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Physicochemical properties of coconut shell and mesquite wood biomass and their Biochar: A comprehensive review

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Abstract
This review paper centres on the production of biochar from coconut shell and mesquite wood biomass, along with an analysis of its physicochemical characteristics. The swift expansion of the global population and industrial sectors has dramatically increased energy consumption, resulting in the exhaustion of fossil fuel resources and contributing to environmental degradation and climate change. Consequently, a strategic transition from fossil-based energy systems to sustainable alternatives has become essential. Among these options, biofuels particularly biochar derived from biomass have attracted significant scholarly attention due to their ecological advantages and alignment with circular economy frameworks and sustainable development objectives. The paper offers an in-depth overview of the transformation of coconut shell and mesquite wood biomass residues into biochar, with a focus on production techniques, physicochemical traits, and a wide range of applications. Methods such as pyrolysis, gasification, torrefaction, and hydrothermal carbonization are examined for their efficiency in generating biochar from coconut shells and mesquite wood, underscoring their potential for sustainable resource management. The relationship between production parameters and the resulting biochar properties is thoroughly explored, with emphasis on feedstock composition, pyrolysis settings, and activation methods. The findings reveal that biochar holds considerable promise in areas such as wastewater treatment, soil enhancement, and carbon sequestration. These applications are enabled by its distinctive physicochemical features, which include high porosity, extensive surface area, plentiful surface functional groups, and strong thermal stability

Keywords: Agricultural residues, coconut shell, mesquite wood, applications

1. Introduction

The rapid expansion of the global population and industrial development has significantly intensified the demand for energy. This growing energy requirement is predominantly met through the use of non-renewable fossil fuels such as coal, oil, and natural gas, which have led to a substantial increase in atmospheric CO_2 concentrations. The combustion of fossil fuels is responsible for the majority of carbon emissions approximately 98% which are a major contributor to global warming. Carbon dioxide, along with other greenhouse gases like methane (CH_4) and nitrous oxide (N_2O), has been recognized as a leading driver of climate change. Consequently, there is an urgent need to tackle the environmental challenges and energy security concerns arising from the continued use and depletion of fossil fuel resources. In recent years, there has been a growing interest in assessing the viability of renewable energy sources, particularly biomass, as sustainable alternatives to traditional fossil-based energy systems (Ighalo *et al.* 2023) [26].

Biochar has been extensively recognized for its versatile applications, including its direct use as a renewable energy source, a soil amendment to enhance fertility and mitigate greenhouse gas emissions from soil, and as a filtration medium in wastewater treatment systems. Compared to the open-field burning of agricultural residues which releases harmful gases such as carbon monoxide (CO), sulfur oxides (Sox), nitrogen oxides (NOx), and carcinogenic smoke particles, the production of biochar generates significantly less air pollution. The thermal transformation of biomass into biochar is influenced by both the operating temperature and the level of oxygen available during the process. This transformation involves several stages, including drying, torrefaction, carbonization, pyrolysis, gasification, and combustion. A variety of reactor types and heating mechanisms are employed in biochar production, such as combustion-based systems, electrical heating, induction, microwave heating, solar heating via external diaphragms, and setups using inert gases or sand as heat transfer media (Khawkomol *et al.* 2021) [36]. Biomass itself refers to a complex mixture of biopolymers composed of diverse compounds like lipids, proteins, and cellulose. It includes materials sourced from forestry operations, cultivated crops, trees, agro-industrial by products, residential refuse, and agricultural waste streams (Adeniyi *et al.* 2021) [2].

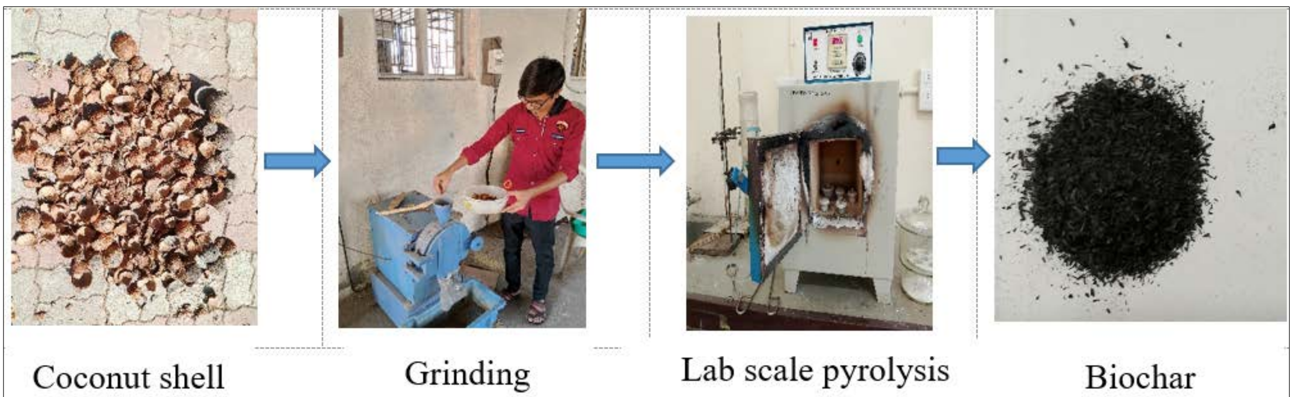
Coconut (*Cocos nucifera*) ranks among the most widely cultivated crops in tropical climates and holds substantial economic value for numerous nations (Wu *et al*., 2016) [79]. The processing of coconuts for various purposes such as food, fuel, and fiber results in the generation of significant quantities of residual biomass, which includes coconut shells, husks, coir, pulp, and fronds (Wang *et al.*, 2021) [76]. Managing the disposal of these coconut-derived residues presents a major environmental challenge in many coconut-producing regions, as they tend to accumulate in landfills and contribute to greenhouse gas emissions (James and Yadav, 2021) [32].

