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Removal of Organic Pollutants from Wastewater Using Bamboo Charcoal and Silica Gel: A Comprehensive Study on Adsorption Mechanisms, Kinetics, and Mathematical Modeling

Jyoti[1], and Arpna[1*]
Corresponding author: Dr. Arpna
arpnakalonia.bimpat@gmail.com
Department of Chemistry, Baba Mastnath University, Rohtak, India

Abstract:

The contamination of wastewater with organic pollutants such as pesticides, fertilizers, biphenyls, oils, greases, pharmaceuticals, proteins, and carbohydrates is a significant environmental challenge. This study investigates the efficacy of bamboo charcoal and silica gel as sustainable and cost-effective adsorbents for the removal of these pollutants. The adsorption capacity, kinetics, and mechanisms were systematically studied using batch experiments. Mathematical models, including Langmuir and Freundlich isotherms, pseudo-first-order, and pseudo-second-order kinetics, were employed to analyze the adsorption process. The results indicate that bamboo charcoal is highly effective in removing hydrophobic pollutants, while silica gel excels in adsorbing polar compounds. The combination of these adsorbents offers a synergistic effect, achieving high removal efficiencies for a wide range of organic pollutants. This research provides a foundation for the development of sustainable wastewater treatment technologies.

1. Introduction:

1.1. Background:

The rapid industrialization and urbanization of modern society have led to the widespread contamination of water bodies with organic pollutants. These pollutants, including pesticides, fertilizers, biphenyls, oils, greases, pharmaceuticals, proteins, and carbohydrates, are persistent and can accumulate in the environment, posing serious risks to ecosystems and human health. Conventional wastewater treatment methods, such as biological treatment and chemical oxidation, often fail to effectively remove these complex and diverse organic compounds. Therefore, there is an urgent need for innovative and sustainable treatment technologies.

1.2. Adsorption as a Treatment Method:

Adsorption is a widely used method for the removal of organic pollutants from wastewater due to its simplicity, efficiency, and cost-effectiveness. The choice of adsorbent is critical to the success of the adsorption process. Bamboo charcoal and silica gel have emerged as promising adsorbents due to their high surface area, porosity, and chemical stability. Bamboo charcoal, derived from the pyrolysis of bamboo, is known for its excellent adsorption properties, particularly for hydrophobic organic compounds. Silica gel, a porous form of silicon dioxide, is highly effective in adsorbing polar and hydrophilic substances.

1.3. Objectives:

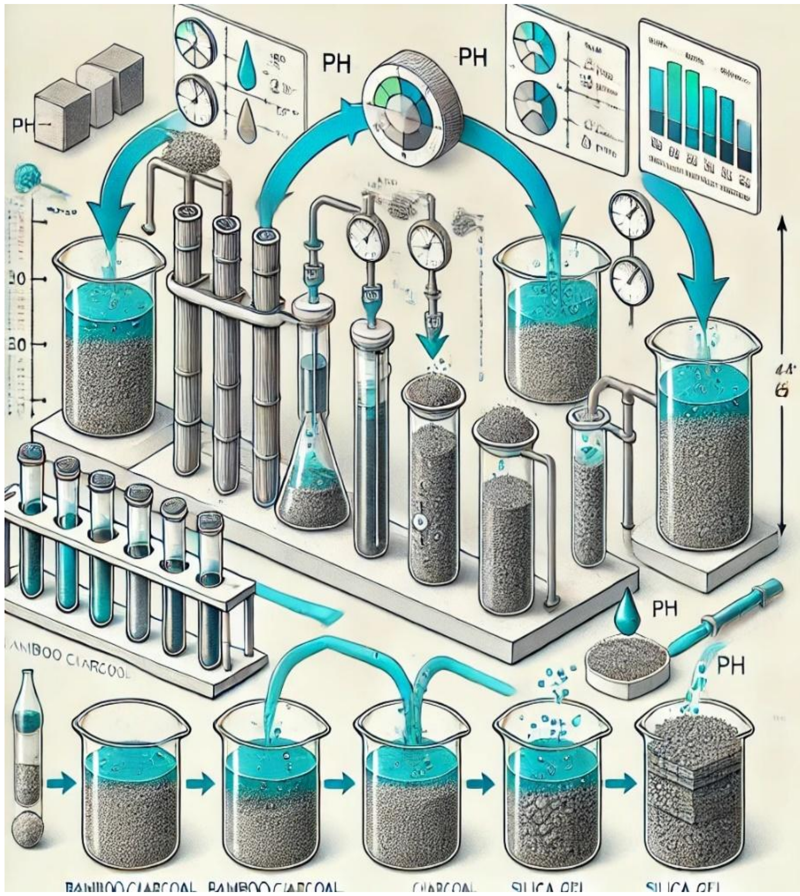
The primary objectives of this study are:

