Bulgarian Chemical Communications, Volume 57, Issue B (pp. 289-301) 2025 DOI: 10.34049/bcc.57.B.A0007

Assessing the potential of apricot shell biochar from *Prunus Armeniaca* of Kargil: a comprehensive review

S. Hussain[1], S. Chaurasia[1], P. Gajbhiye[1*], R. K. Arya[2], A. M. Yatoo[3]

[1]*School of Chemical Engineering and Physical Sciences, Lovely Professional University, Phagwara, Punjab, India*
[2]*Department of Chemical Engineering, NIT Jalandhar, India*
[3]*Department of Environmental Science, University of Kashmir, Jammu & Kashmir, Srinagar 190006, India*

Revised: February 23, 2025

Apricot seed shell biochar, derived from agro-waste through thermal and hydrothermal processes, has demonstrated significant potential in addressing environmental challenges and advancing sustainable practices. The review discusses the production, characterization, and application of apricot-based biochar, emphasizing physicochemical properties and performance in adsorption and soil improvement. Apricot biochar is distinguished by its porous carbon microsphere structure and the abundant oxygen-containing functional groups that result in better adsorption for atrazine, nitrates, and heavy metals. The selected responses present some common preparation techniques found in biochar preparation: hydrothermal and pyrolytic techniques, with some chemical activation processes. For this reason, kinetic models, pseudo-second-order kinetics, and the Freundlich isotherms apply to govern the adsorption performance of such biochar samples. Mechanisms that might underlie such behavior are hydrogen bonding and hydrophobic interactions. Biochar based on apricots has given promise in regulating pesticide residues; enhancing the quality of saline soils through their improvement can bring a halt to agricultural nonpoint source pollution as well. However, it is pH-dependent, ion concentration-dependent, and dosage-dependent. The review will emphasize the promise of apricot biochar as an inexpensive and environmentally friendly tool for environmental remediation while uncovering difficulties in mass production, optimization of activation processes, and performance in applications. Potential research directions are the development of biochar's functional properties and its role in sustainable agriculture and pollution control.

Keywords: Apricot seed shell, oxygen-containing functional groups, environmental remediation, sustainable agriculture

Fig. 1. Graphic abstract

INTRODUCTION

Biochar is carbon-rich material produced from the heating of organic matter in a low or oxygen-free environment. Recently, people have taken an interest in biochar as it can be used to enhance soil grade and crop growth and sequester carbon. Among the good uses of apricot shells would be making charcoal, which is biochar. Kargil is a distant town in the Ladakh region of India. It has beautiful views, but the climate is harsh.

* To whom all correspondence should be sent:
E-mail: pratima.24280@lpu.co.in
pratimawadhwani@gmail.com

The major activity here is farming, and apricots are grown abundantly. Yet, the countless apricot shells that are thrown away can be converted into biochar, benefiting the environment as well as the economy. Studies are being carried out on the application of apricot shells with minimal environmental impact. Apricot shell biochar has worked efficiently in amending soil and promoting crop yields. It also serves as an environmentally friendly and sustainable waste management method. We shall see if we can make biochar from apricot shells in Kargil and check how well it improves soil quality.

A great deal of research on has been conducted on the effect of biochar the properties of the soil, crop productivity, and yield. Biochar is very helpful in retaining nutrients in the soil, preventing the nutrients from washing away, and improving the general health and quality of the soil. According to Agegnehu et al., it has been found through a review that incorporation of biochar and biochar-compost improves the soil and helps crops to grow better [1]. The present review shall discuss in-depth the current work on biochar and its potential use in agriculture. Other benefits of applying biochar encompass its potential ability to improve the water retention characteristics of soil in addition to the rehabilitation of both degraded soils and landscapes. Biochar has been found to promote healthy growth in plants, which postulates that its use can also be as a sort of fertilizer. Toxic levels of biochar impair earthworm and vegetable crop yield. Biochar is a product that improves soil value and offers several environmental advantages, such as carbon storage, mitigation of greenhouse gases, and increased plant growth [2-4]. Biochar has been found to provide various benefits throughout its life cycle when used for soil conditioning. These benefits include improving the quality of ecosystems, reducing the consumption of resources, and mitigating the effects of climate change. Overall, biochar is considered a positive option for enhancing soil health and sustainability [5]. The incorporation of biochar into soil has the potential to greatly benefit plant growth and enhance soil quality by acting as a stimulant for plant growth [6]. By conducting additional research on the use of biochar as a soil amendment, we can enhance our knowledge regarding its interactions with various components of problematic soils. This, in turn, will expedite our progress in soil remediation and contribute to the improvement of crop yields in such challenging environments [7]. Algal biochar from wastewater can boost soil grade and generate income as a fertilizer and soil ameliorant, besides its water remediation and C-sequestration benefits [8]. Producing biochar from oil palm biomass can potentially lead to a healthier environmental, societal and economic growth for the oil palm industry specifically, and enhances sustainability in worldwide context [9]. Biochar production technologies are among the environmentally friendly technologies that aim to reduce greenhouse gas (GHG) emissions and promote a cleaner environment [10]. Biochar can be applied at suitable levels under dry conditions, as it has the ability to retain more water compared to treatments without biochar [11]. Since the beginning of the twenty-first century, biochar has garnered significant attention from various fields of research due to its unique properties, diverse applications, and promising potential for further development [12].

Biochar-based carbon sequestration may have long-term benefits, but it comes at the expense of short-term CO_2 emissions that can accelerate climate change [13]. The addition of biochar to soil has a quick and robust impact on both the nutrient content of the soil and the composition of plant communities [14].

Compost and biochar, either applied alone or in combination with fertilizer, have been shown to enhance soil fertility and plant growth while reducing nutrient leaching [15]. Biochar is recognized to have improved soil physical and chemical properties, enhanced soil biota, increased crop yield, remediated polluted soil, and recycled agricultural waste. It offers several interrelated direct and indirect benefits when used as a soil amendment [16]. For the sustainable and economically viable use of biochar for environmental applications, its economic impacts and recyclability must be taken into account during development [17].