Prosopis juliflora biomass is widely recognized as an invasive weed species due to its detrimental impact on surrounding vegetation within ecosystems. This plant species significantly affects groundwater levels, as its extensive root system draws heavily from underground water sources. In many cases, agricultural activities are hindered by the dense spread of its roots, which severely limit the growth of nearby crops. This phenomenon often transforms large tracts of farmland into fragmented plots, commonly referred to as marginal lands. Over the past three years, the average yield of *Prosopis juliflora* biomass in India has been approximately 12.5 tons per hectare, with the state of Rajasthan contributing nearly 50% of the total output. To combat the spread of this invasive species, the Rajasthan State Government has introduced and supported various initiatives aimed at its complete eradication. As a result, there is an urgent need to develop efficient mitigation technologies that can convert *Prosopis juliflora* biomass into sustainable biofuel (Pawar and Panwar 2022) [56].

Agricultural residues are abundant across India, with wheat straw, cotton stalks, and corn residues being particularly prevalent. Coconut residues are mainly found in the coastal regions, while mesquite wood is commonly available in the desert areas of Rajasthan and Gujarat. These materials are locally accessible and suitable for biochar production. The objectives of this study are: (i) to generate biochar from two widely available agricultural residues coconut shell (CS) and mesquite wood using pyrolysis; (ii) to analyze the physical and chemical characteristics of the resulting biochar for its potential use as an adsorbent and soil enhancer; (iii) to determine which type of biochar is most appropriate for fuel applications; and (iv) to assess the effectiveness of biochar in canal water filtration and seed germination.

Coconut biomass residues refer to the organic byproducts generated during the cultivation, processing, and consumption of coconuts. These include various parts of the coconut tree such as leaves, husks, fronds, and shells, along with residues from coconut oil and coconut milk production. Such biomass is predominantly produced in tropical and subtropical regions, especially in Southeast Asia, the Pacific Islands, and South America, where coconut farming is widespread (Abeysekara and Waidyarathne, 2020) [1]. The composition of coconut biomass includes a variety of organic compounds such as cellulose, hemicellulose, lignin, proteins, lipids, and sugars, as well as inorganic elements like potassium, calcium, and magnesium (Azeta *et al*., 2021; Menon *et al.*, 2021) [9, 50]. Research has also been conducted on the development of a small-scale (5 kg capacity) fixed-bed pyrolysis reactor designed for processing shredded cotton stalks as feedstock (Makavana, J.M. and Sarsavadia, P.N., 2018) [43].

Biochar is a carbon-rich material produced through the pyrolysis, gasification, or hydrothermal carbonization of biomass in environments with limited oxygen. In recent years, biochar has gained popularity as a promising solution to various environmental challenges. Once biomass is converted into biochar, its carbon content becomes "fixed," rendering it stable and resistant to thermal breakdown, which makes it an effective means of carbon sequestration (Hunt *et al.*, 2010) [25]. When incorporated into soil, biochar can retain carbon for centuries or even millennia, thereby helping to reduce atmospheric CO_2 and combat climate change (Neogi *et al.*, 2022; Shalini *et al.*, 2021) [52, 63]. Additionally, biochar improves soil water retention, enhances nutrient availability (Liu *et al.*, 2013) [41], strengthens soil structure (Sukartono *et al*., 2011) [68], lowers soil acidity (Shetty *et al.*, 2021) [64], and boosts crop productivity (Herviyanti *et al.*, 2020) [24]. It also plays a role in minimizing soil erosion, curbing nutrient leaching, and fostering microbial activity (Jahan *et al.*, 2023) [31]. Beyond agricultural benefits, biochar is also effective in wastewater treatment, where it helps remove organic pollutants and excess nutrients from water (Emenike *et al*., 2022) [20].



2. Coconut Shell and Mesquite Wood Biomass Residues: Sources and Properties

Coconut biomass residues refer to the organic materials produced throughout the cultivation, processing, and utilization of coconuts. These residues include various parts of the coconut tree such as leaves, husks, fronds, and shells, along with byproducts from coconut oil and coconut milk production. The generation of coconut biomass residues is most prevalent in tropical and subtropical regions, especially in Southeast Asia, the Pacific Islands, and South America, where coconut farming is extensively practiced (Abeysekara and Waidyarathne, 2020) [1]. These residues are composed of a wide array of organic compounds including cellulose, hemicellulose, lignin, proteins, lipids, and sugars, as well as inorganic constituents like potassium, calcium, and magnesium (Azeta *et al*., 2021; Menon *et al*., 2021) [9, 50].

Mesquite (*Prosopis juliflora*), an aggressive and invasive tree species, contributes significantly to biomass waste accumulation in arid and semi-arid zones across the globe. Utilizing this biomass for biochar production presents a dual benefit: it helps reduce surface-level pollution and offers a means to rehabilitate contaminated soils. Based on this potential, researchers hypothesized that applying biochar derived from mesquite wood waste to soil could improve the retention of doxycycline by facilitating its sorption onto the biochar matrix. Additionally, studies were conducted to examine how different soil types influence the retention and desorption of doxycycline, both in the presence and absence of manure and biochar amendments (Al-Wabel *et al*., 2021) [7].

Table 1: Properties of coconut biomass residues (Azeta *et al.*, 2021; Aziz *et al.*, 2018; Bharath *et al*., 2019; Israel *et al.*, 2011) [9, 10, 15, 30].

