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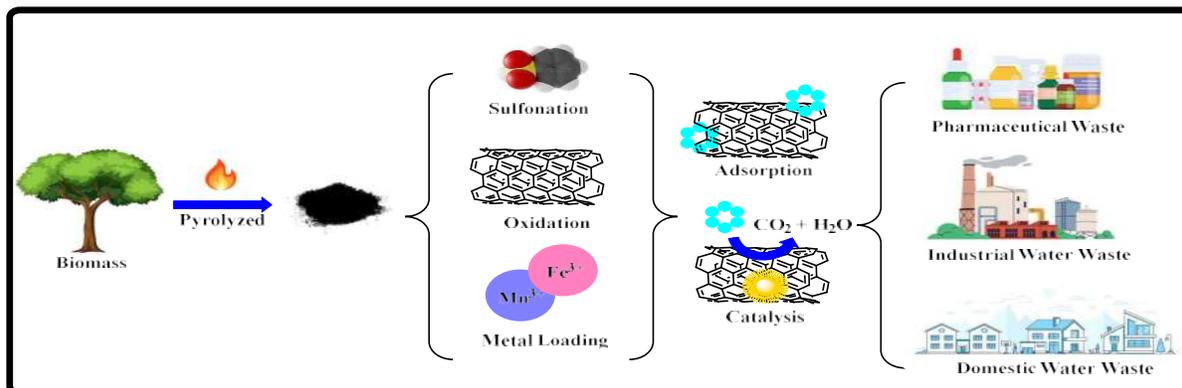
## Plant-Waste Derived Bio-char for Fluoride Removal : Sustainable Pathways in Water and Wastewater Treatment

**Abstract** : Bio-char, a carbon-rich material produced through the pyrolysis of biomass under oxygen-limited conditions, has emerged as a sustainable and multifunctional solution for environmental remediation. Derived from diverse plant wastes such as fruit peels, agricultural residues, and agro-industrial by-products, bio-char exhibits high surface area, porosity, and abundant functional groups, making it highly effective in adsorbing pollutants, including fluoride ions, heavy metals, and organic contaminants from water and wastewater. The performance of bio-char is influenced by its preparation methods, including pyrolysis temperature, feedstock type, and chemical or physical activation, which can enhance adsorption capacity and selectivity. Plant-waste derived bio-chars offer additional benefits by valorizing waste, supporting circular economy principles, and promoting eco-friendly water treatment strategies. Recent studies have demonstrated that chemically modified, hybrid, or magnetically functionalized bio-chars can achieve high fluoride removal efficiency across a wide pH range, following monolayer chemisorption and pseudo-second order kinetics, while maintaining reusability and minimal interference from coexisting ions. Overall, bio-char represents a cost-effective, sustainable, and scalable approach for improving water quality, mitigating fluoride contamination, and addressing broader wastewater challenges, advancing both environmental protection and public health.

**Keywords** : Bio-char, Plant-waste derived bio-char, Fluoride removal, Water treatment, Wastewater remediation, Adsorption, Pyrolysis, Chemical activation,

Circular economy, Sustainable water purification.

**Introduction** : Bio-char, a carbon-rich, porous material produced from the thermal decomposition of biomass under limited or no oxygen conditions, has emerged as a promising tool for environmental remediation and sustainable resource management<sup>1&2</sup>. Derived from a wide variety of organic wastes such as agricultural residues, plant by-products, and food wastes, bio-char exhibits high surface area, porous structure, and abundant functional groups, which enhance its adsorptive capabilities. These properties make bio-char particularly effective in capturing pollutants including heavy metals, dyes, organic contaminants, and fluoride ions from water<sup>3</sup>. Beyond its pollutant removal potential, bio-char contributes to carbon sequestration, soil amendment, and waste valorisation, positioning it as a multifunctional material that addresses both environmental and socio-economic challenges. Its renewable nature and relatively low production cost make it especially attractive for decentralized and community-level water treatment applications<sup>4</sup>. The effectiveness of bio-char in environmental applications is strongly influenced by its mode of preparation and activation. Conventional pyrolysis is the most widely used method, where biomass is heated at high temperatures under oxygen-limited conditions, yielding bio-char along with bio-oil and syngas<sup>5</sup>. The physical and chemical properties of bio-char, including surface area, pore volume, and functional groups, are largely determined by the feedstock, pyrolysis temperature, heating rate, and residence time<sup>6</sup>. To further enhance its adsorption efficiency, bio-char can be chemically activated using acids, bases, or oxidizing agents, or physically modified through steam or CO<sub>2</sub> treatment. Advanced approaches, such as co-pyrolysis with mineral additives or impregnation with metal oxides, have also been developed to produce bio-based chars with tailored surface chemistry, improved adsorption capacity, and catalytic properties. These developments highlight the versatility of bio-char and its adaptability for targeted environmental applications, particularly in water and wastewater treatment.

