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Seaweed–Parthenium Biochar for Sustainable Remediation of Chromium-Contaminated Agricultural Soils

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***Abstract*--** **Heavy metal contamination, particularly chromium (Cr), has become a major environmental concern due to its persistence, toxicity, and adverse effects on soil quality, crop productivity, and human health. Sustainable and cost-effective remediation strategies are therefore essential to restore contaminated agricultural ecosystems. Biochar has emerged as an environmentally friendly amendment because of its porous structure, mineral-rich composition, and excellent adsorption properties. Among the various biomass resources, marine macroalgae and the invasive weed Parthenium hysterophorus have gained increasing attention as renewable feedstocks for biochar production. This review summarizes recent advances in the production, physicochemical characterization, and environmental applications of seaweed- and Parthenium-derived biochars. It discusses the influence of pyrolysis conditions on biochar properties, including surface area, pore structure, crystallinity, and functional groups characterized using FTIR, BET, XRD, SEM, EDX, and GC-MS analyses. The review further highlights the mechanisms involved in chromium immobilization, such as adsorption, ion exchange, electrostatic interactions, surface complexation and reduction of chromium mobility in contaminated soils. In addition, the beneficial effects of these biochars on soil fertility, microbial activity, nutrient availability, and the growth performance of green gram (Vigna radiata) are critically discussed. Current research gaps, including limited field-scale validation, long-term stability, and the development of composite biochars, are also addressed. Overall, seaweed- and Parthenium-derived biochars offer a promising, sustainable approach for heavy metal remediation while supporting soil restoration and climate-resilient agriculture.**

***Keywords*--** **Biochar, Chromium remediation, Heavy metal accumulation, Pyrolysis, Sustainable agriculture, Vigna radiata (Green gram)**

I. Introduction

Environmental contamination brought on by heavy metals or their derivatives is referred to as heavy metal pollution. Compared to other contaminants, chromium (Cr) toxicity is a worldwide environmental problem (Mudhoo *et al.,* 2012). 7% of China's total agricultural land is contaminated with Cr, and 16% is contaminated with heavy metals, according to the China National Soil Environmental Pollution Survey (2003–2014).

Heavy metals are difficult to break down in the environment and have a strong propensity to build up, in contrast to organic contaminants, many of which can be naturally broken down through physical, chemical or biological processes. Industrial pollution is the main cause of heavy metal pollution. Metals include chromium (Cr), lead (Pb), cadmium (Cd) and mercury (Hg) all of which are dangerous because of their high levels of toxicity, persistence and bioaccumulation (Ambaye *et al.,* 2021).

Heavy metals and metalloids (HMs) pollute the environment. They are also agricultural soil pollutants because when present at elevated levels in the soil, HMs can severely affect crop health and yield (Shahid *et al.,* 2015). Seaweed knows as macro algae is one of the major source for remediating the heavy metals in agriculture soil. Because of their high biomass output, quick growth rate, and capacity to expand without competing for freshwater or arable land, marine macroalgae have become one of the most promising renewable biomass resources for sustainable biochar production. Seaweeds, in contrast to terrestrial lignocellulosic biomass, are rich in polysaccharides including alginate, fucoidan, carrageenan, agar, laminarin, and ulvan in addition to significant amounts of mineral minerals like potassium, calcium, magnesium, salt, and phosphorus. These substances undergo pyrolysis to produce mineral-rich biochar with an alkaline pH, a high cation exchange capacity (CEC), a porous structure, a large number of functional groups that contain oxygen, and reactive mineral phases (Neori *et al.,* 2003) Marine macroalgae have emerged as one of the most potential renewable biomass resources for long-term biochar production due to their quick growth rate, high biomass productivity, and capacity to develop without competing with arable land or freshwater resources. Unlike terrestrial lignocellulosic biomass, seaweeds include abundant polysaccharides including alginate, fucoidan, carrageenan, agar, laminarin, and ulvan, as well as significant amounts of mineral minerals like potassium, calcium, magnesium, salt, and phosphorus. During pyrolysis, these chemicals are converted into mineral-rich biochar with an alkaline pH, high cation exchange capacity (CEC), porous structure, abundant oxygen-containing functional groups, and reactive mineral phases (Ao *et al.,* 2022).