Coconut part	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)
Husk	29.58-54.0	25.42-27.81	25.02-42.0	0.92-3.95
Shell	29.58-65.0	23.8-27.77	29.7-53.3	1.7-3.84
Coir	35.99-44.0	12	33.0-53.5	1.6-9.0
Frond	39.05-43.91	22.49-31.58	18.15-21.46	4.96
leaves	32.0-44.2	56.3-67.8	32.8-45.0	2.2-6.8

Table 2: Properties of different coconut biomass residues

Coconut part	Proximate analysis (%)				Ultimate analysis (%)					Biochar yield (%)	Ref.
	MC	VM	FC	Ash	C	N	H	S	O		
Husk	-	5.33	77.35	17.32	67.31	0.87	2.67	0.17	28.98	34.0	(Suman and Gautam, 2017) [96]
Flesh	2.36	12.71	79.09	8.19	83.25	2.98	1.45	1.33	10.99	40.65	(Noor *et al*., 2019) [53]
Husk	28.2	-	-	36.8	41.76	0.38	-	-	-	32.3	(Hariz *et al*., 2015) [23]
Husk	1.69	5.99	83.76	8.56	>60.0	-	-	-	-	33.7	(Khawkomol *et al*., 2021) [36]
Husk	2.96	38.63	53.99	4.42	>60.0	-	-	-	-	23.8	(Khawkomol *et al*., 2021) [36]
Shell	6.57	13.22	76.88	3.33	38.46	2.31	29.1	-	30.62	-	(Konneh *et al*., 2021) [38]
Fiber	-	42.6	48.8	8.60	78.20	1.23	4.31	0.33	15.93	35.3	(Liu *et al*., 2013) [41]
Shell	2.73	18.93	71.30	70.4	78.03	1.60	4.89	<0.01	15.2	49.5	(Rout *et al*., 2016) [61]
shell	2.53	71.67	24.86	0.94	61.84	0.41	4.98	0.01	33.46	92.0	(Ahmad *et al*., 2021) [7]
Shell	5.70	77.20	22.80	0.60	52.60	2.00	6.20	-	53.10	-	Windeatt *et al.* (2014) [77]
Shell	10.1	75.50	11.10	3.20	64.23	0.77	6.89	-	27.73	-	Khuenkaeo and Tippayawong (2020) [37]
Husk	7.50	85.30	14.70	5.30	44.70	0.80	7.50	-	61.80	-	Windeatt *et al.* (2014) [77]

Table 3: Characteristics of coconut shell, mesquite wood and others biomass

Sr. no.	Biomass	Proximate Analysis (wt. %)				Ultimate Analysis (wt. %)					CV (MJ/kg)	Ref.
		MC	VM	FC	Ash	C	H	O	N	S		
1	Coconut shell	46.93	3.96	48.21	0.71	0.19	2.29	81.67	17.50	0.83	19.43	Inayat *et al*.2018 [27]
2	Acacia mangium	43.54	3.59	51.70	1.00	0.16	4.25	88.07	10.61	1.32	17.53	Inayat *et al*.2018 [27]
3	Oil Palm Fronds	42.60	5.71	51.00	0.42	0.29	6.15	80.55	16.43	3.02	17.00	Inayat *et al*.2018 [27]
4	Coconut shell	9.66	71.92	17.75	0.67	47.29	4.91	0.37	47.24	0.19	17.43	Irawan *et al*., 2017 [28]
6	Coconut shell	5.56	70.82	21.80	1.80	40.08	5.22	54.31	0.22	0.17	-	(Ahmad *et al*., 2022) [52]
7	Mesquite wood	8.1±0.95	72.4± 6.71	1.0± 0.16	22.6± 1.23	-	-	-	-	-	-	Al-Wabel *et al*., 2021 [7]
8	*Prosopis juliflora*	10.85	72.83	14.47	1.85	45.20	5.58	51.50	0.65	0.07	-	Mahajan *et al*., 2017 [42]
9	*Prosopis juliflora*	-	66.6	25.5	1.7	48.4	6.26	-	-	-	21±0.3	Kumar *et al*., 2016 [39]
10	Coconut shell	10.5	71.1	17.6	0.80	48.6	5.97	43.8	0.62	1.09	17.43	Isa *et al*., 2024 [24]
11	Coconut shell	-	72.93	19.48	3.2	53.73	6.16	38.45	0.86	0.02	-	Sundaram *et al*., 2009 [71]

3. Biochar Production with Different Mathods

The main strategies for producing biochar from biomass rely on thermochemical conversion processes, which involve heating biomass in environments with limited or no oxygen to generate biochar, bio-oil, and syngas (Umenweke *et al*., 2021). Over the last two decades, the conversion of lignocellulose biomass such as agricultural crop residues, forest biomass, dedicated energy crops, and grasses into biofuels and other high-value bio products has become a prominent area of research. A range of thermochemical methods including torrefaction, pyrolysis, gasification, hydrothermal carbonization, and hydrothermal liquefaction are employed based on the desired output. For example, gasification is primarily used to produce gaseous products like syngas, whereas hydrothermal liquefaction and fast pyrolysis are designed to yield liquid products such as crude or bio-oil, which can be further upgraded through catalytic hydro-treatment into various 'drop-in' biofuels. Table 5 outlines the operational parameters for each conversion technique, detailing factors such as peak temperature, duration of residence, and heating rate. Likewise, processes like hydrothermal carbonization, torrefaction, and slow pyrolysis are mainly utilized to produce solid outputs, including biochar and hydro char. Among these thermochemical conversion options, pyrolysis is frequently chosen for lignocellulose biomass due to its ability to simultaneously produce liquid (bio-oil), solid (biochar), and gaseous (syngas) products. The relative proportions of these outputs can be fine-tuned by adjusting pyrolysis variables such as temperature, heating rate, and residence time (Sivaraman *et al*., 2025) [66]. (Sivaraman *et al*., 2025) [66].

