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Environmental Sustainability of Waste-Derived Adsorbent: Insights from Life Cycle Assessment

Md. Sidratul Montaha Hossain, Abdullah Al Mahmood, M. Bodiul Islam*

Department of Ceramic & Metallurgical Engineering, Rajshahi University of Engineering & Technology (RUET), Rajshahi-6204, Bangladesh

ABSTRACT

Activated carbon has grabbed attention of the researchers. Activated carbon production results in sustainability challenges, as it is heavily dependent on feedstocks which are fossil based. Besides, the steps require high energy. This research carries out a cradle to gate Life Cycle Assessment to compare AC derived from coconut shell with commercial AC. LCA focuses on climate change as well as overall Sustainability outcome. The precursor coconut shells were carbonized at 500-600 ºC. Afterwards; chemical activation was carried out using KOH. Inventory modeling was performed in OpenLCA 1.11 using the Ecoinvent 3.9 database. The results from LCA analysis indicates coconut-shell AC achieves mentionable reduction in environmental impacts. Results include a 66% lower global warming potential and a 70% decrease in particulate matter formation. Reduced energy consumption, renewable feedstock origin are reason for such benefits. Nonetheless, higher ecotoxicity impacts were observed due to the use of chemical activating agents, suggesting the need for more sustainable alternatives. Overall, the study confirms that biomass-derived AC offers a promising low-carbon route. Therefore; alignment with circular economy principles and advancing sustainable material development is found.

Keywords: Life Cycle Assessment, Environmental impact, Adsorbents, Activated Carbon, Waste Recycling.

1. Introduction

Activated carbon (AC) is considered as a highly efficient adsorbent. It has a range of application not only in water treatment and purification of air but also in case if energy storage as well as different industrial separation processes [1]. The global consumption of AC is getting higher in considerable amount. This is due to industrial expansion and increasing need for effective pollution control [2]. However, commercial ACs are not sustainable and often they rely on various nonrenewable source such as coal, petroleum etc. They also involve energy intensive processes. Thus, they contribute to greenhouse gas emission. Additionally, the mining and processing of fossil materials leads to significant land degradation, particulate pollution, and toxic emissions. Thus, compromising air and water quality [2],[3].

As a solution to this problem, researchers have targeted waste derived ACs as a sustainable alternative. Highly efficient adsorbents can be derived from different agricultural wastes such as, rice husk, coconut shell, wood apple shell, bettle nut shell etc. [3]. Among all the available options coconut shell can be considered as a highly efficient adsorbent due to their low ash fraction, high carbon content, excellent mechanical strength. This makes them ideal raw material for the synthesis of activated carbon [4]. Thus, technical sustainability can be earned. Utilization of coconut shell also open doors towards reduction of disposal issues. It supports circular economy as waste is converted into an environmentally friendly material [4],[5]. Some of the major steps in the fabrication of ACs from coconut shell is shown in Fig.1.

To evaluate the broader environmental implications, Life Cycle Assessment (LCA) serves as a robust framework for measuring impacts across a product's entire life cycle—from raw material extraction and processing to use and end-of-life [1], [3]. Although many studies have explored the production of AC from biomass, only limited research provides a direct LCA-based comparison between coconut-shell-derived AC and conventional commercial AC, particularly in terms of climate change mitigation and sustainability indicators [3], [5].

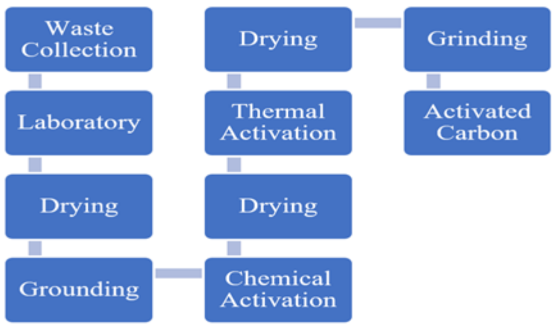

Fig. 1 Activated carbon production steps from the coconut shell.