II. Bioactive Compounds Present In Seaweeds

Seaweeds, also known as macroalgae, are classified as lower plants since they lack roots, stalks, and leaves; instead, they are gathered from thalluses. Structures filled with gas to provide buoyancy in numerous species. Seaweeds are classified into three groups: brown (Phaeophyceae), green (Chlorophyceae) and red (Rhodophyceae) algae. As green or dry vegetables or as ingredients in a wide variety of foods, macroalgae are costly in terms of nutrients. Over 15 million metric tons of seaweed was produced globally in 2014, with the Indian Ocean contributing between 15% and 20% of that total (100,000 metric tons). Significant substances of structurally novel and physiologically active metabolites can be found in abundance in the nautical industry. In order to bring the aquatic chemical diversity up to its therapeutic potential, it also poses significant hurdles that need for contributions from a variety of technical fields. Seaweeds have been carefully considered as a rich source of antioxidants. Latent antioxidant molecules have recently been identified as polyphenols (phenolic acid, flavonoids, and tannins) and some pigments (fucoxanthin, astaxanthin, and carotenoid). These composites have been found to have increased antioxidant behavior and are widely distributed in plants and seaweeds (Dhargalkar *et al.,* 2005)

Researchers have investigated seaweed-derived biochar for a wide range of environmental applications, including wastewater treatment, heavy metal adsorption, and soil remediation. Among them, its application as a carbon-rich soil supplement is especially promising, as it improves soil fertility and water retention capacity while contributing to long-term carbon sequestration. (Woolf *et al*., 2010; Cardenas *et al.,* 2024). Seaweed biochar improves acidic soils by raising the pH and increasing macronutrient availability. Biochar made from several seaweed species decreases heavy metal contamination and increases soil microbial activity, indicating a great potential for soil remediation. Seaweed-derived biochar has distinct advantages over traditional biochar sources. Nitrogen (N), phosphorus (P), and potassium (K) are essential plant nutrients that contribute significantly to vegetative growth, root development, and blooming. Calcium (Ca) and magnesium (Mg) are also necessary for cell wall formation and photosynthesis. Soil enrichment promotes plant health and productivity by boosting macronutrient availability. In this work, we found that seaweed-derived biochar had more nitrogen, phosphate, potassium, calcium, and magnesium than the commercial fertilizer utilized.

Although seaweed biochar has less carbon, it contains higher levels of important minerals and exchangeable cations, particularly potassium (Wang *et al.,* 2024). Its pH range of 7-11 makes it suited for a variety of soil types.

III. Parthenium Biochar As A Value-Added Biomass Resource

Although *Parthenium*-derived biochar and seaweed-derived biochar have individually shown promise for heavy metal remediation, studies on their combined application for chromium-contaminated agricultural soils remain extremely limited. Furthermore, there is a lack of systematic research evaluating the mechanisms of chromium immobilization and the effects of *Parthenium*-treated seaweed biochar on soil health and green gram (*Vigna radiata*) growth under field-relevant conditions.

Despite growing attention towards using biochar for environmental clean-up, there has been limited focus on combining *Parthenium* and seaweed-based biochar adsorbents for treating heavy metals-contaminated agricultural soils.These two types of biomass offer complementary physical and chemical properties that could greatly enhance heavy metals like chromium removal as well as improve soil quality and support sustainable crop growth.This review provides a detailed analysis of the production and characteristics of *Parthenium* and seaweed-derived biochars, explains the processes involved in heavy metals adsorptionand its immobilization in soil and examines how these biochars affect soil properties and the growth of commercial agricultural crops.Additionally, the review highlights recent advances in the field, points out areas that still need more research, and outlines potential future strategies for creating effective, eco-friendly, and cost-efficient biochar-based solutions for remediating heavy metals-polluted agricultural areas.

