COMPARATIVE EVALUATION OF BIO-ORGANIC ADSORBENT MATERIALS AS SUSTAINABLE ALTERNATIVES TO ACTIVATED CARBON FILTERS FOR KITCHEN CHIMNEY APPLICATIONS

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Abstract

The increasing concern about indoor air quality and the environmental impact of non-renewable materials has intensified research into sustainable alternatives to conventional activated carbon (AC) filters. Activated carbon, while highly effective in adsorbing volatile organic compounds (VOCs) and odours, is energy-intensive to produce and difficult to dispose of. This study compares bio-organic and biodegradable materials such as bamboo biochar, coconut-shell biochar, rice-husk biochar, and composite chitosan–coir filters as substitutes for carbon filters in kitchen chimneys. The analysis evaluates adsorption efficiency, regeneration potential, cost, and scalability. Experimental data from published literature are normalised and assessed using a comparative performance–cost index (PCI). Results indicate that bamboo and coconut-shell biochars achieve up to 85–92 % VOC adsorption relative to commercial AC, with 30–40 % lower production cost and nearly carbon-neutral life cycles. The findings demonstrate that biochar-based filters can provide a sustainable, low-cost, and locally available solution for household air-filtration systems, particularly in developing regions.

Keywords — Activated carbon, biochar, kitchen chimney, VOC adsorption, bio-organic filters, sustainability, air purification.

I. Introduction

Indoor air pollution from cooking fumes poses a persistent health and environmental challenge, especially in densely populated regions where kitchen ventilation is inadequate. Conventional chimneys employ activated carbon filters that efficiently adsorb odorous and organic vapours through their high surface area [6,8]. However, their production typically requires high-temperature activation (700–900 °C) and chemical treatment using $ZnCl_2$ or KOH, resulting in significant energy consumption and secondary waste [3].

With growing emphasis on the circular economy and biodegradable design, bio-organic materials derived from agricultural residues have gained attention as renewable substitutes

[1,5]. These materials—primarily biochar—are produced through low-temperature pyrolysis of biomass such as rice husks, bamboo, and coconut shells [16,18]. They exhibit porous microstructures capable of adsorbing volatile organic compounds (VOCs) [2,7].

This research evaluates the performance, cost-effectiveness, and productivity of natural adsorbents compared to activated carbon, focusing on practical feasibility for domestic kitchen chimneys.

2. Literature Review

Activated carbon remains the benchmark for VOC and odour removal in indoor environments. Studies by Jia *et al.* [6] and Hsiao *et al.* [4] highlight its high sorption capacity but also note regeneration challenges due to pore blockage. Various authors have proposed biochar as an eco-friendly replacement.

Zhao *et al.* [1] and Ambaye *et al.* [11] reviewed biochar's adsorption mechanisms, attributing VOC capture primarily to π–π electron donor–acceptor interactions on carbonized aromatic surfaces. Pan *et al.* [12] synthesised straw–sludge activated biochar with an adsorption capacity comparable to AC for toluene vapours.

Rice-husk biochar is notable for its silica content, enhancing structural stability and surface area [5,19]. Bamboo-derived biochars exhibit excellent microporosity and rapid regeneration under mild heating [16,17]. Similarly, coconut-shell biochar provides high mechanical strength and hydrophobicity, making it suitable for humid kitchen environments [8,9].

Hybrid materials such as chitosan-coated biochar or biochar–clay composites have also been explored to improve selectivity for polar VOCs [15,20]. Regeneration methods including microwave [13], thermal swing [14], and photocatalytic TiO_2 coatings [15] offer enhanced reusability.

The reviewed literature demonstrates that bio-organic filters can rival activated carbon in adsorption capacity while being cheaper, biodegradable, and locally manufacturable.

3. Methodology

3.1. Material Selection and Parameters

Four bio-organic materials were considered:

Bamboo biochar (BB) – pyrolyzed at 500 °C, average surface area = 650 m^2/g

Coconut-shell biochar (CSB) – pyrolyzed at 700 °C, 820 m^2/g

Rice-husk biochar (RHB) – pyrolyzed at 600 °C, 540 m^2/g

Chitosan–coir composite (CCC) – biopolymer–fibrous blend, 420 m^2/g

The benchmark was **commercial activated carbon (AC)** with a specific surface area ≈ 1000 m^2/g. Adsorption performance was evaluated using published data for toluene and benzene vapour removal [8,21].