This study compares the environmental impact of activated carbon (AC) made from coconut shells with commercial AC. The comparison uses a life cycle assessment (LCA) from raw material to the factory gate. One kilogram of AC is used as the basis for the study.

The main impacts studied are global warming potential, fossil fuel depletion, terrestrial and marine ecotoxicity, and freshwater eutrophication [1], [2]. Data for coconut-shell AC come from experiments. Data for commercial AC come from life cycle databases [3], [4]. This approach gives a clear comparison of the two types of AC.

The results show that activated carbon (AC) made from coconut shells has lower environmental impact in most areas. It produces less greenhouse gas and uses less fossil fuel. This shows that using agricultural waste as raw material is good for the environment. It also supports the idea of turning waste into useful products. Biomass-based AC can help fight climate change and support circular economy practices [4], [5]. Overall, this study adds evidence that sustainable production methods are practical and can replace traditional industrial processes [1], [3].

2. Methodology

2.1 Materials

In this study, activated carbon (AC) is derived from coconut shells through a stepwise process. Firstly, the shells were cleaned. Then they were sun dried, crushed, and subsequently sieved to 2–5 mm particles. They were carbonized in a muffle furnace at 500–600 °C. The carbonization process took two hours under limited oxygen and then ground into fine powder. For activation, the powder was mixed with KOH (1:1), soaked for 12 hours, dried, and reheated at 450–500 °C. It was reheated for 1.5 hours under nitrogen flow. The product was washed to neutral pH, oven dried at 105 °C, and stored for testing. This simple method offers an eco-friendly route to produce high-quality AC for environmental use.

2.2 Life Cycle Assessment

Life Cycle Assessment (LCA), standardized under ISO 14040/44, evaluates environmental impacts across a product's life cycle. Applying LCA to activated carbon preparation identifies process hotspots and quantifies impacts such as global warming, ozone depletion, and human toxicity, ensuring recycling pathways support sustainability and circular economy objectives. LCA is a method used to identify the environmental risks posed by any product or process. The Life Cycle Assessment, also known as (LCA), is a technique for computing the adverse environmental effects of a product or process throughout its entire life cycle, as established by the Society of Environmental Toxicology and Chemistry (SETAC) [6] and specified by ISO 14040-14044 [7][8].

2.3 Goal and Scope

In this portion, the main goals are identified. The goal of this study is to evaluate the environmental performance of activated carbon produced from coconut shells and compare it with commercially available AC. The scope covers cradle-to-gate system boundaries. Besides comparison, the contribution analysis of different processes during the process.

2.4 Functional Unit

The functional unit was considered as the weight of the materials. It is seen from Table 1.

2.5 System Boundaries

The LCA has been carried out from the 'Cradle-to-gate' perspective. The system boundary for the current study has been extended from the starting materials collection, transportation of the starting materials, and incorporation of the raw materials in the final materials extraction.

Table 1 Weight of the two samples just after the total process.

Samples	Functional Unit
Prepared AC	1 KG
Commercial AC	1 KG

2.6 Life Cycle Inventory

A summary of the processes and associated flows involved in the production of activated carbon is presented in this section. The Life Cycle Inventory (LCI) for both coconut-shell-derived activated carbon and commercially available activated carbon was developed following a comprehensive examination of each step in their production chains, as illustrated in Fig. 2. For the coconut-shell-derived AC, the inventory included mass and energy inputs for washing, drying, crushing, carbonization, chemical activation, thermal activation, washing, and final drying. For commercial AC, secondary data from life cycle databases were used to represent raw material acquisition, high-temperature activation, chemical treatments, and packaging. The mass and energy balances were defined based on functional units of 1 kg of activated carbon, incorporating material yields, emissions to air, water, and soil, and resource consumption. Transportation distances for raw materials and intermediate products were also included, as well as electricity and fuel usage for each process step. Water consumption and effluent discharges during washing and chemical treatment were accounted for, and all emissions were aggregated to provide a complete picture of environmental flows. This detailed LCI serves as the foundation for subsequent life cycle impact assessment, enabling a consistent and transparent comparison of environmental burdens between biomass-derived and conventional activated carbon.