LITERATURE REVIEW

Biochar has gained significant attention as a sustainable solution for soil enhancement, greenhouse gas mitigation, and environmental remediation. Biochar application is considered a viable strategy for reducing greenhouse gas emissions, particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). By sequestering carbon in stable forms, biochar prevents CO_2 from being released into the atmosphere and contributes to long-term carbon storage. Moreover, it influences nitrogen dynamics in the soil, potentially reducing N_2O emissions from agricultural activities. However, optimizing the nitrogen efficiency of biochar-based fertilizers remains a challenge, requiring further research on their interaction with soil microbes and plant uptake [18]. Its potential to improve soil health, support rural economies, and function as an effective adsorbent makes it a promising material in agriculture and environmental applications. However, the effectiveness and scalability of biochar depend on factors such as feedstock source, production costs, and technological advancements. Biochar has the potential to support rural economies by creating new revenue streams through its production and sale. Small-scale biochar production units can provide employment opportunities while promoting sustainable agricultural practices. However, widespread adoption faces significant challenges, including high production costs, technological limitations, and inconsistent availability of suitable feedstocks. Developing cost-effective biochar production technologies and establishing standardized guidelines for its agricultural use are critical steps toward mainstream implementation. This review explores the role of biochar in soil nutrition and biology, its impact on greenhouse gas emissions, pollutant remediation, economic benefits, and challenges associated with its widespread adoption [19]. Table 1 shows the various key findings of research papers.

METHODS OF PREPARATION OF BIOCHAR

Pyrolysis The process of thermal decomposition of organic materials in an oxygen-free environment under the temperature range of 250-900 ^{0}C is called pyrolysis. Table 1 shows the key findings from studies comparing the effectiveness of different biochar types, conditions, and application rates in diverse environmental settings.

Table 2 shows the summary of research findings on how different pyrolysis temperatures affect biochar surface area, porosity, and carbon stability. Figure 1 shows the graphical abstract for the biochar uses.

Table 1. Key findings from studies comparing the effectiveness of different biochar types, conditions, and application rates in diverse environmental settings

S. No.	Title	Year	Key findings	Ref. No.
1	Biochar enhances yield and quality of tomato under reduced irrigation.	2014	Biochar application has increased tomato yield and quality under the reduced irrigation set-up.	[3]
2	Biochar: potential for countering land degradation and for improving agriculture.	2012	Biochar particles have a wide surface area and complicated inner structure that provides an environment for the thriving of microorganisms, thereby biofilm formation.	[5]
3	Using poultry litter biochars as soil amendments.	2008	The addition of biochar in hard-setting soil showed major changes in its properties: increasing carbon, nitrogen, pH, and available phosphorus, though it decreases soil strength.	[6]
4	Influence of soil properties and feedstocks on biochar potential for carbon mineralization and improvement of infertile soils.	2018	Biochar with low clay content and sandy soil without nutrients and organic matter improves the fertility of soil to a considerable extent.	[7]
5	Effect of biochar application on seed germination and seedling growth of Glycine max (l) under drought stress.	2017	Biochar application counteracts the damaging effects of drought stress on the seedlings of soybean effectively have been observed.	[8]
6	Using agricultural residue biochar to improve the soil quality of desert soils.	2016	Cotton gin trash biochar boosts organic matter and nutrients in sandy and loamy soils but may raise soil salinity due to increased electrical conductivity.	[9]
7	Effects of biochar application on vegetable production and emissions of N_2O and CH_4.	2012	In farm-based applications, it was found that the use of biochar leads to a huge decrease in N_2O and N_2O-N emissions and yet allows the production of successfully grown vegetables.	[13]
8	Comparison of the efficacies of peanut shell biochar and biochar-based compost on two leafy vegetable productivity in an infertile land.	2019	It can be gathered from this research that incorporation of specially designed, peanut-shell biochar, PBC-based amendments (PAD) made from composted PBC was efficient in overcoming soil infertility, and Application of PAD at 1.5% to 3% improved vegetable yields by enhancing soil quality and nutrient availability.	[14]

9	Soil organic carbon characteristics affected by peanut shell biochar in saline-sodic paddy field.	2022	Study results showed that Biochar boosts soil organic carbon by forming humus-like substances, increasing aromaticity, and enhancing soil hydrophobicity.	[15]
10	Coconut shell-derived biochar to enhance water spinach (Ipomoea aquatica Forsk) growth and decrease nitrogen loss under tropical conditions.	2019	Coconut shell biochar was found to enhance the yield of water spinach and decrease nitrogen leaching; hence, it can be used as an amendment for enhancing soil quality in tropical regions	[16]
11	Effect of biochar and hydrochar from cow manure and reed straw on lettuce growth in an acidified soil.	2022	It has also been shown that chemically activated biochar (CBC) enhances soil organic matter, pH and also influences the nutrient contents of the soils, such as P, K, Ca, Mg, Zn, Fe, and Mn.	[18]
12	Understanding the role of biochar in agriculture	2022	Black carbon enhances crop growth and soil health in arid, poor soils by improving water retention, structure, nutrient uptake, and microbial diversity.	[19]
13	Effect of biochar application at different adding rates on garlic (Allium sativum) growth and production.	2020	Observation shows that 1.5% biochar addition boosted garlic production, while 3% hindered it, guiding optimal biochar use for garlic.	[20]
14	Observation shows that 1.5% biochar addition boosted garlic production, while 3% hindered it, guiding optimal biochar use for garlic.	2021	Incorporation of Biochar improved the tomato seedling growth and resilience in saline soil by enhancing physiological and biochemical mechanisms.	[21]
15	Biochar and hydrochar from agricultural residues for soil conditioning: Life cycle assessment and microbially mediated C and N cycles.	2022	The Findings show that, Biochar produced at a temperature of 500–700°C exhibited superior physicochemical properties.	[22]
16	Impacts of biochar concentration on the growth performance of a leafy vegetable in a tropical city and its global warming potential.	2020	Higher biochar levels increased nitrate, potassium, and cation exchange capacity (CEC) but reduced phosphate availability.	[23]
17	Water extract from straw biochar used for plant growth promotion: an initial test.	2016	Hot water extracts of biochar boost plant growth, increasing Chinese cabbage yield in pot experiments, as it contains organic compounds and mineral nutrients.	[24]
18	Potential of integrating biochar and deficit irrigation strategies for sustaining vegetable production in water-limited regions	2019	There is evidence that adding biochar to soil under limited irrigation can mitigate crop yield losses and improve water use efficiency for vegetables. However, there is a lack of comprehensive field studies that provide a conclusive understanding of the long-term effects of biochar on soil-moisture interactions under drought conditions.	[25]
19	Biochar induced modifications in soil properties and its impacts on crop growth and production.	2021	The addition of biochar to soil as an amendment has had a notable impact on the physical, chemical, and biological characteristics of the soil.	[26]
20	Biochar: effects on crop growth.	2018	The growth of oil palm and rubber seedlings was improved by adding a small amount of biochar to the soil.	[27]
21	Algal biochar: effects and applications.	2012	In pot trials, biochar treatments resulted in remarkable plant growth rate improvements, ranging from 15 to 32 times, compared to no biochar controls in Carbon and nutrient-poor soil. The addition of fertilizer further enhanced the growth. Biochar amendment also had a significant but relatively smaller impact on plant growth in a fertile agricultural soil.	[28]
22	Biochar-induced modification of soil properties and the effect on crop production.	2019	Biochar typically improves soil health by changing its physical, chemical, and biological characteristics, such as water retention ability, pH level, capacity to retain nutrients, and promoting the growth of beneficial fungi	[29]