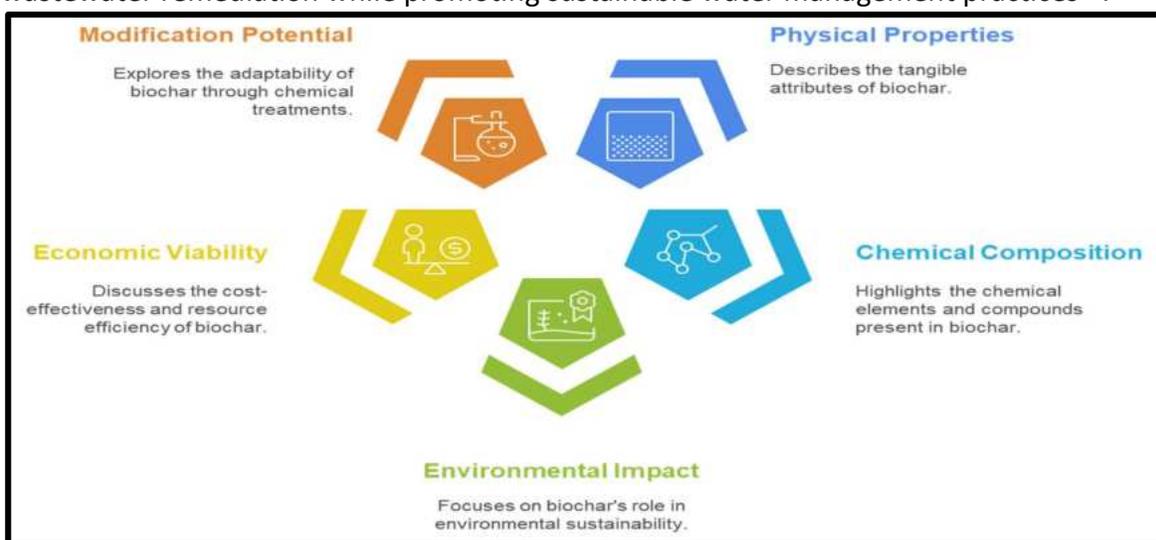


**Figure 1: Pyrolysis and Sulphonation of Biomass**

Among various feedstocks, plant-derived wastes have gained significant attention for bio-char production due to their abundance, renewability, and low cost. Fruit peels, leaves, straw, husks, and other agro-residues not only provide a sustainable source of carbon but also offer an opportunity to address solid waste management challenges<sup>9</sup>. Utilization of these plant wastes for bio-char production aligns with circular economy principles, converting waste into a value-added material. Moreover, bio-chars derived from plant residues are rich in surface functional groups and micro-porous structures, which enhance their ability to adsorb fluoride ions from groundwater. Fluoride contamination, caused by both natural geochemical processes

and anthropogenic sources such as industrial effluents and agricultural runoff, is a global concern due to its health risks, including dental and skeletal fluorosis. Plant-waste derived biochars provide a low-cost, effective, and environmentally friendly solution for fluoride removal, bridging the gap between sustainable waste management and potable water provision<sup>10</sup>.