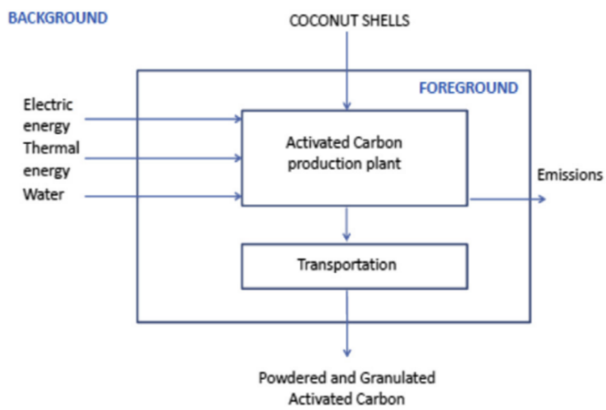

Fig. 2 System boundary for AC prepared from coconut shell [1].

2.7 Software

Various software can be used to perform an LCA analysis. In this study, we used OpenLCA 1.11 software. The Ecoinvent 3.9 database was integrated for performing the analysis. Both reliable results, the latest version of both the software and the database, were taken into consideration.

2.8 Impact assessment

Normalization and weighting sets were not selected as both of these steps are not compulsory steps of life cycle assessment based on ISO 14040 [13]. The impact assessment is carried out by using the Recipe midpoint method. The 18 categories, along with their units, are listed in Table 2.

3. Results & Discussion

3.1 Contribution Analysis for Prepared AC

In the life cycle assessment of activated carbon production from coconut shells, the environmental impact contribution analysis reveals that electricity and transportation are the dominant contributors, whereas water has the least influence as in Fig. 3. Electricity exhibits the highest contributions in categories such as Ionizing Radiation Potential (62.61%) and Water Consumption Potential (59.04%), largely due to the dependence on grid electricity generated from fossil fuel and nuclear sources, which involves significant energy consumption and pollutant emissions [9]. Transportation records major impacts in Freshwater Eutrophication Potential (58.87%) and Marine Eutrophication Potential (48%), which can be explained by the release of nitrogen oxides and other exhaust pollutants during fuel combustion, promoting nutrient enrichment in aquatic systems. By contrast, water use remains negligible across all categories (≤0.35%), as it does not directly generate substantial emissions or toxic releases within the process chain.

Potassium hydroxide, as a key chemical input, demonstrates notable shares in Terrestrial Ecotoxicity Potential (13.44%) and Water Consumption Potential (16.98%), stemming from its energy-intensive production processes and the environmental burdens associated with large-scale alkali chemical use. Heat contributes moderately, with relatively higher shares in Photochemical Ozone Formation Potential (12.85%) and Ozone Depletion Potential (6.69%), due to emissions of ozone precursors and combustion-related pollutants during thermal generation [10]. Coconut shell, despite being the primary raw material, contributes minimally (≤4.28%) because it is a renewable biogenic feedstock with comparatively low direct environmental burdens. Overall, the highest impact values are linked to energy-intensive and emission-heavy processes, while the lowest are associated with renewable or low-emission inputs, underscoring the necessity of improving energy efficiency and chemical handling practices to enhance the sustainability of coconut-shell-based activated carbon production.