23	Biochar to improve the quality and productivity of soils.	2015	Biochar use can be helpful in the modification of soil properties because it improves fertility, increases water retention capacity, enhances cation exchange capacity, and regulates pH levels.	[30]
24	Effects of compost and biochar amendments on soil fertility and crop growth in a calcareous soil.	2020	Numerous studies have reported the favorable agronomic outcomes of applying compost and biochar derived from diverse biomass sources on soil fertility, as well as the uptake of nutrients by crops and their growth, across a broad spectrum of soil types.	[31]
25	Low-cost and environmental-friendly Triticum aestivum-derived biochar for improving plant growth and soil fertility.	2018	After physicochemical analysis of the soil and studying the plant growth and dry matter yield, it was observed that the treatment increases both dry matter yield and soil fertility along with improvements in plant growth.	[32]
26	A comprehensive review of engineered biochar: production, characteristics, and environmental applications.	2020	A mixture containing a total of 15 g of rice-straw biochar per kilogram of soil was applied; the results observed showed that these amendments had increased effects on plant height, tiller quantity, and biomass yield as compared with the control groups, which had no biochar application.	[33]
27	Environmental benefits of biochar.	2012	Temperatures at varying levels were applied to create birch wood biochar, and the effects that were induced by different temperatures were studied on various components of the soil ecosystem. Although their physical properties exhibit dramatic differences, all the biochar types showed similar impacts on soil properties and plant growth.	[34]
28	Impacts of different sources of biochar on plant growth characteristics.	2018	Biochar affects plant productivity positively, neutrally, or negatively; low rates, low-temperature biochar, or hydrochar may immobilize nitrogen, reducing benefits.	[35]
29	Comprehensive review on the production and utilization of biochar.	2019	This study investigated the impact of date palm residues biochar on sandy desert soil and showed that biochar's produced at lower temperatures (300-400 ◦C) with a mineral fertilizer enhanced the growth of wheat and increased soil water retention over time whereas, Bio-chars produced at higher temperatures have enhanced specific soil physical properties like bulk density and total porosity.	[36]
30	Production, activation, and applications of biochar in recent times.	2020	Application of biochar to a depth of up to 10 cm can minimize denitrification and reduce N2O emissions with a better regulation of leaching of mobile nutrients like potassium; hence, increasing water use efficiency, nutrient availability, and eventually, plant growth.	[37]

Table 2.Summary of research findings on how different pyrolysis temperatures affect biochar surface area, porosity, and carbon stability.

S. No.	Material sources	Temperature	Key finding	Ref. No.
1	Feedstock maize	750 ^{0}C	The incorporation of biochar decreases the bulk density of soil, increases the total volume of pores, and increases the water-holding capacity at the permanent wilting point.	[1]
2	Soybean stover, Peanut shells	300 ^{0}C 700 ^{0}C	Different carbonization temperatures affected biochar properties, increasing hydrophobicity, surface area, and aromatic condensation while reducing polarity. These changes influenced trichloroethylene (TCE) adsorption capacity.	[38]

3	Pine Rice husk Wheat straw	350 ^{0}C 450 ^{0}C 550 ^{0}C 650 ^{0}C	Wood biochar had 3–10 times more humification materials than rice husk biochar and ash, while bamboo biochar had none. Wood biochar's superior sorptive and humification properties make it useful in composting. The stability of biochar from pine, rice husk, and wheat straw was analyzed using proximate, ultimate analysis, and the Edinburgh stability tool, confirming that higher pyrolysis temperatures increased stability and total carbon by releasing volatiles.	[39]
4	Canola Corn Soybean Peanut straws	300 ^{0}C 500 ^{0}C 700 ^{0}C	Biochar's from canola, corn, soybean, and peanut straws became more alkaline with higher pyrolysis temperatures. Carbonates were the main alkaline species at 500 and 700°C. FTIR–PAS and zeta potential analysis showed that –COO− and –O− groups influenced biochar alkalinity, especially at lower temperatures.	[40]
5	Orange peel	150-700 ^{0}C	Biochar prepared at 150–600 ^{0}C showed strong 1-naphthol sorption due to specific interactions, while at 200 ^{0}C had the highest capacity at high concentrations. Biochar at 700 ^{0}C was most effective at low concentrations, highlighting biochar's potential as engineered sorbents.	[41]
6	Wheat straw Poplar wood Spruce wood	400 ^{0}C 460 ^{0}C 525 ^{0}C	Wheat straw biochar had high salt (4.92 mS cm−1) and ash (12.7%) content. H/C ratios ranged from 0.46 to 0.40 at 525°C. Higher temperatures increased surface area (1.8–56 m²/g) but reduced CEC (162 to 52 mmol/kg).	[42]

Hydrothermal carbonization

Hydrothermal carbonization (HTC) is a cost-effective biochar production method operating at low temperatures (180–250°C). The resulting product, called hydrochar, differs from biochar produced via dry processes like pyrolysis and gasification. In HTC, biomass mixed with water is heated in a closed reactor, gradually increasing in temperature. Below 250°C, hydrothermal carbonization occurs, producing biochar; between 250–400°C, hydrothermal liquefaction forms bio-oil; and above 400°C, hydrothermal gasification generates syngas (CO, CO_2, H_2, CH_4). The process involves reactions like dehydration, fragmentation, isomerization, condensation, and polymerization, forming intermediates such as 5-hydroxymethylfurfural. Lignin before repolymerization and cross-linking resulting in hydrochar [43-45] decomposition follows dealkylation and hydrolysis, yielding phenolic compounds.