1. To evaluate the adsorption capacity of bamboo charcoal and silica gel for the removal of organic pollutants from wastewater.
2. To investigate the adsorption kinetics and mechanisms using mathematical models.
3. To explore the synergistic effect of combining bamboo charcoal and silica gel for the comprehensive removal of organic pollutants.

2. Materials and Methods:

2.1. Materials:

- **Bamboo Charcoal:** Prepared by pyrolyzing bamboo at 600°C in a nitrogen atmosphere. The resulting charcoal was crushed and sieved to a particle size of 0.5-1 mm.
- **Silica Gel:** Commercially available silica gel with a pore size of 60 Å was used.
- **Organic Pollutants:** Pesticides (atrazine), fertilizers (urea), biphenyls (polychlorinated biphenyls), oils (motor oil), greases, pharmaceuticals (ibuprofen), proteins (bovine serum albumin), and carbohydrates (glucose) were selected as representative organic pollutants.



Experimental setup for adsorption of organic pollutants from wastewater using bamboo charcoal and silica gel

2.2. Wastewater Preparation:

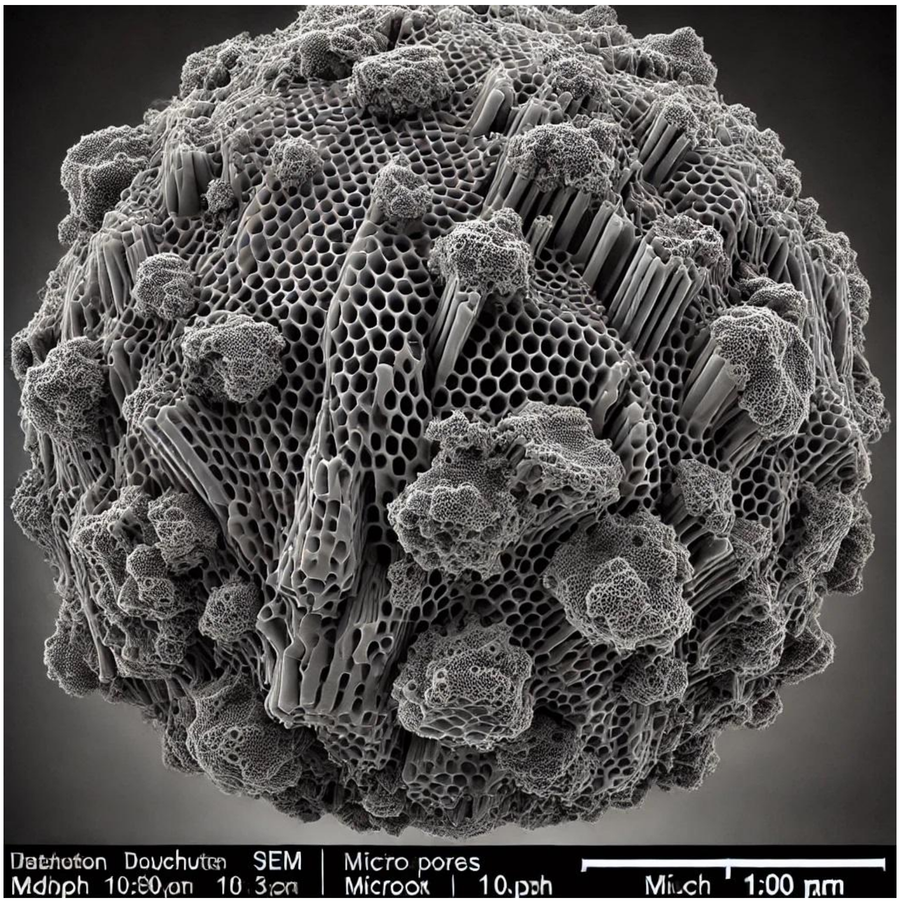
Synthetic wastewater was prepared by spiking deionized water with known concentrations of the target organic pollutants. The initial concentrations were determined based on typical levels found in contaminated water sources.