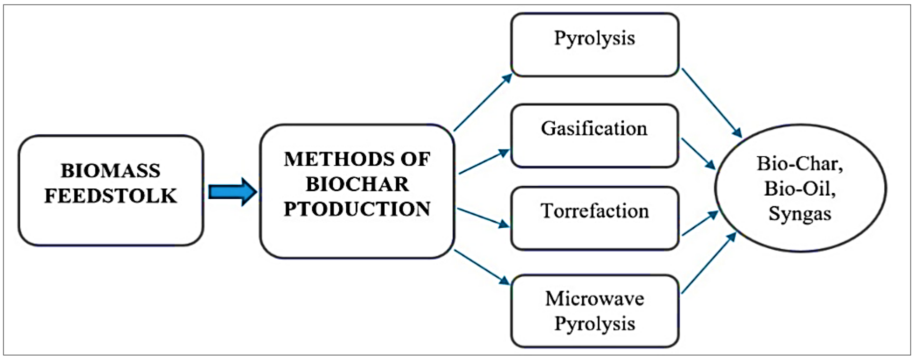


Fig 1: Conversion of biomass into bio-char (Bambhaniya *et al*., 2025) [13]

Table 4: Biochar production with different methods (Makavana *et al*., 2024) [47]

Process	Liquid(bio-oil)	Solid(biochar)	Gas(syngas)
Moderate temperature (~500 °C) short hot residence time (<2s)	75% (25% water)	12%	13%
Intermediate pyrolysis Low-moderate temperature, Moderate hot vapour residence time	50% (50% water)	25%	25%
Slow pyrolysis Low-moderate temperature, Long residence time	30% (70% water)	35%	35%
Gasification High temperature (>800 °C) Long vapour residence time	5% tar (5% water	10%	85%

Table 5: Biochar production with different methods

Biomass materials	process	Peak temp.(◦C)	Heating rate (◦C/min)	Residence time	Ref.
Coconut shell	Fast pyrolysis	800	100-500	1-8 min	Tsai *et al*., 2006 [74]
Coconut shell	Fast pyrolysis	650	175	20 min	Siengchum *et al*., 2013) [65]
Coconut shell	Slow pyrolysis	500	10	3 h	Pituya *et al*., 2017 [57]
Coconut shell	Gasification	850	20	1h	Romero Millan *et al*., 2021 [60]
Coconut shell	Torrefaction	300	20	90 min	Ahmad *et al*., 2021 [7]
Coconut shell	Muffle furnace	700	7.0	2 h	Baharum *et al*. 2020 [11]
Coconut shell	Muffle furnace	300	10.0	1 h	Behera *et al*. 2020 [14]

4. Characterization of Coconut Shell and Mesquite Wood Biochar

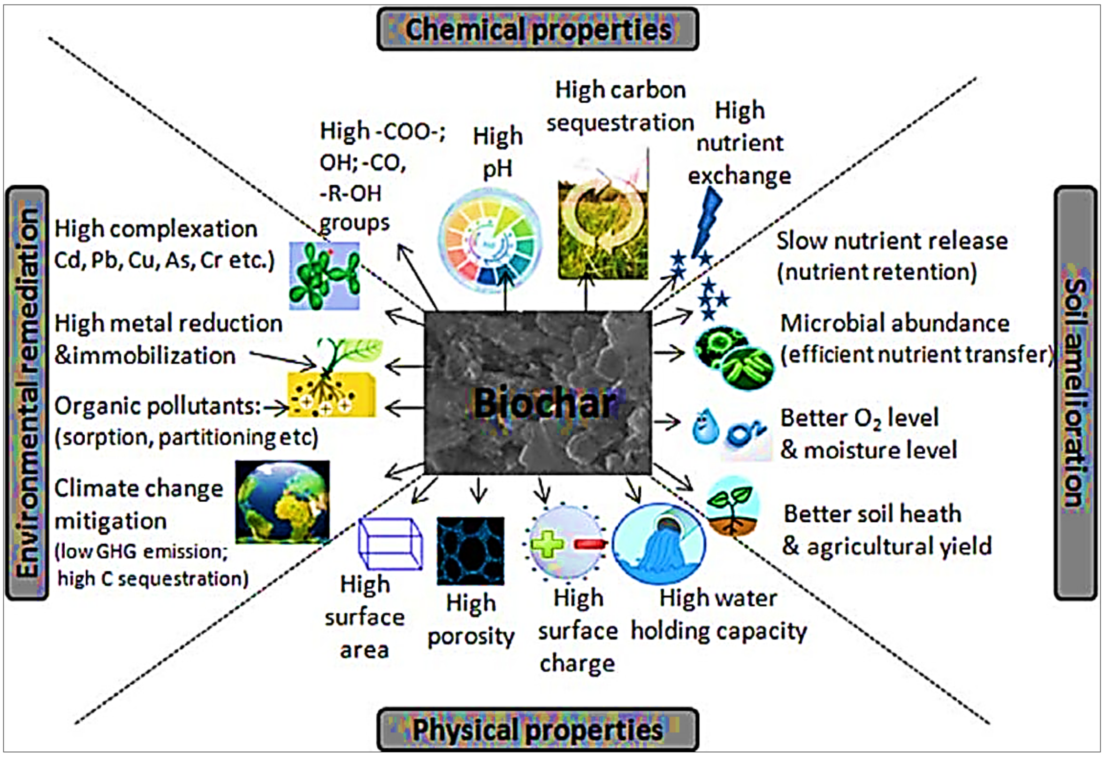


Fig 2: Biochar characteristics and suitability for specific applications (Oliveira *et al*., 2017)