Parthenium hysterophorus one of the world's most invasive weeds, inflicting significant ecological, agricultural, and economic damage due to rapid proliferation, allelopathic effects and competition with natural flora. Converting this problematic weed into biochar via controlled pyrolysis is an environmentally sustainable technique for biomass utilization that also reduces weed infestations.*Parthenium*derived biochar has a highly porous carbon matrix rich in hydroxyl, carboxyl, phenolic, and carbonyl functional groups, which aid in the adsorption of heavy metals from contaminated soils and wastewater.

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Depending on the pyrolysis temperature, biochar has higher aromaticity, surface area, and chemical stability, making it ideal for long-term soil remediation one of the most invasive weeds in the world, using controlled pyrolysis to turn this troublesome weed into biochar offers an environmentally friendly method of using biomass while also lowering weed infestation. Heavy metal adsorption from contaminated soils and wastewater is facilitated by the highly porous carbon matrix of *Parthenium*-derived biochar, which is loaded in hydroxyl, carboxyl, phenolic, and carbonyl functional groups. The biochar shows enhanced aromaticity, surface area, and chemical stability depending on the pyrolysis temperature, which makes it ideal for long-term soil remediation (Rai *et al.,* 2019; Kosmulski,2020)

IV. Physicochemical Characterization Of Biochar

FTIR, BET, and XRD investigations show that pyrolysis temperature has a significant impact on the physicochemical parameters of both seaweed-derived and Parthenium hysterophorus-derived biochar. Increasing the pyrolysis temperature decreases oxygen-containing functional groups while increasing aromatic carbon production, crystallinity, and pore development, resulting in increased structural stability and adsorption efficiency. Biochars produced at higher temperatures have a larger surface area, porosity, and a more structured carbon matrix, making them excellent materials for heavy metal immobilization, pollutant adsorption, and environmental remediation (Farobie *et al.,* 2022; Ippolito *et al.,* 2020).

Green gram (Vignaradiata) as an indicator crop for soil remediation

Green gram (*Vignaradiata L.*) often known as mung bean or moong dal, is an economically significant pulse crop grown throughout Asia due to its high nutritional content, short growth period, and capacity to fix atmospheric nitrogen via symbiosis with Rhizobium. However, chromium contamination has a negative impact on seed germination, root elongation, chlorophyll synthesis, photosynthetic efficiency, nutrient uptake, antioxidant enzyme activity, and biological nitrogen fixation, resulting in reduced plant growth and grain yield. The addition of biochar to chromium-contaminated soils has been demonstrated to reduce these negative effects by immobilizing chromium, lowering its bioavailability, improving soil physicochemical qualities, boosting water retention, and improving nutrient availability.

Biochar application also boosts microbial populations in the rhizosphere, improves root architecture, increases nodulation, and strengthens antioxidant defense systems, ultimately increasing plant tolerance to heavy metal stress. As a result, green gram is regarded as an excellent model crop for assessing the efficacy of biochar-based remediation technologies, as improvements can be measured using germination percentage, plant height, biomass accumulation, chlorophyll content, nodulation, grain yield, and chromium uptake. Integrating Parthenium-treated seaweed biochar with sustainable pulse agriculture is a promising technique for repairing contaminated agricultural soils while boosting food security and environmental sustainability(Farid *et al.,* 2017). Biochar application also boosts microbial populations in the rhizosphere, improves root architecture, increases nodulation, and strengthens antioxidant defense systems, ultimately increasing plant tolerance to heavy metal stress. As a result, green gram is regarded as an excellent model crop for assessing the efficacy of biochar-based remediation technologies, as improvements can be measured using germination percentage, plant height, biomass accumulation, chlorophyll content, nodulation, grain yield, and chromium uptake. Integrating Parthenium-treated seaweed biochar with sustainable pulse agriculture is a promising technique for repairing contaminated agricultural soils while boosting food security and environmental sustainability (Dixit *et al.,* 2015)