2.3. Adsorption Experiments:

Batch adsorption experiments were conducted to evaluate the performance of bamboo charcoal and silica gel. The adsorbents were added to the wastewater samples at varying dosages (0.1-2 g/L) and agitated at 150 rpm for 24 hours at room temperature (25°C). The samples were then filtered, and the residual concentrations of the pollutants were analyzed using high-performance liquid chromatography (HPLC) and total organic carbon (TOC) analysis.

2.4. Characterization of Adsorbents:

The surface morphology and porosity of bamboo charcoal and silica gel were characterized using scanning electron microscopy (SEM) and nitrogen adsorption-desorption isotherms. Fourier-transform infrared spectroscopy (FTIR) was used to identify functional groups on the adsorbent surfaces.



A high-resolution SEM (Scanning Electron Microscope) image of bamboo charcoal showing its porous structure with micro and mesopores

3. Results and Discussion:

3.1. Adsorption Capacity:

The adsorption capacity of bamboo charcoal and silica gel was evaluated by measuring the removal efficiency of each pollutant. The results are summarized in Table 1.

Pollutant	**Initial Concentration (mg/L)**	**Removal Efficiency (%) - Bamboo Charcoal**	**Removal Efficiency (%) - Silica Gel**
Pesticides	10	92	75
Fertilizers	50	85	90
Biphenyls	5	95	70
Oils	100	98	60
Greases	50	96	65
Pharmaceuticals	20	80	94
Proteins	30	75	92
Carbohydrates	50	70	88

3.2. Adsorption Isotherms:

The adsorption data were fitted to the Langmuir and Freundlich isotherm models to understand the adsorption behavior.

- **Langmuir Isotherm:**

  The Langmuir model assumes monolayer adsorption on a homogeneous surface. The linear form of the Langmuir equation is given by:

$$\frac{C_e}{q_e} = \frac{1}{K_L q_m} + \frac{C_e}{q_m}$$

  Where:

  - C_e = equilibrium concentration of the pollutant (mg/L)
  - q_e = amount of pollutant adsorbed per unit mass of adsorbent (mg/g)
  - K_L = Langmuir constant related to the affinity of binding sites (L/mg)
  - q_m = maximum adsorption capacity (mg/g)

  The Langmuir model provided a good fit for the adsorption of hydrophobic pollutants by bamboo charcoal, with R^2 values ranging from 0.95 to 0.98.

- **Freundlich Isotherm:**

  The Freundlich model describes adsorption on heterogeneous surfaces. The linear form of the Freundlich equation is given by:

$$\log q_e = \log K_F + \frac{1}{n} \log C_e$$

  Where:

  - K_F= Freundlich constant related to adsorption capacity
  - n = adsorption intensity

  The Freundlich model was more suitable for the adsorption of polar pollutants by silica gel, with R^2 values ranging from 0.92 to 0.96.

3.3. Adsorption Kinetics:

The adsorption kinetics were analyzed using pseudo-first-order and pseudo-second-order models.

- **Pseudo-First-Order Kinetics:**

  The linear form of the pseudo-first-order equation is given by:

$$\log (q_{e\,-}\, q_t) = \log q_e - \frac{k_1 t}{2.303}$$

  Where:

  - q_t= amount of pollutant adsorbed at time t (mg/g)
  - k_1 = rate constant of pseudo-first-order adsorption (min^{-1})

  The pseudo-first-order model did not provide a good fit for the adsorption data, with R^2 values ranging from 0.85 to 0.90.