The issue of water contamination extends beyond fluoride, encompassing a wide range of pollutants in wastewater from industrial, agricultural, and domestic sources. Heavy metals, nitrates, phosphates, dyes, and other toxic compounds often contaminate surface and groundwater, posing severe environmental and public health challenges<sup>11</sup>. Conventional wastewater treatment technologies such as chemical precipitation, membrane filtration, and ion exchange are effective but often expensive, energy-intensive, and less feasible for rural or resource-limited communities. In this context, bio-char offers a versatile, low-cost alternative that can efficiently remove both inorganic and organic contaminants through adsorption, ion exchange, and catalytic degradation mechanisms. Its integration into constructed wetlands, filtration systems, or as an amendment in treatment processes enhances the overall efficiency of wastewater remediation while promoting sustainable water management practices<sup>12</sup>.



**Figure 2: Characteristics of Bio-char.**

Recent research on bio-char has focused on enhancing its performance for water and wastewater treatment, particularly for fluoride removal. Studies demonstrate that chemical modification, hybridization with metal oxides, and the development of composite adsorbents can significantly improve the selectivity, adsorption capacity, and reusability of bio-char. Batch and column experiments reveal that fluoride adsorption often follows pseudo-second order kinetics and fits well with Langmuir or Freundlich isotherms, indicating chemisorption and monolayer adsorption. Furthermore, incorporating bio-char into decentralized water treatment systems provides an eco-friendly, cost-effective, and reliable approach for managing water contamination while simultaneously reducing carbon footprint and valorising waste biomass. These advancements underscore the potential of plant-waste derived bio-char as a sustainable, scalable, and effective solution for addressing fluoride contamination and broader wastewater challenges, contributing to both environmental protection and public health improvement. Building on recent advances in bio-char research, **Li et al. (2025)** developed an innovative magnetic aluminium–iron bimetallic bio-char (PPB-Al-500Fe) derived from pomelo peel via a

two-step solvo-thermal-pyrolysis process for sustainable and efficient fluoride removal from water. The synthesized material exhibited high saturation magnetization ( $14.57 \text{ emu}\cdot\text{g}^{-1}$ ), enabling rapid magnetic separation within 30 seconds and eliminating energy-intensive filtration steps. PPB-Al-500Fe achieved a maximum fluoride adsorption capacity of  $37.84 \text{ mg}\cdot\text{g}^{-1}$  at pH 7 and maintained over 80% removal efficiency across a broad pH range (3–9), surpassing conventional bimetallic adsorbents. Mechanistic studies revealed that fluoride removal occurred through electrostatic attraction ( $\text{pH}_{\text{pzc}} = 9.3$ ), ion exchange with C–O–C and –OH groups, and Al/Fe–F coordination complexation. Furthermore, the bio-char demonstrated strong regeneration ability, retaining >80% efficiency after two reuse cycles, and showed minimal interference from coexisting anions. This study provides a sustainable pathway for valorising fruit waste into high-performance, magnetically separable adsorbents, advancing circular economy and water purification technologies. Similarly, **Li and his team, (2025)** successfully synthesized Fe–La–Ce modified bio-char (BBCFLC) from the invasive plant *Bidens pilosa L.* to address the urgent problem of fluoride contamination in water through a sustainable adsorption approach. Characterization confirmed the effective incorporation of Fe, La, and Ce into the bio-char structure, significantly enhancing its fluoride removal efficiency. The BBCFLC exhibited a remarkable maximum adsorption capacity of  $192.79 \text{ mg}\cdot\text{g}^{-1}$  and reached equilibrium within 60 minutes, outperforming most reported adsorbents. The primary mechanisms involved in fluoride removal were electrostatic interaction, ligand exchange, and complexation between fluoride ions and metal active sites. Overall, BBCFLC demonstrated outstanding fluoride selectivity, rapid adsorption kinetics, and excellent potential as an eco-friendly adsorbent. This work presents a promising strategy for integrating environmental remediation with invasive plant management by converting unwanted biomass into high-value materials for water purification<sup>13</sup>.