3.2 Comparison of the Environmental Impact of Prepared and Commercial AC

The comparison between laboratory-prepared activated carbon (AC) from coconut shells and commercial AC shows clear differences across environmental impact categories (Fig. 4). In case of Terrestrial Acidification Potential (25%), Global Warming Potential (34%), Fossil Fuel Depletion (38%), as well as Freshwater Eutrophication (29%), the prepared AC records notably lower impacts. In all the mentioned categories commercial AC set as the reference (100%). These reductions result from the renewable nature of coconut shells. It lowers energy emissions and acidifying pollutants [11]. In contrast, the prepared AC shows maximum normalized contributions (100%) in Freshwater, Marine, and Terrestrial Ecotoxicity, and in Ionizing Radiation Potential. These impacts result from not only the intensive KOH-based activation process but also higher energy demand. This adds toxicity burdens [12]. Other categories, such as Ozone Depletion (67% vs. 100%) and Water Consumption (82% vs. 100%), show narrower margins.

Table 2 Impact category along with their units for assessing life cycle assessment.

Category of Impact	Unit	Acronyms
Terrestrial acidification potential	kg SO_2-Eq	TAP
Global warming potential	kg CO_2-Eq	GWP
Freshwater-ecotoxicity potential	kg 1,4-DCB-Eq	FETP
Marine-ecotoxicity potential	kg 1,4-DCB-Eq	METP
Terrestrial-ecotoxicity potential	kg 1,4-DCB-Eq	TETP
Fossil fuel potential	kg oil-Eq	FFP
Freshwater eutrophication potential	kg P-Eq	FEP
Marine-eutrophication potential	kg N-Eq	MEP
Carcinogenic-human toxicity potential	kg 1,4-DCB-Eq	HTPc
Non-carcinogenic - human toxicity potential	kg 1,4-DCB-Eq	HTPnc
Ionizing radiation – ionizing radiation potential	kBq Co-60-Eq	IRP
land occupation potential	m^2*a crop-Eq	LOP
Surplus ore potential	kg Cu-Eq	SOP
Ozone depletion potential	kg CFC-11-Eq	ODP
Particulate matter formation potential	kg PM2.5-Eq	PMFP
Human health - photochemical oxidant formation potential: humans	kg NO_x-Eq	HOFP
Ecosystems - photochemical oxidant formation potential: ecosystems	kg NO_x-Eq	EOFP
Water consumption potential	m^3	WCP

The study summarizes that coconut-shell AC significantly lowers particulate matter as well as carbon footprint. Utilization of KOH as an activating chemical raises ecotoxicity indices (freshwater, marine, and terrestrial). The manufacturing of potassium hydroxide uses a lot of energy as well as produces hazardous byproducts when wastewater is released. This trade-off suggests that while AC produced from biomass enhances climatic performance, improper management of chemical activators may cause toxicity issues. Overall, the results highlight strong climate and resource benefits of prepared AC but also reveal ecotoxicity challenges. It emphasizes the need for greener activating agents and process improvements.

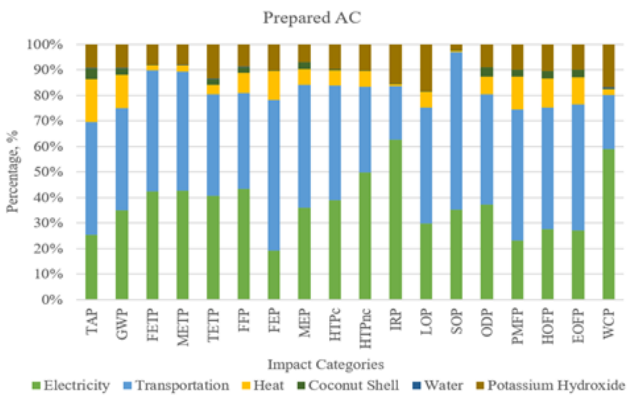

Fig. 3 Contribution of different process steps in the various impact for Prepared AC.