Table 6: Characteristics of coconut shell and mesquite wood biochar

Sr. no.	Biochar	Proximate Analysis (wt. %)				Ultimate Analysis (wt. %)					CV (MJ/kg)	Ref.
		MC	VM	FC	Ash	C	H	O	N	S		
1	*Posopis juliflora*(300 ˚C)	-	39.1	63.4	2.5	65.8	3.7	-	0.41	-	24.0(±0.01)	kumar *et al*., 2016
	Posopis juliflora (400 ˚C)	-	25.8	77.2	3.0	76.1	3.9	-	0.52	-	29.9(±0.04)	kumar *et al*., 2016
	Posopis juliflora (500 ˚C)	-	18.6	84.6	3.2	79.6	3.3	-	0.63	-	31.2(±0.04)	kumar *et al*., 2016
	Posopis juliflora (600 ˚C)	-	11.2	92.4	3.6	83.3	2.8	-	0.61	-	32.8(±0.01)	kumar *et al*., 2016
	Posopis juliflora (700 ˚C)	-	8.9	94.7	3.7	82.9	2.1	-	0.70	-	32.1(±0.03)	kumar *et al*., 2016
	Posopis juliflora (800 ˚C)	-	7.9	95.5	3.4	83.4	1.7	-	0.52	-	31.7(±0.02)	kumar *et al*., 2016
2	coconut shell (300 ˚C & 75 min)	5.04	35.58	62.78	1.63	-	-	-	-	-	-	Ridwan *et al*., 2024
	coconut shell (300 ˚C & 90 min)	4.81	33.12	65.00	1.83	-	-	-	-	-	-	Ridwan *et al*., 2024
	coconut shell (300 ˚C & 105 min)	4.53	31.55	66.51	1.94	-	-	-	-	-	-	Ridwan *et al*., 2024
	coconut shell (300 ˚C & 120 min)	4.29	29.79	67.96	2.24	-	-	-	-	-	-	Ridwan *et al*., 2024
	coconut shell (300 ˚C & 135 min)	3.83	26.75	70.72	2.53	-	-	-	-	-	-	Ridwan *et al*., 2024
	coconut shell (400˚C & 75 min)	4.35	31.84	66.29	1.87	-	-	-	-	-	-	Ridwan *et al*., 2024
	coconut shell (400 ˚C & 90 min)	3.84	29.93	67.70	2.37	-	-	-	-	-	-	Ridwan *et al*., 2024
	coconut shell (400 ˚C & 105 min)	3.39	26.39	71.70	2.51	-	-	-	-	-	-	Ridwan *et al*., 2024
	coconut shell (400 ˚C & 120 min)	3.17	26.53	70.72	2.74	-	-	-	-	-	-	Ridwan *et al*., 2024
	coconut shell (400 ˚C & 120 min)	2.80	25.65	71.55	2.80	-	-	-	-	-	-	Ridwan *et al*., 2024
3	Mesquite wood	-	07.6±00.81	75.8±06.13	14.5±01.32	80.08±06.20	01.64±00.05	02.49±00.11	01.30±00.08			Al-wabel *et al*., 2021
4	*Posopis juliflora* (400 ˚C)		22.6	74.6	2.8	72.4	3.9	20.0	0.9		27.6	Chandrasekaran *et al*., 2017
	Posopis juliflora (500 ˚C)		18.6	78.1	3.3	76.5	3.2	15.9	1.1		30.8	Chandrasekaran *et al*., 2017
	Posopis juliflora (600 ˚C)		15.2	80.7	4.0	78.6	2.8	13.4	1.2		32.3	Chandrasekaran *et al*., 2017

Table 7: The physical and chemical properties of the coconut shell biochar (Angalaeeswari *et al.* 2017) [8].

Sr. No.	parameter	Coconut shell biochar	Mesquite wood biochar
1	pH	8.66	8.73
2	EC (dSm-1)	0.98	2.20
3	Bulk density (g cm-3)	0.54	0.34
4	Particle density (g cm-3) 0.34	0.25	0.23
5	Pore space (%)	31.01	37.3
6	Moisture content (%)	0.43	0.35
7	Ash content (%)	1.46	1.29
8	Total organic carbon (%)	9.52	8.90
9	Cation exchange capacity (cmol (p^+) kg $^{-1}$)	11.93	9.76
10	Zeta potential (mV)	-42.10	-26.20
11	Particle size (nm)	56.40	87.40

Table 8: Physical and physio-chemical properties of biochar from different biomass (Kanagasuppurathinam *et al.* 2024) [35]

Biomass	Physical Properties						Physio-chemical properties			
	M.C. (%)	A.C. (%)	Bulk density (Mg m^{-3})	Porosity (%)	pH	EC (dS m^{-1})	CEC (cmol kg^{-1})	Total C (%)	Organic C (%)	C:N ratio
Coconut shell	14.60	12.30	0.39	37.86	9.60	3.12	18.29	60.9	0.48	80.86
Prosopis wood	12.45	0.99	0.46	72.44	10.31	3.86	20.61	64.0	0.69	69.47

Table 9: Chemical properties of biochar from different biomass (Kanagasuppurathinam *et al.* 2024) [35]

Biomass	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)	Total S (%)	Available N (mg kg $^{-1}$)	Available P (mg kg $^{-1}$)	Water soluble carbon (mg kg $^{-1}$)
Coconut shell	0.76	0.37	2.51	1.50	0.27	0.37	8.47	43.61	75.73
Prosopis wood	0.93	0.18	1.31	1.04	0.99	0.26	42.16	74.69	153.98