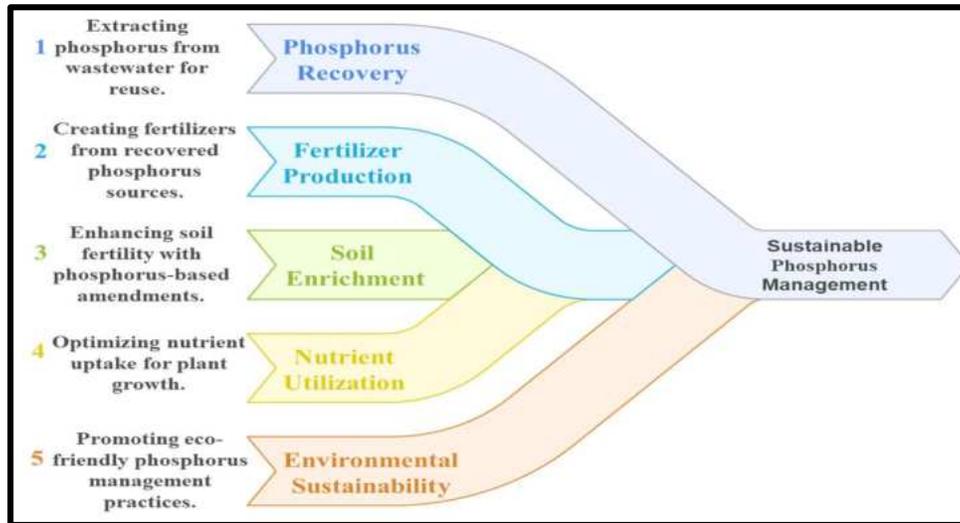
**Aboulsoud et al.** also investigated an economical and eco-friendly approach for fluoride removal from water using bio-char derived from domestic tea waste. The bio-char was prepared through a pre-pyrolysis chemical activation process and modified using two agents phosphoric acid ( $\text{H}_3\text{PO}_4$ ) and sodium hydroxide (NaOH) producing **H-modified** and **OH-modified** forms, respectively. Comprehensive characterization (ash content, bulk density, BET surface analysis, elemental, TGA, and FTIR) revealed that the H-modified bio-char possessed greater surface area, pore volume, and more functional groups such as –COOH, –OH, and C=O, leading to superior fluoride adsorption performance. Under optimal conditions (**pH 2, 0.25 g/L dosage, 50°C, 500 mg/L  $\text{F}^-$ , 30 min contact, 300 rpm**), the H-modified bio-char achieved a maximum adsorption capacity of **109.18 mg  $\text{F}^-/\text{g}$** , while the OH-modified bio-char showed **49.39 mg  $\text{F}^-/\text{g}$** . Competing anions reduced fluoride uptake in the order  **$\text{PO}_4^{3-} > \text{SO}_4^{2-} > \text{Cl}^- > \text{NO}_3^- > \text{HCO}_3^-$** . Application to real industrial wastewater from Borg El-Arab City demonstrated **80.89–93.31% fluoride removal**, bringing concentrations within safe limits. The study highlights that **tea waste bio-char**, particularly the acid-modified form, is a **low-cost, sustainable, and efficient bio-sorbent** for industrial wastewater treatment, offering dual environmental benefits **waste utilization and contaminant removal**<sup>14</sup>. In a similar vein, **Peng et al.** conducted a comprehensive meta-analysis to evaluate how bio-char application to soil affects the accumulation of toxic elements (TEs) in plants. The study synthesized 1,813 data points from 97 research articles, assessing the impact of bio-char type, production conditions, and application rate on TE concentrations in various plant parts. The analysis revealed that bio-char significantly

reduced TE concentrations in plant tissues, particularly for cadmium (Cd) and lead (Pb) in edible and indirectly edible parts. In contrast, arsenic (As) concentrations were not notably affected. Factors such as bio-char feedstock, pyrolysis temperature, and experimental setup strongly influenced the outcomes with manure, herbaceous, and wood-derived bio-chars, especially those produced at  $\leq 400$  °C, showing the greatest reduction effects. Pot experiments showed stronger TE reduction than field studies, and higher bio-char dosage and surface area correlated with more effective TE suppression. Key moderators, including soil phosphorus content and initial TE levels, also played critical roles. Overall, the study concluded that bio-char serves as an effective soil amendment, decreasing the bioaccumulation of hazardous metals in crops, enhancing food safety, and lowering human health risks. They provided the first large-scale quantitative evidence that bio-char application can significantly mitigate the transfer of multiple toxic elements within agricultural systems, supporting sustainable soil and food management<sup>15</sup>.