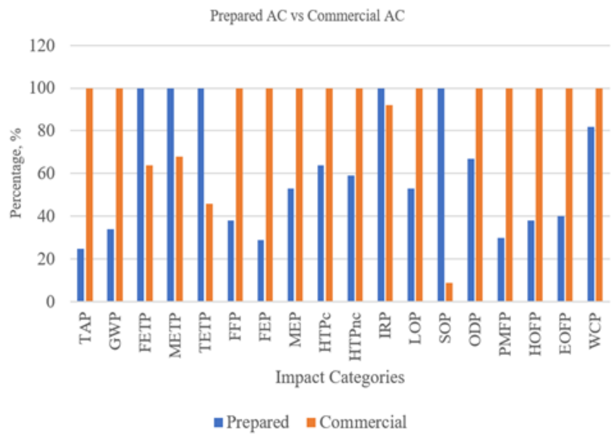

Fig. 4 Comparison of environmental impacts between Prepared and Commercial AC.

3.3 Comparison of the GWP between Prepared and Commercial AC

Life cycle assessment results show that prepared activated carbon (AC) has a markedly lower global warming potential (GWP) of 2.9322 kg CO_2-eq compared to 8.6676 kg CO_2-eq for commercial AC as in Fig. 5. This reduction arises primarily from the use of lignocellulosic agricultural residues as precursors, which act as near carbon-neutral feedstocks since biogenic carbon emissions during activation are offset by prior CO_2 uptake during biomass growth [13]. In contrast, commercial AC is largely derived from fossil-based precursors such as coal, where all emissions are fossil in origin, resulting in higher net climate impacts. Additionally, prepared AC production generally employs moderate-temperature pyrolysis with chemical activation, requiring less energy than the high-temperature steam activation (>800 °C) used in conventional processes. Localized biomass sourcing further minimizes transportation-related emissions compared to the global supply chains of commercial AC [14]. These combined factors account for the nearly threefold reduction in GWP, confirming prepared AC as a technically viable and environmentally sustainable alternative for industrial applications.

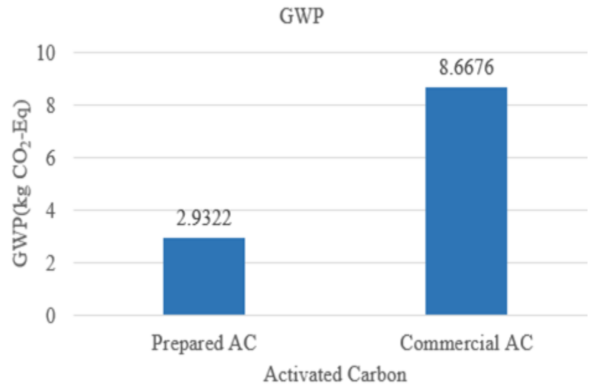

Fig. 5 Comparison of the Global warming potential between Prepared and Commercial AC.

3.4 Comparison of the ODP between the Prepared and Commercial AC

Fig. 6 illustrates the comparison of ozone depletion potential (ODP) between prepared and commercial activated carbon (AC) indicates that prepared AC exhibits a lower environmental impact. With a numerical value of 9.66E-07 kg CFC-11-eq for prepared AC, compared to 1.44E-06 kg CFC-11-eq for commercial AC. The higher ODP is seen to be associated with commercial AC. It can be attributed to not only its reliance on fossil-based raw materials but also energy-intensive activation processes. Due to involvement of electricity and heat production from non-renewable sources they are linked to ozone-depleting emissions [15]. In contrast, prepared AC derived from biomass residues utilizes renewable precursors. Moreover, they require less energy input. Thus, reducing emissions of ozone-depleting substances across its life cycle [16]. Overall, the nearly 33% lower ODP of prepared AC demonstrates its environmental advantage, reinforcing its potential as a more sustainable alternative to conventional commercial AC.