Table 10: Result of physical and chemical properties of acacia wood and coconut shell biochar at different temperature and time (pituya *et al*., 2017) [57]

Sample	Pyrolysis Condition		Physical and Chemical Properties of Biochar								
	Temp. (°C)	Time (h)	SA (m^2/g)	APD (Å)	C (%)	H (%)	N (%)	O (%)	pH	CEC (cmol/kg)	WHC (%)
AW	300	1	02.14	71.87	68.85	3.44	0.02	27.66	6.0	69.86	426.20
	300	2	04.09	57.78	66.91	3.41	0.02	29.55	5.5	106.30	344.40
	300	3	06.09	59.73	67.56	3.52	0.02	28.85	5.0	127.45	355.10
	400	1	04.56	63.8	68.21	3.62	0.02	28.07	5.6	87.80	352.60
	400	2	108.89	25.55	66.98	4.30	0.22	28.46	6.8	102.60	303.30
	400	3	100.56	26.85	68.68	3.13	0.06	28.09	6.3	96.81	380.20
	500	1	330.63	22.87	72.98	2.92	0.10	23.99	7.9	41.30	313.80
	500	2	370.37	22.41	70.74	2.98	0.10	26.07	7.8	69.26	345.60
	500	3	376.51	23.07	73.26	2.91	0.01	23.64	7.7	64.40	365.70
CS	300	1	01.03	60.60	53.47	3.70	0.01	42.567	6.4	34.76	69.78
	300	2	01.03	95.26	48.32	3.93	0.01	47.56	6.5	26.25	70.03
	300	3	00.95	80.07	43.46	3.62	0.01	52.76	6.9	55.09	75.30
	400	1	04.01	48.21	31.84	3.08	0.02	64.87	7.2	19.92	56.65
	400	2	08.76	40.57	43.08	3.17	0.01	53.62	8.8	13.67	52.62
	400	3	11.32	40.30	54.28	3.16	0.01	42.54	9.1	26.34	49.15
	500	1	199.38	27.07	65.48	3.15	0.01	31.35	9.3	24.95	54.13
	500	2	347.96	22.06	64.77	2.93	0.01	32.29	8.9	14.74	38.90
	500	3	351.95	22.20	64.06	2.70	0.01	33.20	8.9	61.23	35.30

5. Applications of Biochar

The surge in industrial development and the widespread adoption of agrochemical-based farming practices since the Green Revolution have significantly contributed to the accumulation of persistent organic pollutants and heavy metals within the food chain and the surrounding environment. This growing contamination has sparked serious public concern regarding environmental protection and human health (Spokas *et al*., 2009; WHO, 2017) [67, 78]. Biochar, a cost-effective carbon-rich material, is gaining recognition as an economical alternative to activated carbon for the removal of various organic pollutants, including agrochemicals, antibiotics, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), volatile organic compounds (VOCs), and aromatic dyes (Beesley *et al*., 2010; Qiu *et al*., 2009; Teixido *et al*., 2011; Xu *et al*., 2012; Zheng *et al*., 2010) [13, 72, 51, 81, 84]. It is also effective in eliminating a range of inorganic contaminants such as heavy metals, ammonia, nitrate, phosphate, and sulfide from aqueous, gaseous, and solid media (Ahmad *et al*., 2014; Sun *et al*., 2011; Jung *et al*., 2015; Xu *et al*., 2011; Yu *et al*., 2009) [4, 70, 33, 80, 82]. Biochar is produced as a result of thermochemical conversion processes including pyrolysis, gasification, torrefaction, and hydrothermal carbonization (Kambo and Dutta, 2015) [34]. Applied to carbon-rich biomass sources such as agricultural residues, algal biomass, forest waste, animal manures, activated sludge, energy crops, and digestate. These processes are conducted at elevated temperatures ranging from 300 to 900 °C under oxygen-limited conditions (Ahmad *et al*., 2012; Lehmann *et al*., 2009) [3, 40]. Among various experimental conditions, biochar derived from shredded cotton stalk at a temperature of 500 °C and a residence time of 240 minutes demonstrated superior quality. Under these specific parameters, the biochar exhibited a high calorific value of 8101.3 cal/g (equivalent to 33.89 MJ/kg), along with notable concentrations of nitrogen (1.56%), carbon (79.30%), and a carbon-to-nitrogen ratio (C/N) of 50.83 (Makavana *et al*., 2018) [44].

The use of biochar in soil not only aids in the remediation of pollutants but also enhances overall soil quality. Biochar contributes to improvements in physical properties such as water retention capacity, oxygen availability, and moisture levels; chemical properties including the immobilization of pollutants and carbon sequestration; and biological properties like increased microbial abundance, diversity, and activity (Gul *et al*., 2015) [21]. These attributes of biochar play a vital role in promoting soil carbon storage (Windeatt *et al*., 2014) [77], reducing greenhouse gas (GHG) emissions (Stewart *et al*.,), and ultimately fostering better soil health (Zhang *et al*., 2013) [82]. One of biochar distinctive features is its ability to bind polar compounds through its charged surface functional groups, which facilitates the immobilization of heavy metals and agrochemicals in the rhizosphere, thereby limiting their uptake by crops (Bolan *et al*., 2014; Spokas *et al*., 2009) [16, 67]. In addition, various engineering properties of agricultural residues such as rice husk, rice straw, sugarcane bagasse, and cotton stalk were evaluated. These engineering characteristics are crucial for the design of processing equipment, improving plant productivity, and developing innovative technologies that utilize agricultural residues as raw materials (Makavana *et al*., 2018) [43].