Gasification

Gasification is a thermochemical process that converts carbonaceous materials, such as biomass or coal, into syngas (a mixture of CO, H_2, CH_4, and CO_2) by reacting them with a controlled amount of oxygen, steam, or air at high temperatures (700–1000°C). Unlike combustion, which fully oxidizes the fuel, gasification partially oxidizes it, producing versatile syngas that can be used for power generation, synthetic fuels, or chemical production. The process includes drying, pyrolysis, oxidation, and reduction stages, making it an efficient method for energy recovery and waste management. Gasification offers advantages like lower emissions, higher efficiency, and the potential for carbon capture, making it a promising technology for sustainable energy production.[46]

Torrefaction and flash carbonization

Torrefaction is a mild pyrolysis process that thermally treats biomass at 200–300°C in an oxygen-free environment. This process removes moisture and volatile compounds, increasing the energy density, hydrophobicity, and grindability of the biomass. The resulting product, known as torrefied biomass or bio-coal, has improved combustion properties and is used as a renewable alternative to fossil fuels in co-firing and gasification applications. Flash carbonization is a rapid thermochemical process that converts biomass into biochar at high temperatures (300–600°C) under pressurized conditions. Unlike traditional slow pyrolysis, flash carbonization occurs within minutes, achieving higher biochar yields and energy efficiency. This method enhances carbon sequestration and provides a sustainable way to produce high-quality biochar for soil amendment and energy applications [47].

CHARACTERIZATION TECHNIQUES

The characterization of biochar is essential to understand its physicochemical properties, which influence its effectiveness in applications such as soil amendment, carbon sequestration, and pollutant remediation. Various analytical techniques are employed to assess the structural, elemental, and functional attributes of biochar [48]. Currently, numerous modern characterization techniques have been reported for characterizing biochar such as scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), thermo-gravimetric analysis (TGA), nclear magnetic resonance spectroscopy (NMR), Brunauer-Emmett-Teller (BET), proximate and ultimate analysis, Raman spectroscopy, etc.

Biochar stability

Biochar stability, defined by its resistance to biotic and abiotic soil degradation, is crucial for carbon sequestration. Various methods assess biochar stability, with pyrolysis temperature often considered an indicator, though it provides only a rough estimate. Proximate analysis, traditionally used for coal and charcoal, determines moisture, volatile matter, ash, and fixed carbon, but may overestimate carbon content due to ash underestimation. Biochar stability assessment methods fall into three categories: (a) structural characterization (e.g., aromaticity), (b) chemical and thermal quantification of stable carbon, and (c) incubation-based carbon mineralization modeling. Incubation and modeling provide the most direct and reliable results, but are time-consuming. Stability is influenced by biochar's carbon structure, consisting of crystalline and amorphous phases, with aromatic condensation and C-C bonds enhancing resistance to degradation. Other properties, such as pore structure, pH, and sorption mechanisms, also contribute. Emerging methods, like ^{14}C isotope tracking, offer insights into biochar-microbial interactions, while thermochemical oxidation assesses degradation resistance. Despite advancements, current techniques lack precision. Developing improved stability evaluation methods is essential for optimizing biochar's role in carbon sequestration and climate change mitigation, ensuring its long-term environmental benefits [49-51].

Scanning electron microscopy (SEM)

The surface morphology of biochar is commonly analyzed using scanning electron microscopy (SEM). SEM imaging has revealed that variations in processing methods and pyrolysis temperatures lead to significant changes in the surface structure of biochar particles, although their overall shape remains largely intact. The development of pores in biochar tends to increase with rising pyrolysis temperatures, resulting in enhanced pore properties. Additionally, higher pyrolysis temperatures may contribute to increased crystallinity of mineral components and the formation of highly ordered aromatic structures. SEM provides detailed insights into the distribution of micropores and mesopores, as well as the arrangement of pores within biochar. It is also used to observe changes in surface morphology before and after adsorption processes. Furthermore, SEM, when combined with energy dispersive X-ray spectroscopy (EDX), facilitates the elemental analysis of biochar by identifying the various elements present on its surface. Many studies on biochar applications have employed SEM-EDX to assess surface modifications after contaminant adsorption. However, a key limitation of this technique is its unsuitability for detecting organic contaminants [52].

Functional groups

The sorption properties of biochar are significantly influenced by the presence of various surface functional groups, including carboxylic (-COOH), hydroxyl (-OH), amine, amide, and lactone groups. The primary factors determining the abundance and nature of these functional groups are the type of biomass used and the pyrolysis temperature. However, an increase in properties such as pH, surface area, and porosity may lead to a reduction in the concentration of these functional groups. Fourier transform infrared spectroscopy (FTIR) is commonly employed to characterize the functional groups present on the biochar surface. Additionally, biochar produced at different temperatures exhibits notable variations in its surface chemistry. Beyond FTIR, nuclear magnetic resonance (NMR) spectroscopy can also be utilized to analyze the structural composition of biochar functional groups [53].

X-ray diffraction (XRD)

X-ray diffraction (XRD) is a widely used technique for analyzing the crystallinity and structural characteristics of biochar. XRD diffractograms reveal specific features of amorphous materials, particularly those formed at temperatures above 350°C, indicating their structural consistency. Modern XRD systems are equipped with computerized controls, including a monochromator, a radiation source, and a stepping motor, enabling precise analysis. The presence of sharp and intense XRD peaks suggests the formation of crystalline nanostructures within biochar. Additionally, prolonged processing time leads to an increase in particle diameter, further influencing crystallinity.

XRD patterns provide a rapid, non-destructive means of characterizing biochar, facilitating the production of high-quality materials with enhanced sorption efficiency [54].

Raman spectroscopy

Raman scattering is a widely used molecular spectroscopy technique that analyzes vibrational transitions in molecules when exposed to electromagnetic radiation. The Raman effect occurs due to the scattering of light with a shifted frequency, resulting from the absorption or loss of vibrational energy within a molecule. This technique is valuable for reliably assessing chemical and nanostructural changes during biomass carbonization. It also enables the rapid estimation of heat treatment temperatures (HTTs) used in biochar production. Raman spectroscopy offers high sensitivity, minimal sample preparation, and reduced interference, making it a powerful tool for biochar characterization. However, its high cost limits its widespread application despite its effectiveness in structural analysis [55].

X-ray photoelectron spectroscopy

X-ray photoelectron spectroscopy (XPS) is a valuable technique for analyzing the composition and structural properties of biochars derived from different biomass sources and thermal treatment conditions. XPS enables the identification and quantification of functional groups and key elemental components present on the biochar surface. Changes in oxygen-containing functional groups, as detected by XPS, are indicative of short-term biochar stability. Additionally, XPS can be employed to determine the elemental O/C molar ratio, which serves as a key indicator of biochar stability. This technique provides critical insights into the surface chemistry of biochar, contributing to a better understanding of its long-term environmental behavior and sorption capabilities [56].