3.5 Comparison of the HTPc between the Prepared and Commercial AC

Fig. 7 shows the comparison of human toxicity potential (carcinogenic) between prepared and commercial activated carbon (AC) reveals that prepared AC has a lower impact, with a value of 1.92E-01 kg 1,4-DCB-eq, compared to 3.00E-01 kg 1,4-DCB-eq for commercial AC. The environmental and health advantage of prepared AC is highlighted by nearly 36% of reduction. The higher toxicity potential of commercial AC may be due to its dependence on fossil-based raw materials as well as production processes which are energy intensive [17]. They contribute to the release of toxic by-products during activation. On the other hand, prepared AC which is produced from renewable biomass residues, generally requires less fossil energy input [18]. They generate fewer carcinogenic emissions across its life cycle. Overall, the results demonstrate that prepared AC is a safer and more sustainable alternative, minimizing human health risks compared to commercial AC.

3.6 Comparison of the PMFP between the Prepared and Commercial AC

The comparison of particulate matter formation potential (PMFP) between prepared as well as commercial activated carbon (AC) is depicted in Fig. 8. It highlights a clear sustainability advantage in favor of the prepared AC. It is clear from the graph, prepared AC shows a lower PMFP value of 5.04E-03 kg PM2.5-Eq, which is considerably lower than the 1.66E-02 kg PM2.5-Eq observed for commercial AC. Particulate matter emissions are a major contributor to air pollution, climate change, and adverse public health impacts [19]. The reduced PMFP of prepared AC underscores its potential as a more sustainable alternative. Prepared AC lowers not only the atmospheric pollutant load but also mitigates climate-related risks [20]. It aligns with the goals of cleaner production pathways, improved air quality, and sustainable material development.

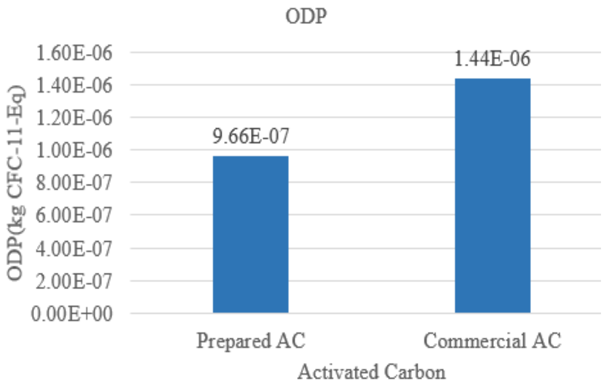

Fig. 6 Comparison of Ozone deletion Potential values between Prepared and Commercial AC.

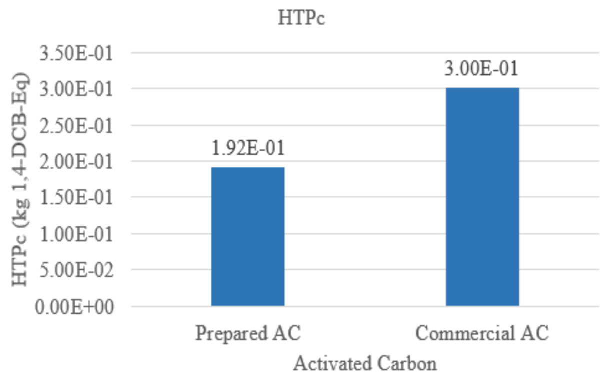

Fig. 7 Comparison of Human toxicity potential between the Prepared and Commercial AC.

3.7 Reduction of Percentage Across Categories

In Fig. 9 the comparative percentage reduction analysis across four key environmental impact categories is illustrated. It clearly shows the sustainability advantages of prepared activated carbon (AC) over commercially available AC. Among the assessed categories, prepared AC demonstrates the highest reduction in particulate matter formation potential (PMFP). It is an achievement of a 70% decrease. It directly contributes to reduced public health risks associated with fine particulate emissions. On the other hand, a 66% reduction in global warming potential (GWP) is identified. It indicates its capacity to substantially lower greenhouse gas emissions. It aligns with international efforts to mitigate climate change [21]. While the reductions in ozone depletion potential (ODP) and human toxicity potential (HTPc) are comparatively moderate at 33% and 36%, respectively. Therefore, they still reflect meaningful progress toward minimizing harmful emissions and protecting human-health. These improvements collectively underscore the role of prepared AC as a more sustainable material that supports cleaner production pathways.