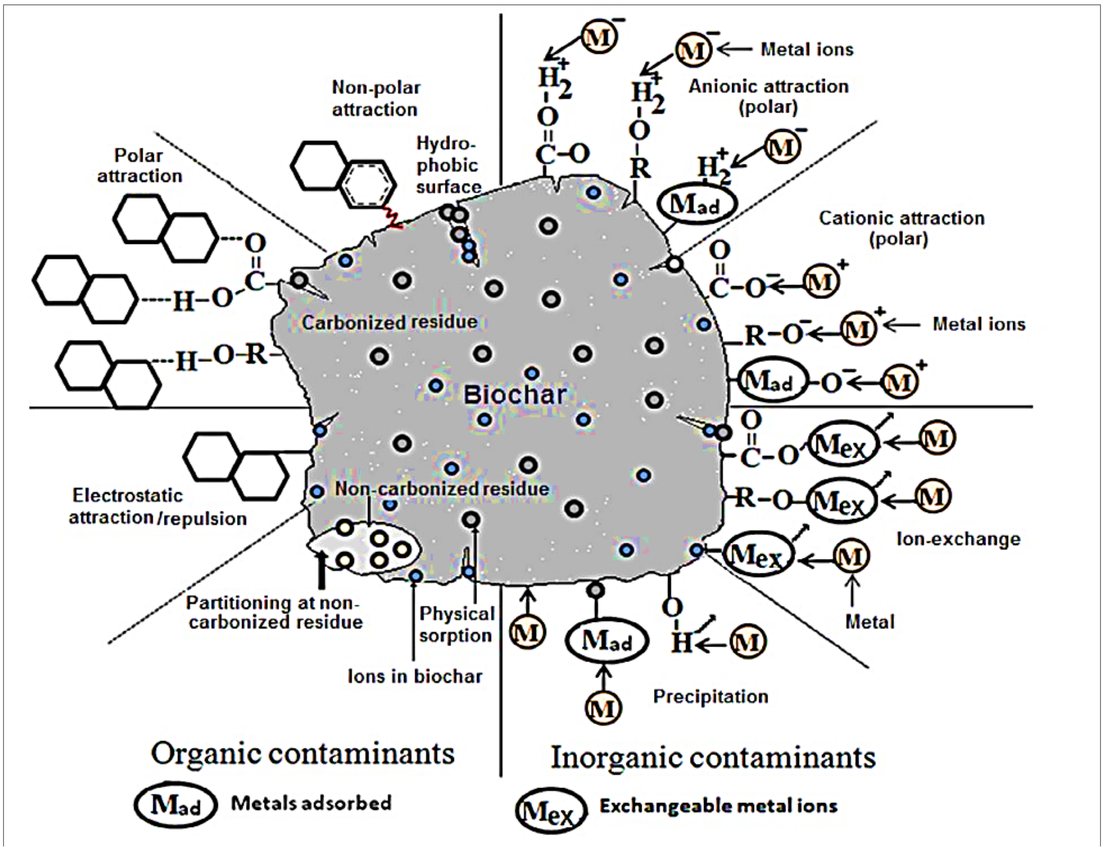


Fig 3: Various mechanisms of biochar interactions with organic and inorganic pollutants (Oliveira *et al*., 2017).

Biochar derived from a wide range of biomass feed stocks has been identified for 55 valuable applications across both industrial and environmental domains (Schmidt, 2012) [62]. Within industrial settings, biochar serves as a cost-effective alternative to cement in the construction sector (Marousek *et al*., 2020) [49] and can also function as an energy source (Mardoyan & Braun, 2016) [48]. In environmental contexts, biochar is utilized as a soil conditioner, fertilizer, and material for water purification (Braghiroli *et al*., 2018) [17]. The versatility of biochar in these applications is largely attributed to its surface properties (Bushra and Remya, 2020) [18]. One of the most common environmental uses of biochar made from coconut shell and coconut husk is soil amendment. This is due to their beneficial attributes, including high cation exchange capacity (CEC), excellent water-holding capacity (WHC), nutrient composition, mineral release dynamics, and optimal pH levels. Under specific pyrolysis conditions, coconut shell biochar has demonstrated a maximum CEC of 61.23 cmol kg^{-1} and a WHC of 75.30% (Pituya *et al*., 2017) [57]. Biochar with elevated CEC and WHC levels can significantly enhance nutrient absorption by plants, promote robust root growth, and improve overall soil fertility, ultimately leading to increased crop yields (Hansen *et al*., 2016). The pH of biochar ranged between 5.85 and 9.86, with electrical conductivity (EC) values spanning from 0.04 to 0.10 dS/m, and cation exchange capacity (CEC) varying from 38.02 to 24.39 cmol/kg, depending on the specific temperature and residence time applied during production (Makavana *et al*., 2025) [46]. Additionally, biochar derived from coconut shell and coconut husk contains a notably high concentration of essential minerals, including phosphorus (P), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), molybdenum (Mo), zinc (Zn), manganese (Mn), copper (Cu), nickel (Ni), iron (Fe), and silicon (Si) (Millan *et al*., 2021; Windeatt *et al*., 2014) [60, 77]. These types of biochar also demonstrate a strong capacity for carbon sequestration, which refers to the process of capturing and storing atmospheric CO_2 a major contributor to global climate change and greenhouse effects. Theoretical assessments have been conducted to estimate the amount of CO_2 that can be sequestered by coconut shell and coconut husk biochar (Windeatt *et al*., 2014) [77].