**Gourai et al.** presented the first report on thermal plasma-based synthesis of bio-char from *Moringa oleifera* for the removal of fluoride from contaminated groundwater in Nuapada district, Odisha, India an area severely affected by fluorosis. Moringa leaves were processed at 1600 °C for 3 minutes under an inert argon atmosphere to produce highly porous, carbon-rich (>72%) bio-chars with large exposed surface areas. Characterization through XRD and Raman spectroscopy revealed the presence of CaO, MgO, Ca(OH)<sub>2</sub>, and active carbon structures containing carbonyl, thioether, and sulfhydryl groups, which provided protonated adsorption sites for fluoride binding. In both synthetic and real groundwater samples, the Moringa leaf bio-char demonstrated >85% fluoride removal within 18 hours (using 1 g bio-char per 100 mL of 4 ppm F<sup>-</sup> water). Interestingly, while seed bio-char performed better in standard fluoride solutions, leaf bio-char showed superior adsorption in real groundwater highlighting that adsorbent efficiency depends on both bio-char composition and local water chemistry. The study concluded that biosorption using plasma-synthesized Moringa bio-char is an eco-friendly, cost-effective, and non-toxic approach for groundwater defluoridation. The findings emphasize that no single bio-char is universally effective, and site-specific bio-char development is essential for addressing diverse contamination conditions. This pioneering research provides a foundation for scaling up plasma-based bio-char production for sustainable and localized water purification solutions<sup>16</sup>.

**Kopecký et al.** investigated the recovery and reuse of phosphorus (P) from wastewater using iron-modified bio-char, addressing the global concern of depleting phosphate rock reserves and phosphorus loss to water bodies. In this study, bio-char was impregnated with FeCl<sub>3</sub> and neutralized with NaOH, enabling it to adsorb significant quantities of phosphorus from municipal wastewater. The results showed that  $1 \times 10^5$  g of modified bio-char captured up to  $2.79 \times 10^3$  g of P, equivalent to about one-third of the phosphorus content in conventional superphosphate fertilizer. The phosphorus-saturated bio-char and iron(III) phosphate recovered from reused filters demonstrated strong agrochemical potential, containing high levels of plant-available phosphorus fractions (CaP-I and CaP-II: 61.5 and 59.6 g  $\times 10^{-3}$  P/g  $\times 10^3$  soil, respectively). Compared to struvite, a naturally occurring by-product in wastewater treatment plants, the modified bio-char retained more readily available phosphorus, making it a superior fertilizer alternative. Although sludge water had the highest total P content, its direct agricultural use remains limited due to regulatory constraints. This study confirms that Fe-

modified bio-char can serve as both a phosphorus sorbent and a slow-release fertilizer, offering a dual environmental and agricultural benefit—removing P from wastewater while returning it safely to soil. The method supports sustainable phosphorus recycling and provides a technologically viable route for nutrient recovery and soil enhancement<sup>17</sup>.