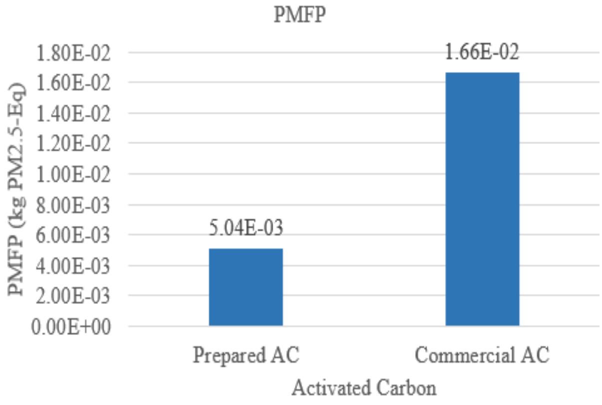

Fig. 8 Comparison of the particulate matter formation potential Prepared and Commercial AC

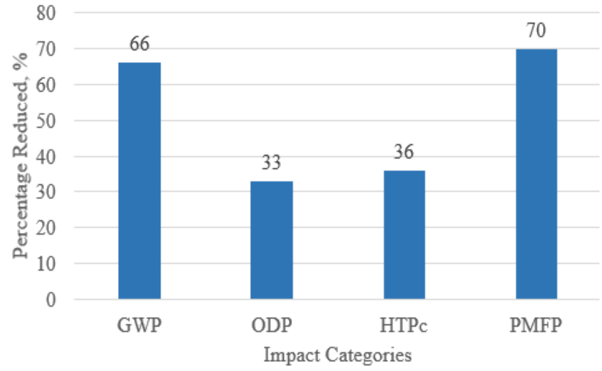

Fig. 9 Percent reduction across categories between the Prepared and Commercial AC.

4. Conclusions

The Life Cycle Assessment study confirms that activated carbon derived from coconut shell waste shows not only a sustainable but also a low-carbon alternative to fossil-based ACs. The LCA analysis showed that coconut-shell-derived AC not only reduced global warming potential by 66% (2.93 vs. 8.67 kg CO_2-eq) but also particulate matter formation by 70% (5.04E–03 vs. 1.66E–02 kg $PM_{2.5}$-eq). Moreover, a further reduction in ozone depletion potential (33%) and human toxicity (36%) can be seen. This is due to the renewable, carbon-neutral nature of coconut shells as well as localized sourcing. However, change in the precursor biomass for the AC production may lead to change in sustainability. For instance; rice husk's high silica content may not only lower carbon yield but also increase processing waste. Besides, bamboo offers lower waste as well as rapid regeneration enhance adsorption efficiency which may lead to environmental friendliness.

However, usage of KOH in the activation process, trade-offs were noted in ecotoxicity categories. Thus, the study highlights the need for greener activation techniques and improved effluent management. Physical activation can be a workable solution against this problem. Besides, usage of less KOH can be considered which results in hybrid activation. In order to recover alkali and avoid aquatic toxicity, closed-loop washing systems and effluent treatment units should be combined.

Industries can enhance the sustainability so that they can adopt several measures based on these findings: (i) Use agricultural residues (e.g., coconut shell) instead of fossil feedstocks. (ii) Optimization activation and waste heat recovery, (iii) Replacement of chemical activation with steam or CO_2 methods. (iv) Usage of closed-loop washing systems to recycle chemicals. (v) Renewable energy (solar or biomass) utilization in production.

These practices should be implemented so that industries can significantly not only reduce the environmental footprint of AC manufacturing but also align with circular economy principles. Overall, the study establishes that coconut-shell-derived AC contributes to climate change mitigation as well as provides a viable pathway for sustainable industrial production of adsorbent materials.

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