Table 11: Application of coconut shell biochar for industrial and environmental purposes

Application	Technology	Temperature(time)	Findings	Reference
Biodiesel production	Pyrolysis (slow pyrolysis)	300-600°C (30 min to 1h)	Coconut shell biochar achieved its maximum sulfonic density (0.45 mmol g^{-1}) at 300°C, and the sulfonic density decline (0.12 mmol g^{-1}) at 600°C, may indicate its potential as a catalyst for transesterification to produce biodiesel	Behera *et al.* (2020) [14]
Soil amendment	Pyrolysis (slow pyrolysis)	300°C (3 hours)	Coconut shell biochar has a 75.30% maximum water-holding capacity	Pituya *et al.* (2017) [57]
		500°C (3 hours)	Coconut shell biochar has 61.23 cmol kg^{-1} of the maximum cation exchange capacity.	
		600°C (1 hour)	Coconut shell biochar contains approximately 2000 mg kg^{-1} of K, 1000 mg kg^{-1} of Ca and 100 mg kg^{-1} of Mg.	Windeatt *et al.* (2014) [77]
Soil amendment	Gasification	850°C (1 hour)	Coconut shell contains 20,393.80 mg kg^{-1} of K, 4188.70 mg kg^{-1} of Na, 387.70 mg kg^{-1} of Ca, 274.00 mg kg^{-1} of P, 954.60 mg kg^{-1} of Si and 561.20 mg kg^{-1} of Cu.	Millan *et al.* (2021) [60]
Water treatment	Pyrolysis (microwave assisted)	126-205.40°C (15-20 min)	The methylene blue adsorption capacity of the coconut shell biochar decreases from 0.6875 (removal efficiency = 55.00%) to 0.5165 mg g^{-1} (removal efficiency = 41.32%) as the carbonization time increases from 15 to 20 minutes at 550 W.	Nuryana *et al.* (2020) [54]
Carbon sequestration	Pyrolysis (slow pyrolysis)	600°C (1 hour)	4.90 million tons of coconut shell biochar can theoretically capture or store 9.900 million tons of atmospheric CO2.	Windeatt *et al.* (2014) [77]

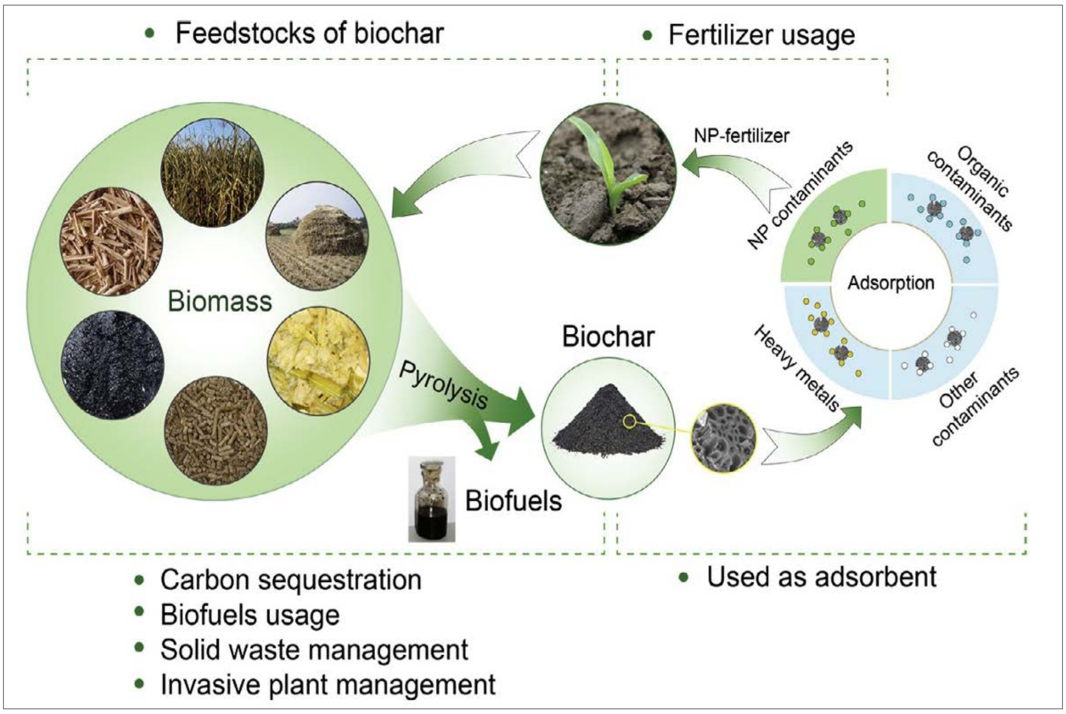


Fig 4: The benefits of biochar applied as an effective adsorbent for waste water treatment (Tan *et al*., 2015)

6. Conclusion

This review paper highlights the development of biochar from coconut shell and mesquite wood biomass, exploring the methods of production, material properties, and various applications of this multifunctional substance. Biochar derived from coconut shell exhibits superior characteristics, including a higher cation exchange capacity of 11.93 cmol (p^+) kg^{-1}, total organic carbon content of 9.52%, a negatively charged zeta potential of -42.1 mV, and surface area dimensions ranging from 0.26 µm to 10.00 µm in diameter, with lengths varying between 12.95 µm and 15.69 µm, in comparison to biochar produced from mesquite wood. As more functional groups undergo deprotonation, the surface of the biochar becomes increasingly negatively charged. The purpose of this study was to offer foundational insights into the potential reuse of biochar generated from different biomass sources. Producing biochar presents a practical solution for waste management, and both coconut shell and mesquite wood appear to be promising feed stocks due to their abundant availability. Utilizing biomass such as coconut shell and mesquite wood for biochar production could serve as an efficient strategy for recycling organic waste materials. In summary, converting coconut residues into biochar holds considerable promise for addressing environmental and agricultural challenges, and with continued research and innovation, it has the potential to evolve into a commercially valuable product.

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