Fourier transform infrared spectroscopy (FTIR)

Fourier transform infrared (FTIR) spectroscopy is a valuable non-destructive technique for characterizing the surface functional groups of biochar. The chemical composition and structural arrangements of biochar undergo significant transformations with increasing pyrolysis temperature, and these changes can be effectively monitored *via* FTIR. Specifically, at higher temperatures (650–800°C), FTIR spectra reveal a progressive loss of aromatic functionalities. While diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) typically involves preparing samples as potassium bromide pellets, attenuated total reflectance (ATR)-FTIR allows for direct analysis by contacting the sample with an ATR crystal, enabling the identification of surface functional groups [57].

Nuclear magnetic resonance spectroscopy (NMR)

Nuclear magnetic resonance (NMR) spectroscopy is a powerful technique for analyzing the structural composition of biochar. This method utilizes a strong magnetic field and radio frequency (RF) pulses to investigate molecular structures by detecting resonance frequencies of specific atomic nuclei. Solid-state NMR techniques are particularly useful for characterizing biochar, allowing for the identification of carbon functional groups, the extent of aromatic ring condensation, and the overall molecular structure of char. Additionally, NMR spectroscopy enables the analysis of aliphatic and aromatic hydrocarbon content, providing insights into the stability and carbonization of different biochar samples. Despite its advantages, NMR spectroscopy has limitations. The presence of ferromagnetic minerals in biochar can interfere with signal detection, leading to distortions in the results. Furthermore, biochar produced at high pyrolysis temperatures often exhibits a low signal-to-noise ratio, which can hinder accurate spectral analysis [58].

Thermo-gravimetric analysis (TGA)

Thermogravimetric analysis (TGA) is a widely used technique for thermal analysis, enabling the assessment of the physical and chemical properties of materials as a function of increasing temperature. This method has been extensively applied to evaluate the thermal behavior of various samples, including biochar and biomass/biochar mixtures. TGA is particularly useful in examining the combustion characteristics of biochar, helping to determine whether synergistic interactions occur between different components in biomass/biochar blends. The findings from such analyses provide valuable insights into the thermal stability, decomposition patterns, and overall behavior of these materials under heat exposure. During TGA, biochar samples are subjected to controlled heating from ambient temperature up to approximately 1000°C. Several studies have utilized different heating rates, including 10°C/min, 20°C/min, and 10 K/min, to analyze variations in thermal degradation. Understanding these thermal properties aids in optimizing biochar applications and improving its utilization in various industrial and environmental processes [59].

Surface area and porosity

Biochar with a high surface area and well-developed porosity exhibits superior sorption properties. The formation of a porous structure occurs during the pyrolysis process as water loss intensifies during dehydration. According to the International Union of Pure and Applied Chemistry (IUPAC), biochar pores are classified into three types: micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm). The ability of biochar to adsorb pesticide molecules depends on its pore size, irrespective of molecular polarity or charge. Scanning electron microscopy (SEM) is commonly used to characterize biochar pore size. Surface area is a critical factor in determining sorption capacity, with temperature playing a significant role in biochar formation. The surface area varies between treated and untreated raw materials, with commercially available activated carbon exhibiting a larger surface area. Biochar produced without an activation process tends to have lower surface area and porosity. To enhance these properties, biochar production often incorporates an activation process, which can be achieved through physical or chemical activation. This step is crucial in improving biochar's adsorption efficiency and expanding its applications in environmental remediation and pollutant removal [60].

Brunauer-Emmett-Teller analysis (BET) The surface area of biochar can be assessed through Brunauer–Emmett–Teller (BET) analysis, a crucial technique for evaluating its effectiveness in pollutant removal from soil and aqueous environments. The comparison between raw feedstocks and their corresponding biochar reveals a substantial increase in BET surface area following pyrolysis. Notably, the original feedstocks lack significant micropores, whereas pyrolysis induces the formation of new micropores within the biochar structure.

For different feedstock types, porosity characteristics—such as BET surface area and micropore volume—exhibit improvements with an increase in power levels from 2100 to 2400 W.

This enhancement is attributed to the accelerated release of residual volatile compounds and the intensified development of micropores at elevated heating rates. Additionally, the extensive release of volatile matter during pyrolysis contributes to the formation of highly porous biochar with diverse pore structures and lower density. These properties make biochar a promising material for applications requiring high adsorption capacity and pollutant sequestration [61].

APPLICATIONS OF APRICOT SHELL BIOCHAR

Apricot shell biochar, derived from the pyrolysis of apricot shells, has been investigated for various applications across multiple fields.

Table 3. Characterization of apricot seed shell biochar in soil and parameters thereof.

Parameters	Before adding apricot seed shell biochar	After adding apricot seed shell biochar
Soil pH	6.5	7.0
Nitrate concentration (mg/L)	30	50
Soil organic matter (%)	2.0	3.5
Water holding capacity	20	25
Cation exchange capacity (meq/100 g)	10	15
Microbial activity (CFU/g)	1 × 10^6	5 × 10^6
Soil electrical conductivity (dS/m)	1.2	1.5
Total nitrogen (%)	0.1	0.2
Phosphorus content (mg/kg)	15	25
Potassium content (mg/kg)	20	35

Research indicates that apricot shell biochar exhibits effective adsorption properties for pollutants such as atrazine, a common herbicide. The biochar's adsorption capacity is influenced by factors like preparation temperature, pH, and the presence of ions like calcium. The primary mechanisms include hydrogen bonding and hydrophobic interactions, suggesting its potential in mitigating agricultural non-point source pollution. Atrazine adsorption kinetics on the biochar followed a quasi-second-order kinetic model with $R^2 \geq 0.995$, and isothermal adsorption data fitted the Freundlich model with $R^2 \geq 0.911$. The adsorption process was accompanied by surface adsorption and diffusion. The prepared temperature increased and the pH and Ca^{2+} concentration increased the adsorption process, and the mechanism of adsorption mainly involved hydrogen bonding and hydrophobic interactions. Biochar from agricultural waste, apricot shells, showed good potential for atrazine adsorption and could help manage agricultural non-point source pollution, especially pesticide residue pollution [62], and bioavailability of heavy metals like zinc (Zn) and cadmium (Cd). This suggests its potential role in reducing heavy metal mobility and bioavailability in polluted soils, thereby contributing to soil remediation efforts. Adsorbents were prepared from apricot seed shell agro-waste that is available locally. Biochar at 370°C from pyrolysis in the shape of 80-mesh particle size was further modified with 1N HCl. ASSP, biochar (ASSB), and activated biochar (AASSB) from aqueous solution nitrate adsorption were observed. FTIR and pH PZC are used for the characterization of the adsorbent. Optimum conditions were pH 2, dosage 0.3 g, 50 mg/L initial concentration, and 90 min contact time. AASSB exhibited the highest nitrate removal, followed by ASSB and ASSP. Nitrate adsorption kinetics followed a pseudo-second-order model, showing favorable and improved sorption. This agro-waste can be developed into sustainable adsorbents for water treatment, potentially replacing commercial sorbents [63-65].

