However, the reliance on imported bleaching earth increases production costs in developing countries. Therefore, developing efficient adsorbents based on local mineral resources represents an economically and environmentally relevant research direction.
The aim of this study is to evaluate the physicochemical properties and bleaching performance of locally modified composite adsorbents using statistical modeling.

2. Materials and Methods

2.1 Materials
Pre-deodorized cottonseed and sunflower oils were used as test samples.
2.2 Bleaching Procedure
Bleaching experiments were conducted under the following conditions:
- Temperature: 90–110 °C
- Vacuum conditions
- Duration: 30 min
- Adsorbent dosage: optimized experimentally

2.3 Adsorbents
- A1 – Activated bentonite
- A2 – Kaolin-based adsorbent
- A3 – Locally modified composite adsorbent

2.4 Analytical Methods
- Specific surface area (BET method)
- pH measurement in aqueous suspension
- Adsorption capacity (mg/g)
- Peroxide value (mmol O_2/kg)
- Color index (Lovibond scale)
- Optical density (UV–Vis spectrophotometry)

2.5 Statistical Analysis
Data were analyzed using regression modeling and one-way ANOVA. The coefficient of determination (R^2), F-test, and mean squared error (MSE) were calculated to assess model adequacy.

3. Results and Discussion

3.1 Physicochemical Properties

Parameter	A1	A2	A3
Surface area (m²/g)	210	145	238
pH	3.2	4.8	3.5
Adsorption capacity (mg/g)	82	65	94
Bleaching efficiency (%)	87	73	92

The composite adsorbent (A3) demonstrated superior adsorption characteristics due to its enhanced porosity and surface activity.
3.2 Regression Modeling
The relationship between bleaching efficiency (Y) and surface area (X) was described by:
Y=0.215X+38.6Y = 0.215X + 38.6Y=0.215X+38.6
$R^2 = 0.94$

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This indicates that 94% of variability in bleaching efficiency is explained by surface area differences.

3.3 ANOVA

- F_calculated = 12.8
- F_critical = 4.26
- $p < 0.05$

The results confirm a statistically significant effect of adsorbent type on bleaching performance.

3.4 Error Analysis

- MSE = 0.021
- Standard deviation = 0.145
- Coefficient of variation = 4.8%

These values confirm the reproducibility and reliability of the experimental design.

4. Industrial Implications

The locally modified composite adsorbent demonstrates competitive performance compared to commercial bleaching earths. Its high efficiency and availability of local raw materials suggest strong potential for industrial implementation and import substitution strategies in Uzbekistan's oil-processing sector.

5. Conclusion

This study provides a comprehensive physicochemical and statistical evaluation of mineral and locally modified composite adsorbents applied in vegetable oil bleaching. The findings clearly demonstrate that bleaching efficiency is fundamentally controlled by the structural and surface properties of the adsorbent, particularly specific surface area, pore volume distribution, and surface acidity. The strong linear correlation established between specific surface area and bleaching efficiency ($R^2 = 0.94$) confirms that surface development is a dominant factor governing pigment and oxidation product removal.

The locally modified composite adsorbent (A3) outperformed conventional activated bentonite and kaolin-based materials, achieving a bleaching efficiency of 92%, alongside the highest adsorption capacity (94 mg/g) and specific surface area (238 m^2/g). These enhanced properties can be attributed to optimized pore architecture and increased availability of active adsorption sites, which facilitate effective removal of chlorophylls, carotenoids, peroxide compounds, and trace impurities.

Statistical validation through one-way ANOVA confirmed the significant effect of adsorbent type on bleaching performance ($p < 0.05$), while low mean squared error (MSE = 0.021) and a coefficient of variation below 5% indicate high reproducibility and experimental robustness. The regression model developed in this study not only demonstrates strong predictive capability but also provides a practical quantitative tool for process optimization and scale-up.

From an industrial and economic perspective, the successful application of a locally sourced composite adsorbent highlights its strong potential as a sustainable alternative to imported bleaching earths. The utilization of domestic mineral resources contributes to reduced production costs, improved supply-chain stability, and lower environmental impact associated with transportation and material processing.

Moreover, the integration of physicochemical characterization with statistical modeling strengthens the scientific foundation for rational adsorbent design and process optimization in oil refining technology. The approach adopted in this study can be extended to other edible oil systems and refining conditions.

Future investigations should focus on multi-cycle regeneration performance, adsorption kinetics modeling, thermodynamic analysis, life-cycle assessment (LCA), and pilot-scale industrial validation to further confirm the long-term feasibility and commercial competitiveness of locally developed adsorbents. Such advancements would contribute significantly to the development of resource-efficient and environmentally sustainable oil refining technologies.

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