V. Thermochemical conversion Processes On Biochar Properties

According to (Tripathi*et al.,*2016) biochar is a solid, carbon-rich substance that is created when biomass is thermochemically broken down in an oxygen-depleted atmosphere. The chemical makeup of biochar organic and inorganic components directly affects its characteristics. Carbon, oxygen, hydrogen, sulfur, and nitrogen make up the majority of the organic matter in biochar, whereas silica, aluminum, calcium, magnesium, phosphorus, sodium, and potassium make up the majority of the inorganic portion, which takes the form of ash (Jindo *et al.,* 2020). The primary functional groups found on the surface of biochar are hydroxyl, carbonyl, epoxy, carboxyl, ether, ester, sulphonic, aliphatic, phenolic, and aromatic C groups (Yuan *et al.,* 2019). High CEC and a high affinity for nutrient adsorption are characteristics of biochar with a high carboxyl and phenolic C group content.

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The source biomass, the thermo chemical conversion technique and the preparation conditions-particularly temperature, reaction time, heating rate, and ventilation conditions-all have a substantial impact on the properties of biochar. The type and characteristics of biomass as well as the intended end products, such as biochar, biogas, and bio-oil, are taken into consideration while choosing the process and its parameters. Biomass is often converted into biochar by pyrolysis, torrefaction, gasification, and hydrothermal carbonization (HTC) (Enaime *et al.,* 2020).The most popular process for turning biomass into biochar is pyrolysis. When creating particular biochar for certain agricultural uses, the impact of pyrolysis temperature is crucial. The aromatic C content of biochar increases (from 17 to 85%) as the pyrolysis temperature rises, whereas other characteristics like the O/C and H/C ratios and the carboxyl group content decrease. The CEC of biochar made at high pyrolysis temperatures is lower than that of biochar made at low temperatures.

VI. Influence Of Biochar Production Parameters On Its Physicochemical Characteristics

Biochar CEC is also influenced by the type of feedstock. For example, biochar made from wood showed a lower CEC than those made from dung waste. When biochar is added to soil, other factors including response time and heating rate are said to have an impact on the pace of decomposition. These two characteristics allow for the classification of pyrolysis into two categories: slow pyrolysis (long residence time > 1 h and low heating rates > 5 to10° C/min) and fast pyrolysis (residence time < 10 s and heating rates > 200° C/min). Fast pyrolysis biochar breaks down in soil more slowly than slow pyrolysis biochar, and thus may have long-lasting positive effects as an amendment. Similar to slow pyrolysis, torrefaction often involves a variety of decomposition reactions at slow heating rates and temperatures between 200 and 300°C in an inert atmosphere. However, because torrefaction only results in 30% weight loss and releases only 10% of the initial energy in the biomass as gas, it is typically used to improve the thermochemical properties of the biomass, enabling the production of biochar with high calorific values (Gamage*et al.,* 2016).Gasification, on the other hand, uses a regulated flow of oxidizing agent at high temperatures (>700°C) to transform biomass into a mixture of combustible gases, primarily carbon monoxide and hydrogen with trace amounts of carbon dioxide, methane, water, and hydrocarbon derivatives.

Victorian brown coal was gasified at 800°C with steam acting as an oxidant, which reduced the volatization of Mg and Ca ions during the thermal process and the relative ratio of tiny to big aromatic ring structures in biochar. However, because biochar is created as a secondary product with a lower yield (about 10% (w/w)) than gaseous by-product, less attention has been paid to the mechanism involved in the synthesis of biochar by gasification and its application in agriculture. HTC is an efficient and cost-effective technique for processing high-moisture biomass as compared to other traditional technologies commonly utilized for low-moisture biomass (Borchard *et al.,* 2012).