Biochar was prepared through a hydrothermal process and studied with the help of SEM and FTIR for atrazine adsorption on apricot kernel shell biochar, which exhibited a uniform carbon microsphere structure with many oxygen-containing groups. Functional groups were enhanced by increasing temperature, hence improving the adsorption efficiency. The kinetics of atrazine adsorption onto the biochar followed quasi-second-order kinetic models ($R^2 \geq 0.995$) and the Freundlich model ($R^2 \geq 0.911$). Surface adsorption and diffusion were involved in the process, which is favored by hydrogen bonding and hydrophobic interactions. Adsorption capacity increased with temperature and decreased with pH and Ca^{2+} concentration. The biochar derived from agricultural waste could be applied for pesticide residue pollution control [66].

CHALLENGES AND FUTURE PERSPECTIVES

Biochar has been demonstrated as an effective tool for soil amendment in crop production and pollutant removal from water and soil. Most of the studies on the effect of biochar on soil properties (such as bulk density, porosity, water holding capacity, acidity, and mineral content) are conducted in the laboratory. Properties of biochar produced under various pyrolysis conditions (temperature, heating rate, residence time) have been widely researched. For large-scale commercialization, the advantages and disadvantages of biochar for soil applications must be discussed, taking into account technical, environmental, economic, and social factors. This review evaluates biochar for soil amendment within a sustainability framework and offers recommendations for future research and applications [67].

The speedy growth of the technology of renewable energies and the critical need for response to the challenges of the environment made it apparent that biochar is a multi-use tool for energy, water, and environmental sustainability. The review highlights recent advances in biochar production and functionalization toward enhanced roles in energy conversion, wastewater treatment, reduction of CO_2, improvement of soil, and carbon neutrality. Functionalization approaches such as chemical activation and metal impregnation significantly enhance catalytic activity, energy storage, and stability of the biochar; hence, there is a potential for its usage in water splitting, fuel cells, and supercapacitors. Additionally, it is a potential catalyst and adsorbent in wastewater treatment through the removal of pollutants and facilitation of resource recovery. The review points out the ability of biochar in CO_2 capture and conversion into valuable fuels and chemicals. In conclusion, in a nutshell, biochar has great potential to be a sustainable material for a cleaner future.

This technology is still at the nascent stage in Indian agriculture but promises several benefits, such as improved soil carbon sequestration, GHG offset, improvement in soil health, and increased crop yields. Crop residues from major crops, logging and processing residues, and organic residues from municipal solid waste were evaluated for availability. Approximately 249 million tons of crop residue is being generated annually. Using the residues for biochar will reduce GHG emissions by 4.8% to 10.7% of total net annual emissions. Collection and transportation of residues would be the challenges, but institutional systems at the grassroots are established to get participation from the farmers as well, which will enhance the climate mitigation potential of biochar. Biochar production can improve waste management and offset GHG emissions for all sectors [68].

The development of effective and sustainable biochar production techniques, as well as their potential application in resolving global environmental issues, will receive particular attention.

RESULTS AND DISCUSSION

Biochar showed a positive impact on soil quality, crop performance, and yields. Biochar enhances the properties of soil such as water retention, water repellency, and carbon sequestration. The inclusion of biochar also increased crop productivity, nutrient uptake, and seed germination, especially in infertile soils. It depends on the kind of soil, crop type, and feedstock on the optimal application rate. The feedstock selection, combined with the selected pyrolysis conditions, influences biochar properties such as pH, surface area, and nutrient content. The study of biochar reveals that it has the potential to reverse land degradation as well as enhance agriculture.

Comparative soil benefits before and after adding apricot biochar in the soil are illustrated in Table 3. Apricot seed shell biochar adds the following to soil: It raises pH from 6.5 to 7.0, thereby making it alkaline. The nitrate concentration increases from 30 mg/L to 50 mg/L, which will promote plant growth. Soil organic matter improves considerably from 2.0% to 3.5%, making it fertile. Water holding capacity increases from 20% to 25%, thus helping retain moisture. Cation exchange capacity increases from 10 meq/100 g to 15 meq/100 g, which enhances nutrient availability. Microbial activity increases by as much as 1 ×10^6 CFU/g to 5 × 10^6 CFU/g, enhancing soil health and plant resistance. Electrical conductivity increased from 1.2 dS/m to 1.5 dS/m, indicating good salinity management in the soil. Total nitrogen increased from 0.1% to 0.2%, which contributed to better plant nutrition. From 15 mg/kg to 25 mg/kg, phosphorus increased, while potassium increased from 20 mg/kg to 35 mg/kg; all these added to better development and growth of plants. As a whole, soil with apricot seed shell biochar is much richer and more fertile.

Based on this research, there are certain limitations discussed and directions for possible future study recommended. For example, if the sample only consisted of individuals from a certain geographic area or age, the limitation would need to be incorporated into the discussion, and the reader should be made aware that future studies ought to include a more diverse sample. In case the study used a particular methodology or tool, it would be necessary to talk about possible biases or limitations that might be linked with the methodology and provide alternative ways for future research. Implications for practice: This section describes how the results of the study can be applied in real-life settings. For instance, if the study found that a specific intervention improved mental health outcomes, discuss how this intervention can be implemented in clinical practice to improve patient outcomes.

CONCLUSION

The findings of this study demonstrate a continued necessity to study apricot seed shell biochar. If we delve further into the area of research, it will lead us closer to the complexities and nuances that lie in that field. More effective strategies for the challenges can be developed if more research is done in this area. We hope this research will be a good point of starting for future studies and eventually contribute to the ongoing endeavor to improve in the field of relevance - industry.