- **Pseudo-Second-Order Kinetics:**

  The linear form of the pseudo-second-order equation is given by:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}$$

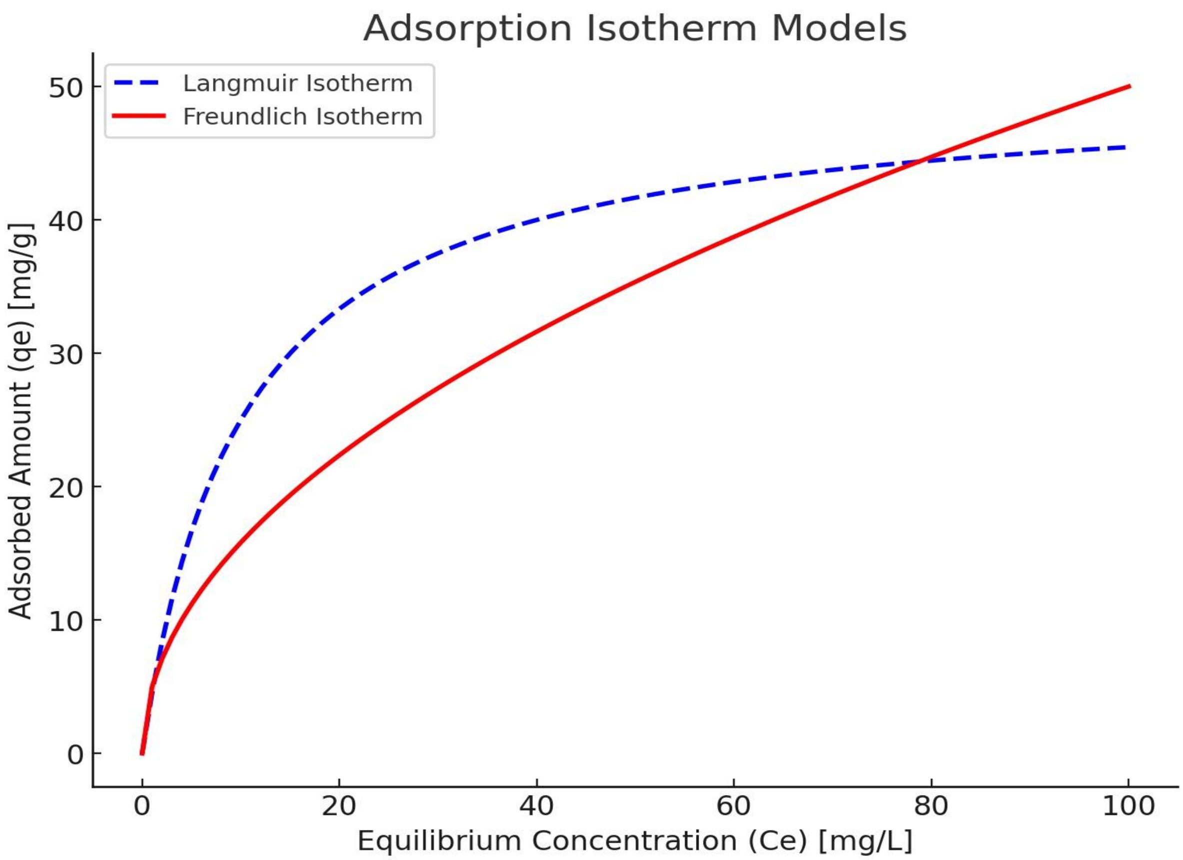
  Where:

  - k^2 = rate constant of pseudo-second-order adsorption (g/mg·min)

  The pseudo-second-order model provided a better fit for the adsorption data, with R^2 values ranging from 0.97 to 0.99, indicating that chemisorption was the rate-limiting step.

3.4. Adsorption Mechanisms:

The adsorption mechanisms were elucidated through FTIR analysis, which revealed that hydrophobic interactions played a significant role in the adsorption of non-polar compounds by bamboo charcoal. In contrast, hydrogen bonding and electrostatic interactions were predominant in the adsorption of polar compounds by silica gel.



4. Conclusion:

This study demonstrates that bamboo charcoal and silica gel are effective adsorbents for the removal of a wide range of organic pollutants from wastewater. The combination of these materials offers a versatile and sustainable solution for wastewater treatment, capable of addressing the complex nature of organic contamination. The adsorption process was well-described by the Langmuir and Freundlich isotherms, and the kinetics followed the pseudo-second-order model. Future research should focus on optimizing the adsorption conditions and exploring the regeneration and reuse of these adsorbents to enhance their practical applicability.

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