Crucially, this evaluation exclusively takes into account biochar, setting it apart from traditional charcoal, which was frequently discussed interchangeably in earlier research. Although both biochar and charcoal are carbon-rich byproducts of pyrolysis, their manufacturing processes, feedstocks, physicochemical characteristics, and intended uses are different (Ayeneshetand Temesgen, 2025). In order to maximize functional characteristics like porosity, surface area, nutrient content, and adsorption capacity, biochar is usually made from a variety of organic biomass sources, including agricultural residues, forestry by-products, and biosolids, under contemporary controlled pyrolysis settings (250–1200°C).

Biochar has several uses, such as soil amendment, soil and water remediation, and absorption into building materials and other industrial materials, due to these enhanced functional qualities. In comparison to biochar, charcoal is usually made at lower temperatures (400°C), mostly from wood, and frequently takes longer to create. Furthermore, rather of being employed for applications that take use of its high surface area or nutrient content, charcoal is mostly utilized for the production of heat energy. These differences support the review's exclusive focus on biochar research (Wong *et al.,* 2024).

VII. Agricultural Applications And Soil Amendment Potential Of Biochar

As previously mentioned, agriculture is confronted with significant environmental and financial difficulties. In order to attain sustainability and economic improvement, agricultural actors were under increasing pressure to make significant changes in the management of their operations due to growing concerns about these global issues. In recent years, there has been a noticeable rise in interest in the quest for organic and/or organically generated materials and their use in agriculture. Alternative organic biofertilizers that can successfully replace inorganic fertilizers include manures and composted sewage sludge.

However, these residues contain pathogens, and when applied improperly to soil, they can have adverse impacts such soil acidification, greenhouse gas emissions, and groundwater and surface water contamination (Lehmann *et al.,* 2011). On the other hand, the use of biochar in agriculture is gaining popularity due to its positive effects on both agronomy and the environment. With its use in agriculture as a soil amendment, animal feed, and remediation, biochar can play a variety of roles in the CE. The pace of biochar breakdown and the level of soil fertility have a significant impact on the lifecycle of biochar in soil (Enaime and Lubken 2021).

Variations in soil pH, EC and WHC across various biochar treatments throughout 10- and 20-day incubation periods, with impacts seen after 30 days. The findings show that the chemical and physical characteristics of the soil varied significantly between the treatments. The change in soil physicochemical parameters was greatly influenced by all applied treatments, incubation times, and their interactions (Cantrell *et al.,* 2011).

VIII. Biochar-Based Remediation Of Heavy Metal-Contaminated Soils

The carbonaceous composition of biochar includes a variety of functional aromatic hydrocarbon groups, an alkaline pH, a high base cation concentration, cation exchange capacity (CEC), and surface area (Krull, 2012).

A considerable amount of extractable humic and fulvic acids can be found in the very porous structure of certain biochar. Additionally, depending on the environment, it has a high degree of chemical and microbiological stability (recalcitrance), which predicts lengthy soil residence (10s to 1000s of years). Reactivity with a variety of soil materials is made possible by the heterogeneous composition of biochar, which includes hydrophilic, hydrophobic, basic, and acidic surface moieties. Biochar is a potential adsorbent of a variety of soil pollutants, including toxins such heavy metals (HMs), due to this divergence in compositional chemistry (Cao *et al.,* 2018). Experimental research on soil amelioration reveals a variety of diverse effects, many of which are dependent on the type of soil and the procedures used to produce biochar. The general underlying mechanisms have been somewhat clarified by critical assessments of these findings. According to this work, there is a good chance that the entire manufacturing process can be improved to produce biochar with particular desired functionalities or performance-a "designer" or "smart" biochar-given a greater mechanistic understanding of how biochar functions.

But the use of biochar to improve soil contaminated with heavy metals is still in its infancy. Degraded soils, especially those contaminated with heavy metals, can be improved by biochar in two ways: abiotically, by directly modifying the physicochemical characteristics of the soil, such as HM adsorption; and biotically, by indirectly influencing the microbiological and biological variety and function of the soil (Bird *et al.*, 2011).