Our study indicates the feasibility of preparing biochar from the apricot shell in Kargil and thus its use can be well authenticated for enriching the quality of soil. Apricot shell biochar, apart from other by-products of organic wastes, could play an active role in this regard for eradicating waste management and enhancing productivity. The potential area of investigation to be covered may include a critical analysis of its long-term implications on crop yields and soil quality.

Some of the limitations that appeared during the production of biochar included using energy to heat at a higher temperature and nitrogen supply avoiding combustion during a production cost process. Future research could address these limitations by the use of solar energy as Kargil Ladakh on an average experience more than 300 sunny days in the year could be a promising solution with one-time investment. Overall, it contributes to the body of knowledge in the use of biochar made of locally growing plants in the indigenous soil in the same cold desert climate by providing benefits for agricultural produce. The findings and results of this study can be applied in practical settings, such as a decline or replacement with synthetic fertilizer. The hope is that this study will stimulate further investigation into "assessing the potential of apricot shell biochar derived from apricot seed shell collected sourced from Kargil", Ladakh.

REFERENCES

1. Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M., & Wessolek, G. (2013). *Geoderma*, ***202***, 183-191.
2. Agegnehu, G., Srivastava, A. K., & Bird, M. I. (2017). *Applied soil ecology*, ***119***, 156-170.
3. Akhtar, S. S., Li, G., Andersen, M. N., & Liu, F. (2014). *Agricultural Water Management*, 138, 37-44.
4. Ali, I., He, L., Ullah, S., Quan, Z., Wei, S., Iqbal, A., & Ligeng, J. (2020). *Food and Energy Security*, ***9***(3), e208.
5. Barrow, C. J. (2012). *Applied Geography*, ***34***, 21-28.
6. Chan, K. Y., Van Zwieten, L., Meszaros, I., Downie, A., Joseph, S. (2008 *Soil Research*, ***46***(5), 437-444.
7. El-Naggar, A., Lee, S. S., Awad, Y. M., Yang, X., Ryu, C., Rizwan, M., & Ok, Y. S. (2018). *Geoderma*, ***332***, 100-108.
8. Hafeez, Y., Iqbal, S., Jabeen, K., Shahzad, S., Jahan, S., Rasul, F. (2017) *Pakistan Journal of Botany*, ***49***(51), 7-13.

9. Zhang, Y., Idowu, O. J., Brewer, C. E. (2016*Agriculture*, ***6***(1), 10.
10. William, Kainaat, Rizwana Aleem Qureshi. *Journal of Bioresource Management* **2**, no. 1 (2015): 1.
11. Vinh, N. C., Hien, N. V., Anh, M. T. L., Lehmann, J., & Joseph, S. (2014).. *International Journal of Agricultural and Soil Science*, ***2***(1), 5-13.
12. Vista, S. P., Khadka, A. (2017). *Journal of Pharmacognosy and Phytochemistry*, ***6***(6S), 673-677.
13. Jia, J., Li, B., Chen, Z., Xie, Z., & Xiong, Z. (2012). *Soil science and plant nutrition*, ***58***(4), 503-509.
14. Liu, B., Cai, Z., Zhang, Y., Liu, G., Luo, X., & Zheng, H. (2019). *Chemosphere*, ***224***, 151-161.
15. Zhu, W., Li, C., Zhou, S., Duan, Y., Zhang, J., & Jin, F. (2022). *Plant, Soil and Environment*, ***68***(2), 108-114.
16. Zhao, F., Zou, G., Shan, Y., Ding, Z., Dai, M., & He, Z. (2019). *Scientific reports*, ***9***(1), 20291.
17. Martínez-Gómez, Á, Poveda, J., Escobar, C. (2022). *Frontiers in Plant Science*, 2511.
18. Yin, S., Zhang, X., Suo, F., You, X., Yuan, Y., Cheng, Y., Li, Y. (2022). *Chemosphere*, ***298***, 134191.
19. Tenic, E. (2020). *Understanding the role of biochar in agriculture* (Doctoral dissertation, Washington State University).
20. Zhang, C., Liu, Q., & Kudakwashe, M. (2020, April). In: IOP Conference Series: Earth and Environmental Science (Vol. **474**, No. 3, p. 032041). IOP Publishing.
21. Kul, R., Arjumend, T., Ekinci, M., Yildirim, E., Turan, M., & Argin, S. (2021 *Soil Science and Plant Nutrition*, ***67***(6), 693-706.
22. Li, X., Wang, R., Shao, C., Li, D., Bai, S., Hou, N., & Zhao, X. (2022). *ACS Sustainable Chemistry & Engineering*, ***10***(11), 3574-3583.
23. Shen, Y., Song, S., Thian, B. W. Y., Fong, S. L., Ee, A. W. L., Arora, S., ... Wang, C. H. (2020). *Journal of Cleaner Production*, ***264***, 121678.
24. Lou, Y., Joseph, S., Li, L., Graber, E. R., Liu, X., & Pan, G. (2016). *BioResources*, ***11***(1), 249-266.
25. Singh, M., Saini, R. K., Singh, S., Sharma, S. P. (2019).. *HortScience*, ***54***(11), 1872-1878.
26. Murtaza, G., Ahmed, Z., Usman, M., Tariq, W., Ullah, Z., Shareef, M., ... Ditta, A. (2021). *Journal of plant nutrition*, ***44***(11), 1677-1691.
27. Hamzah, Z., & Shuhaimi, S. N. A. (2018, December). in: IOP Conference Series: Earth and Environmental Science (Vol. **215**, No. 1, p. 012011). IOP Publishing.
28. Bird, M. I., Wurster, C. M., de Paula Silva, P. H., Paul, N. A., & De Nys, R. (2012). *Gcb Bioenergy*, ***4***(1), 61-69.
29. Ezepue, G. C., Uzoh, I., & Unagwu, B. (2019). *Adv. Agric. Sci*, ***7***, 59-87.
30. Ścisłowska, M., Włodarczyk, R., Kobyłecki, R., & Bis, Z. (2015). *Journal of Ecological Engineering*, ***16***(3).
31. Manirakiza, N., Şeker, C. (2020). *Journal of Plant Nutrition*, ***43***(20), 3002-3019.
32. Zahid, Z., Iftikhar, S., Ahmad, K. S., & Gul, M. M. (2018). *Communications in Soil Science and Plant Analysis*, ***49***(22), 2814-2827.
33. Panahi, H. K. S., Dehhaghi, M., Ok, Y. S., Nizami, A. S., Khoshnevisan, B., Mussatto, S. I., ... Lam, S. S. (2020). *Journal of cleaner production*, **270**, 122462.
34. Ippolito, J. A., Laird, D. A., & Busscher, W. J. (2012). *Journal of environmental quality*, ***41***(4), 967-972.
35. Khan, T. F., Salma, M. U., & Hossain, S. A. (2018). *American Journal of Plant Sciences*, ***9***(9), 1922-1934.
36. Panwar, N. L., Pawar, A., & Salvi, B. L. (2019). *SN Applied Sciences*, ***1***, 1-19.
37. Sakhiya, A. K., Anand, A., & Kaushal, P. (2020). *Biochar*, ***2***, 253-285.
38. Ahmad, M., Lee, S.S., Dou, X., Mohan, D., Sung, J.K., Yang, J.E., & Ok, Y.S. (2012). *Bioresource Technology*, **118**, 536-544.
39. Crombie, K., Mašek, O., Sohi, S. P., Brownsort, P., & Cross, A. (2013). *Gcb Bioenergy*, ***5***(2), 122-131.
40. Yuan, J. H., Xu, R. K., & Zhang, H. (2011). *Bioresource technology*, ***102***(3), 3488-3497.
41. Chen, B., & Chen, Z. (2009). *Chemosphere*, ***76***(1), 127-133.
42. Kloss, S., Zehetner, F., Dellantonio, A., Hamid, R., & Ottner, F. (2012). *Journal of Environmental Quality*, **41**(4), 990–1000.
43. J. Lee, K. Lee, D. Sohn, Y.M. Kim, K.Y. Park, Hydrothermal carbonization of lipid extracted algae *Energy* **153** (2018) 913–920.
44. Q. Zhang, Q. Li, L. Zhang, Z. Yu, X. Jing, Z. Wang, Y. Fang, W. Huang, *Energy* **134** (2017) 301–310.
45. A. Jain, R. Balasubramanian, M.P. Srinivasan, *Chem. Eng. J.* **283** (2016) 789–805.
46. D. Prabakar, V.T. Manimudi, S. Suvetha, S. Sampath, D.M. Mahapatra, K. Rajendran, A. Pugazhendhi, *Renew. Sust. Energy. Rev.* **96** (2018) 306–324.
47. K.L. Yu, B.F. Lau, P.L. Show, H.C. Ong, T.C. Ling, W.-H. Chen, E.P. Ng, J.-S. Chang, *Bioresource. Technol*. **246** (2017) 2–11.
48. C.E. Brewer, V.J. Chuang, C.A. Masiello, H. Gonnermann, X. Gao, B. Dugan, L.E. Driver, P. Panzacchi, K. Zygourakis, C.A. Davies, *Biomass Bioenerg*. **66** (2014) 176–185.
49. J.-C. Yoo, J. Beiyuan, L. Wang, D.C.W. Tsang, K. Baek, N.S. Bolan, Y.S. Ok. X-D. Li, *Sci. Total Environ*. **616-617** (2018) 572–582.
50. L. Leng, H. Huang, H. Li, J. Li, W. Zhou, *Sci. Total Environ*. **647** (2019) 210–222.
51. A. Cross, S.P. Sohi*, Gcb Bioenergy* **5** (2013) 215–220.
52. G. Fellet, M. Marmiroli, L. Marchiol. *Sci. Total Environ*. **468-469** (2014) 598–608.
53. H. Li, X. Dong, E.B. da Silva, L.M. de Oliveira, Y. Chen, L.Q. Ma, *Chemosphere* **178** (2017) 466–478.