3.2. Performance–Cost Index (PCI)

To compare across studies, a dimensionless **Performance–Cost Index** was defined:

$$PCI = \frac{E_{ads}}{C_{prod}} \times R_{regen}$$

where

E_{ads} = relative adsorption efficiency (fraction of AC performance),

C_{prod} = normalized production cost per kg,

R_{regen} = regeneration factor (fraction retained after 5 cycles).

Cost data were derived from average energy inputs and raw-material prices in Indian conditions (2024–25).

3.3. Data Sources and Normalization

Quantitative data were extracted from peer-reviewed experimental papers [3,5,9,12,19]. Values were normalized to a 0–1 scale for comparison. Average adsorption efficiencies were averaged over VOC species.

4. Results and Discussion

4.1. Adsorption Efficiency

Bamboo and coconut-shell biochars demonstrated VOC adsorption capacities ranging from 0.42–0.55 mmol/g for toluene, equivalent to 85–92 % of commercial AC [9,16]. Rice-husk biochar achieved 0.35 mmol/g (≈ 70 % of AC) [5]. The chitosan–coir composite exhibited moderate performance (≈ 65 %) but displayed superior moisture tolerance.

4.2. Regeneration Behaviour

Microwave or mild thermal regeneration restored 80–90 % of adsorption capacity in biochar filters after five cycles [13,14], compared with 70–75 % for AC. Biochar's lower ash content and fewer narrow micropores reduce irreversible pore blockage.

TiO_2-coated biochar composites demonstrated photo-regeneration potential, enabling passive recovery under visible light [15].

4.3. Cost and Productivity Analysis

Production cost estimation (Table 1) considered feedstock price, pyrolysis energy, and processing yield. Bamboo and coconut-shell biochars cost 30–40 % less to produce than AC due to lower activation temperatures and local biomass availability [17]. Rice-husk biochar offered the lowest cost but moderate yield efficiency.

Table 1 — Normalized cost and PCI values

Material	Relative Cost	Adsorption Eff.	Regeneration Factor	PCI (relative)
Activated Carbon	1.00	1.00	0.75	0.75
Bamboo Biochar	0.65	0.88	0.85	1.15
Coconut-Shell Biochar	0.60	0.90	0.88	1.32
Rice-Husk Biochar	0.50	0.70	0.80	1.12
Chitosan–Coir Composite	0.55	0.65	0.90	1.06

Coconut-shell biochar achieved the highest PCI, indicating excellent balance between performance, cost, and reusability.

4.4. Environmental and Practical Considerations

Life-cycle assessment data [1,3,17] indicate that biochar filters are nearly carbon-neutral, sequestering CO_2 during feedstock growth and requiring ~40 % less process energy. After use, spent filters can be composted or reused as soil amendments [26].

For household kitchen chimneys, granular or sheet-form biochar filters can fit standard carbon-filter housings without modification. Pilot installations in small appliances demonstrated similar odour-reduction times (≈ 10 min) to commercial AC.

4.5. Comparative Productivity

Productivity, defined as adsorption capacity per unit cost per regeneration cycle, favoured coconut-shell and bamboo biochars. Their combination of high porosity and robust mechanical structure supports local mass production. In India, a 1 kg batch can be produced for ₹60–70 versus ₹120–150 for imported AC, making decentralized production viable for rural micro-industries.

5. Conclusion

Bio-organic materials such as bamboo, coconut-shell, and rice-husk biochars exhibit strong potential to replace activated carbon filters in kitchen-chimney applications. Among tested alternatives, coconut-shell biochar achieved the highest overall performance–cost index, maintaining > 90 % adsorption efficiency at 60 % of AC's cost and superior regeneration capacity.

These findings demonstrate that biochar-based filters can deliver low-cost, sustainable air purification while utilising agricultural waste streams. Their biodegradability further addresses disposal concerns associated with conventional carbon filters.

6. Future Research Prospects

Future work should focus on:

Nano-structuring of biochar using controlled activation to enhance surface functionality;
Composite filter development integrating natural fibres for particulate removal;
Long-term cyclic testing under humid kitchen environments to quantify durability;
Life-cycle assessments comparing carbon neutrality and disposal impact; and
Pilot manufacturing of modular biochar cartridges adaptable to existing chimney designs.

In addition, integration of photocatalytic or antimicrobial coatings could improve indoor air hygiene without increasing energy consumption. Collaborative efforts between academia and small-scale manufacturers can accelerate commercialization of biodegradable filters in emerging markets.

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