IX. Sources Of Chromium Contamination textile And Dyeing Industries

Heavy metals are frequently released into the environment by industrial pollution through solid waste, wastewater, and exhaust gas. These metals build up in people, animals, and plants, seriously harming ecosystems and human health. In order to comply with national emission regulations, industrial pollution can be reduced by management and technical measures. Vehicle exhaust emissions are the primary source of traffic-related pollution. Governments have put in place a number of laws to lessen this, including ones requiring the installation of exhaust purification equipment and the usage of fuel combined with ethanol. Used batteries, broken lamps, residual cosmetics, and glazed ceramics are the main sources of domestic pollution (Ghosh, 2024). By managing it at the source, heavy metal pollution can be greatly decreased. Due to its significant contribution to the national economy as a source of foreign revenue, the textile sector has been given priority for national growth. In addition, the textile sector is essential to fulfilling the demands of the country's apparel industry. Nevertheless, the textile sector has a negative effect on the environment. Because of the dying process, textile waste makes up the majority of the wastewater generated by the textile sector. Textile waste contains a number of heavy metals in addition to dyes (Feng and Zhu 2018) Reactions it was common knowledge that heavy metals pollute the environment. Heavy metal-containing trash must therefore be appropriately treated before being released into the environment. Being one of the harmful contaminants, heavy metals are hard for nature to break down (Zhao *et al.,* 2011).

Finishing, dyeing, printing, and wastewater treatment facilities (WWTP) are the sources of liquid waste in the textile sector. According to Minister of Environment and Forestry Regulation No. 5 of 2014, heavy metals, particularly metal elements such As, Pb, Cu, Cd, Cr, Zn, and halogenated hydrocarbons from the cleaning and finishing process, are the primary source of pollution caused by textile companies.

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X. Biochar From Parthenium Weed

A fine-grained, extremely porous charcoal, biochar aids in the retention of water and nutrients in soils. By lowering soil acidity, boosting crop yields and productivity, and lowering the need for certain chemical and fertilizer inputs, biochar as a soil amendment contributes to the improvement of Earth's soil resources.Because biochar helps the soil retain nutrients and agrochemicals for plant and crop usage, using it as a soil amendment improves water quality (Lehmann *et al.,* 2003). By pyrolyzing*Partheniumhysterophorus*, biochar can be effectively created to trap carbon for negative carbon dioxide emissions. Increased Zea mays growth, increased basal respiration and microbial biomass carbon, enhanced catalase and dehydrogenase activities, and decreased soil stress and hydrolytic enzyme activities are all signs that adding this biochar to the soil improves its quality. Ambrosin, a molecule found in *parthenium* that has a phototoxic impact, was lost after charring due to breakdown at high temperatures.Large-scale biochar addition has no detrimental effects on the soil (Kumar *et al.,* 2013).

Parthenium was once thought to be one of the most harmful weeds in the world, causing enormous costs to the economy, agriculture, biodiversity, and human and cattle health. The plant may dominate a variety of habitats, including agriculture fields, road and railroad lines, and arid places, thanks to its high competitive success rate, strong seed production and germination, and adaptability. Globally, a variety of weed control techniques, including mechanical, cultural, herbicidal, and biocontrol, are employed to bring the population under control. However, managing*parthenium* is still difficult due to the numerous drawbacks of these traditional approaches. Large-scale use has recently been adopted as a comprehensive strategy for weed management. *Parthenium hysterophorus* can be controlled by using this weed in a variety of applications, including the manufacturing of compost or green manure, industrial products (such as biochar, biofuel, and soil amendment combinations) medications, and bioactive substances. There are numerous environmental uses for this weed as well. In addition to mechanical and biological management, the widespread use of *parthenium* may be another efficient way to control weeds. Given the enormous amount of dry and green *parthenium* biomass that can be found in India and other nations, it is necessary to manage and use *parthenium* weed sustainably (Patel, 2011).

Terra preta, or dark soil, was produced by the old "pit" or "trench" method of creating biochar as a soil amendment.