**Figure 3:** Pathways to Phosphorus Sustainability

Following a comparable approach, **Kasak et al.** explored the impact of bio-char amendment on the wastewater purification efficiency of horizontal subsurface flow (HSSF) constructed wetlands (CWs) planted with *Typha latifolia* (cattail). The experimental setup compared systems filled with lightweight expanded clay aggregates (LECA), both with and without bio-char (10% v/v). Results showed that the LECA + bio-char + plants (LBP) treatment notably improved both plant growth and wastewater treatment efficiency. Aboveground and belowground biomasses increased by 1.9× and 1.5×, respectively, compared to the LECA + plants (LP) system. Additionally, bio-char lowered water pH and enhanced nutrient removal, with total nitrogen (TN) and total phosphorus (TP) removal efficiencies reaching 20.0% and 22.5%, respectively higher than in LP (13.7%, 16.2%) and LECA + bio-char (LB) filters (9.5%, 15.6%). The presence of bio-char in the substrate also facilitated greater N and P uptake by plants, indicating improved nutrient retention and biological activity within the filter system. Overall, the study demonstrated that bio-char serves as an effective supplement in planted HSSF constructed wetlands, improving both plant productivity and wastewater purification performance. Kasak et al. concluded that integrating bio-char into CW substrates enhances the synergistic interaction between filter media, microbial activity, and plant nutrient uptake offering a promising strategy for sustainable and efficient wastewater treatment<sup>18</sup>.

Leveraging recent developments, in a study, **Kulsoom et al.** investigated aluminium hydroxide–sweet lime (AIOH-SL) bio-sorbent for fluoride removal from groundwater. The AIOH-SL (1:3) was characterized using Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDX), X-ray Diffraction (XRD), and Fourier Transform Infrared Spectroscopy (FTIR). Optimization of the defluoridation process considered bio-sorbent dose, fluoride concentration, contact time, and pH. Results showed high fluoride removal efficiency (94.5% at 2 ppm and 74% at 10 ppm) at pH 6 with 5 mg/L adsorbent, reaching saturation within 30 minutes. Fluoride adsorption followed monolayer chemisorption, fitting the Langmuir isotherm

( $R^2 = 0.975$ ) and pseudo-second order kinetics ( $R^2 = 0.985$ ). The approach highlights sustainable water treatment using fruit peel waste, offering eco-friendly waste management, reduced carbon footprint, and a cost-effective groundwater defluoridation solution. Multiple batch experiments confirmed the method's reliability, positioning AIOH-SL as a promising candidate for sustainable fluoride removal<sup>19</sup>.

**Conclusion :** Access to clean and safe water is one of the most pressing challenges of our time, and the invisible threat of contaminants such as fluoride, heavy metals, and organic pollutants continues to affect millions worldwide. In this context, bio-char has emerged as a transformative solution—turning waste into a powerful tool for water purification. Derived from plant-based and agro-industrial residues, bio-char combines high porosity, large surface area, and abundant functional groups, making it exceptionally effective in adsorbing a wide spectrum of pollutants from water and wastewater. Its efficiency is further enhanced through tailored preparation techniques, including pyrolysis under controlled conditions and chemical or physical activation, which allow precise tuning of surface chemistry and adsorption capacity. Recent advancements have taken bio-char's potential even further. Magnetic functionalization, hybridization with metal oxides, and the creation of composite bio-chars have dramatically improved adsorption kinetics, regeneration ability, and operational convenience. Such innovations enable rapid separation, high removal efficiency over broad pH ranges, and sustained performance through multiple reuse cycles. In particular, plant-waste derived bio-chars, such as those from fruit peels and agricultural residues, exemplify the circular economy in action—transforming discarded biomass into a valuable, sustainable resource while simultaneously addressing environmental pollution and solid waste challenges. The significance of bio-char extends beyond its adsorption capacity. It provides an eco-friendly, low-cost alternative to conventional water treatment technologies, making it highly suitable for rural and resource-limited regions where access to clean water is constrained. By removing fluoride and other harmful contaminants, bio-char not only protects public health but also enhances water security and contributes to sustainable development goals. Its integration into decentralized treatment systems, constructed wetlands, or filtration setups exemplifies its versatility and practical applicability.

In conclusion, bio-char represents a convergence of innovation, sustainability, and environmental stewardship. Through its ability to transform waste into a high-performance adsorbent, it offers a scalable, cost-effective, and environmentally responsible pathway for water purification. By mitigating fluoride contamination and other water quality challenges, bio-char bridges the gap between scientific advancement and real-world solutions, providing a promising vision for cleaner, safer, and more resilient water systems globally. The continued exploration and optimization of bio-char-based technologies signal a future where waste is no longer discarded, water is no longer compromised, and environmental sustainability is fully realized.