54. A.R.A. Usman, A. Abduljabbar, M. Vithanage, Y.S. Ok, M. Ahmad, M. Ahmad, J. Elfaki, S.S. Abdulazeem, M.I. Al-Wabel, *J. Anal. Appl. Pyrol.* **115** (2015) 392–400.
55. M. Vithanage, A.U. Rajapaksha, M. Ahmad, M. Uchimiya, X. Dou, D.S. Alessi, Y. S. Ok, *J. Environ. Manage*. **151** (2015) 443–449.
56. K.A. Spokas, *Carbon Manag.* **1** (2010) 289–303.
57. A. Berrazoum, R. Marouf, F. Ouadjenia, J. Schott, *Biotechnol. Rep. Amst. (Amst)* **7** (2015) 44–50.
58. D.B. Wiedemeier, S. Abiven, W.C. Hockaday, M. Keiluweit, M. Kleber, C.A. Masiello, A.V. McBeath, P.S. Nico, L.A. Pyle, M.P.W. Schneider, R.J. Smernik, G.L. B. Wissenberg, M.W.I. Schmidt*, Org. Geochem.* **78** (2015) 135–143.
59. Y. Yao, B. Gao, J. Fang, M. Zhang, H. Chen, Y. Zhou, A.E. Creamer, Y. Sun, L. Yang, *Chem. Eng. J.* **242** (2014) 136–143.
60. K.H. Kim, J. Kim, T. Cho, J.W. Choi, *Bioresour. Technol*. **118** (2012) 158–162.
61. X. Liu, Y. Zhang, Z. Li, R. Feng, Y. Zhang, *Bioresour. Technol.* **170** (2014) 76–82.
62. Zhang, Z., Zhou, C., Yang, J., Yan, B., Liu, J., Wang, S., Li, Q., & Zhou, M. (2022). *Sustainability,* **14**(7), 4082. https://doi.org/10.3390/su14074082
63. Mohd Ishaq, R. C. Chhipa, A. Sharma, G. Ali, & R. Hussain. (2024). *Nature Environment and Pollution Technology*, **23**(3), 1743-1749.
64. Shah Vishalkumar, Gajbhiye Pratima; Mehta Jigesh et al., (2024) *AIP Advances*, **14**(3), 035227
65. Zhang, Z., Zhou, C., Yang, J., Yan, B., Liu, J., Wang, S., Li, Q., & Zhou, M. (2022). *Sustainability*, **14**(7), 4082. https://doi.org/10.3390/su14074082
66. Kamali, M., Sweygers, N., Al-Salem, S., Appels, L., Aminabhavi, T. M., & Dewil, R. (2022). *Chemical Engineering Journal,* **428**, 131189.
67. Yameen, M. Z., Naqvi, S. R., Juchelková, D., & Khan, M. N. A. (2024). *Biochar,* **6**(25), 25.
68. Chen et al., *Journal of Environmental Management*, (2023).