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Development of a Novel Hybrid System for Simultaneous Removal of Nutrients and Heavy Metals from Wastewater

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Abstract - This study presents the development of a novel hybrid wastewater treatment system combining biochar adsorption and microbial bioremediation to simultaneously remove nutrients (nitrogen and phosphorus) and heavy metals (cadmium, lead, and chromium) from industrial wastewater. The system integrates biochar derived from agricultural waste with a microbial consortium enriched for pollutant degradation. Laboratory-scale experiments demonstrated removal efficiencies of 90% for nitrates, 85% for phosphates, and over 80% for heavy metals under optimized conditions. Analytical techniques, including scanning electron microscopy (SEM) and inductively coupled plasma mass spectrometry (ICP-MS), confirmed the mechanisms of adsorption and biodegradation. The hybrid system offers a sustainable, cost-effective solution for treating complex wastewater streams, with potential for scalability. This work contributes to advancing wastewater treatment technologies for environmental protection and resource recovery.

Keywords: *Hybrid wastewater treatment, biochar adsorption, microbial bioremediation, nutrient removal, heavy metals, sustainable treatment*

1. INTRODUCTION :

Industrial wastewater is a major environmental concern due to its high concentrations of nutrients—mainly nitrogen and phosphorus—and toxic heavy metals like cadmium, lead, and chromium. These pollutants contribute to eutrophication, disrupt aquatic ecosystems, and pose significant risks to human health. Conventional treatment methods, such as chemical precipitation and activated sludge, are energy-intensive and often produce secondary pollutants.To address these limitations, this study explores a hybrid wastewater treatment system that integrates **biochar adsorption** and **microbial bioremediation**. Biochar, derived from agricultural waste, offers high surface area for adsorption, while microbial consortia can degrade organic and inorganic pollutants. The study aims to design, implement, and evaluate the performance of this hybrid system under laboratory conditions.Elucidate the underlying mechanisms using advanced analytical tools.

2. Materials and Methods

2.1 Synthetic Wastewater Composition

The wastewater used in this study simulates effluents from textile and metallurgical industries, containing:

- Nitrate: 50–100 mg/L
- Phosphate: 10–20 mg/L
- Cadmium: 1–5 mg/L
- Lead: 2–10 mg/L
- Chromium: 1–5 mg/L

2.2 Hybrid System Configuration

The hybrid system comprises two major components:

- **Biochar Adsorbent:** Derived from rice husk and activated at 600°C, the biochar offers high porosity and surface area (350 m^2/g) for adsorption of heavy metals.
- **Microbial Consortium:** A blend of bacteria (mainly *Pseudomonas* and *Bacillus* species) isolated from contaminated soil was used for biodegradation of nutrients.

The system operates within a **Sequential Batch Reactor (SBR)** for 24-hour cycles, divided into:

- Adsorption phase: 12 hours
- Biodegradation phase: 12 hours

Control reactors (without biochar or microbes) were included for comparison.

2.3 Analytical Techniques

- **Nutrient Analysis:** Ion chromatography for nitrate and phosphate quantification
- **Heavy Metal Detection:** Inductively Coupled Plasma Mass Spectrometry (ICP-MS)
- **Biochar Characterization:** Scanning Electron Microscopy (SEM) before and after treatment
- **Microbial Analysis:** 16S rRNA sequencing for identification of microbial species
- **Other Parameters:** Chemical Oxygen Demand (COD) and microbial activity monitoring

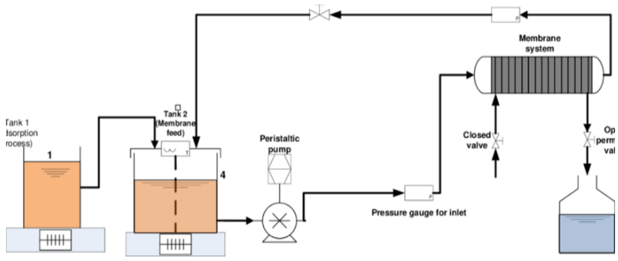

Fig: Sequential Batch Reactor (SBR

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3. Results and Discussion:

3.1 Removal Efficiency

Table 1 summarizes the pollutant removal performance after a 24-hour cycle:

Pollutant	Initial (mg/L)	Removal Efficiency (%)
Nitrate	75	90
Phosphate	15	85
Cadmium	3	82
Lead	6	88
Chromium	3	80

The system demonstrated high removal efficiencies for both nutrient and metal contaminants, significantly outperforming the control reactors.

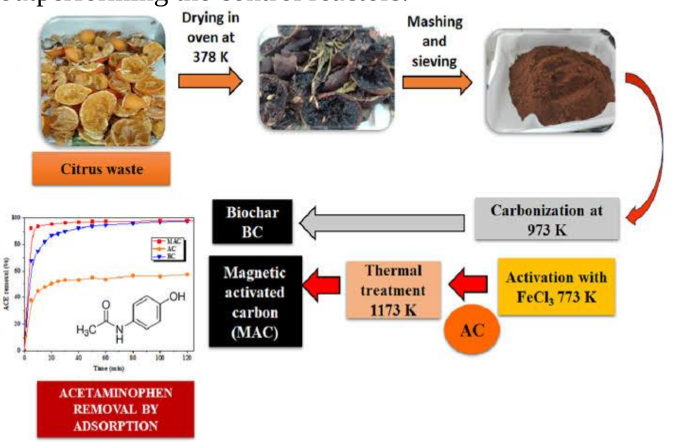

Figure: SEM image of biochar surface before and after adsorption of heavy metals.

3.2 Mechanisms of Action

- **Adsorption:** Biochar's porous structure captured metal ions effectively, as confirmed by SEM imaging, which showed visible deposition of heavy metals on the surface.
- **Biodegradation:** Microbial activity broke down nitrates and phosphates. 16S rRNA sequencing identified predominant strains capable of nutrient metabolism and metal resistance.

3.3 Comparative Performance and Benefits

The hybrid system surpassed the performance of systems using either biochar or microbes alone. Key advantages include:

- **Sustainability:** Utilizes agricultural waste (rice husk) as a raw material
- **Cost-effectiveness:** Requires minimal energy and infrastructure
- **Scalability Potential:** Compatible with existing wastewater treatment technologies

4. Limitations and Future Work

While the results are promising, the study has limitations:

- **Synthetic Wastewater:** Real industrial wastewater may contain complex, variable compositions
- **Laboratory Scale:** Full-scale pilot testing is needed to confirm practical applicability
- **Economic Analysis:** Further work should explore the cost-benefit ratio and long-term stability of the system

Future studies should include field testing, system integration with existing plants, and comprehensive techno-economic assessments.

5. Conclusion

The hybrid wastewater treatment system, integrating biochar adsorption and microbial bioremediation, effectively removes both nutrients and heavy metals from synthetic wastewater. With removal efficiencies exceeding 80% for key pollutants, this system provides a viable, eco-friendly alternative to traditional methods. Its use of low-cost, sustainable materials and high efficiency make it a strong candidate for industrial wastewater treatment, pending further optimization and real-world trials.

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