#### References:

1. Wang, J., & Wang, S. (2019). Preparation, modification and environmental application of bio-char: A review. *Journal of Cleaner Production*, 227, 1002-1022.
2. Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2010). A review of bio-char and its use and function in soil. *Advances in agronomy*, 105, 47-82.
3. Mukherjee, A., & Lal, R. (2014). The bio-char dilemma. *Soil research*, 52(3), 217-230.

4. Qian, K., Kumar, A., Zhang, H., Bellmer, D., & Huhnke, R. (2015). Recent advances in utilization of bio-char. *Renewable and sustainable energy reviews*, 42, 1055-1064.
5. Verheijen, F., Jeffery, S., Bastos, A. C., Van der Velde, M., & Diapas, I. (2010). Bio-char application to soils. *A critical scientific review of effects on soil properties, processes, and functions. EUR*, 24099(162), 2183-2207.
6. Ippolito, J. A., Laird, D. A., & Busscher, W. J. (2012). Environmental benefits of bio-char. *Journal of environmental quality*, 41(4), 967-972.
7. Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., ... & Lehmann, J. (2021). How bio-char works, and when it doesn't: A review of mechanisms controlling soil and plant responses to bio-char. *Gcb Bioenergy*, 13(11), 1731-1764.
8. Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., ... & Whitman, T. (2021). Bio-char in climate change mitigation. *Nature Geoscience*, 14(12), 883-892.
9. Leng, L., Huang, H., Li, H., Li, J., & Zhou, W. (2019). Bio-char stability assessment methods: a review. *Science of the total environment*, 647, 210-222.
10. Cha, J. S., Park, S. H., Jung, S. C., Ryu, C., Jeon, J. K., Shin, M. C., & Park, Y. K. (2016). Production and utilization of bio-char: A review. *Journal of Industrial and Engineering Chemistry*, 40, 1-15.
11. Lee, J., Kim, K. H., & Kwon, E. E. (2017). Bio-char as a catalyst. *Renewable and Sustainable Energy Reviews*, 77, 70-79.
12. Oliveira, F. R., Patel, A. K., Jaisi, D. P., Adhikari, S., Lu, H., & Khanal, S. K. (2017). Environmental application of bio-char: Current status and perspectives. *Bioresource technology*, 246, 110-122. .
13. Li, X., Gan, T., Zhang, J., Shi, Z., & Xiao, Z. (2023). Performance of Fe–La–Ce bio-char derived from *Bidens pilosa* L. for adsorbing fluoride in water. *Environmental Technology & Innovation*, 32, 103261.
14. Aboulsoud, Y. I. (2025). Biosorptive removal of fluoride from wastewater using tea domestic waste bio-char. *Environment, Development and Sustainability*, 27(7), 16451-16468.
15. Peng, X., Deng, Y., Peng, Y., & Yue, K. (2018). Effects of bio-char addition on toxic element concentrations in plants: A meta-analysis. *Science of the Total Environment*, 616, 970-977
16. Gourai, M., Nayak, A. K., Nial, P. S., Satpathy, B., Bhuyan, R., Singh, S. K., & Subudhi, U. (2023). Thermal plasma processing of *Moringa oleifera* bio-chars: adsorbents for fluoride removal from water. *RSC advances*, 13(7), 4340-4350.
17. Kopecký, M., Kolář, L., Konvalina, P., Strunecký, O., Teodorescu, F., Mráz, P., ... & Bucur, D. (2020). *Modified bio-char-a tool for wastewater treatment. Energies* 2020, 13.
18. Kasak, K., Truu, J., Ostonen, I., Sarjas, J., Oopkaup, K., Paiste, P., ... & Truu, M. (2018). Bio-char enhances plant growth and nutrient removal in horizontal subsurface flow constructed wetlands. *Science of the Total Environment*, 639, 67-74.
19. Fluoride Removal from Drinking Water Using Chemically Modified Biosorbent Prepared