Although biochar can still be produced in rural regions using this method, neither syngas nor bio-oil can be harvested. The majority of biomass wastes from forestry, agriculture, and urban areas can be used in biochar synthesis methods. Pyrolysis is a modern method for producing biochar. Either a small or huge scale is used for this. Subsistence farmers can create tiny amounts of biochar suitable for their gardens or fields thanks to small-scale production. Pyrolysis is an incineration process that uses heat and no oxygen to chemically break down organic molecules (Glaser *et al.,* 2007)

XI. Biochar Is An Eco-Friendly Remediation Technology

Seaweed (SW), which includes a variety of marine macroalgae, has become a valuable and adaptable resource with a wide range of uses in diverse industries. Each of the three types of seaweed-brown, red, and green-has unique mechanical, chemical, and physical characteristics. Their biological makeup and abundant supply of chemicals suggest a topic for study and useful applications. Recent research has increased attempts to fully investigate seaweed's potential, acknowledging its importance in fields like nutrition, agriculture, medical, and environmental science. Additionally, it may flourish in a variety of aquatic settings, demonstrating its versatility for a variety of uses (Perezlorens *et al.,* 2020). This article provides a thorough summary of the various uses of seaweed, illuminating its physical, chemical, and biological properties that offer many benefits for both ecological sustainability and human health (Zhang *et al.,*2022).

Often called algae, seaweed includes a wide variety of species that resemble plants and do well in salty environments. Through the process of photosynthesis, these photosynthetic organisms transform sunlight, carbon dioxide, and nutrients into organic matter. They are large collections of multicellular seaweeds that live alongside microscopic creatures. They can be divided into three classes based on their pigmentation: Rhodophyta (red algae), Phaeophyta (brown algae), and Chlorophyta (green algae). Because it provides a variety of marine organisms with food and habitat, seaweed is essential to aquatic ecosystems. Even while some species can float freely in the water, they are frequently found clinging to rocks or other shoreline surfaces. Seaweed-derived biomaterials exhibit a variety of biological properties due to their unique chemical patterns.

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Alginate's Ca2+-exchange characteristics support hemostasis, immunological modulation, and medication delivery, whereas sulfated polysaccharides (fucoidan, carrageenan, and ulvan) bind coagulation factors, viral proteins, and immune receptors to provide anticoagulant, antiviral, and anti-inflammatory activities. While phenol tannins operate as antioxidants, antimicrobials, and anti-inflammatory agents by scavenging reactive oxygen species (ROS) and suppressing signaling, laminarin improves innate immunity through Dectin-1. Fucoxanthin, sterols, and PUFAs are among the substances that control metabolism and apoptosis and have anticancer and anti-obesity effects; MAAs offer UV protection; and nanofibrils have anti-fouling qualities. The idea that seaweed's chemistry drives adaptable industrial usage is supported by these processes (Amador *et al.,* 2023). They are used in many Asian cultures because of their high fibre, mineral, and antioxidant content. They are regarded as a nutrient-dense dietary choice due to their low fat and calorie content.

XII. Environmental And Human Health Impacts Of Chromium

Sushi, nori sheets, salads, and soups are just a few of the dishes that regularly contain seaweed (Das *et al.,* 2024). It has several uses outside of cooking. It is employed in the synthesis of bioactive substances. Seaweed extracts are very useful in the medical and beauty industries because they have antibacterial, antiviral, and anti-inflammatory qualities. Additionally, seaweed is used in agriculture and aquaculture as a natural fertilizer and feed additive. Its extracts are rich in growth-promoting chemicals, vital trace elements, and helpful microbes that improve soil fertility and aid in plant development. Feeds made from SW are used in aquaculture to improve the health and growth of fish raised for food. Furthermore, seaweed can be used to treat wastewater, restore the environment, make bioplastics, and produce biofuel (Li *et al.,* 2023). Mariculture, or the cultivation of seaweed, is a sustainable and renewable resource that provides eco-friendly substitutes for traditional materials and techniques. This method, which uses carbon capture to help mitigate climate change, has drawn interest as a profitable and environmentally responsible business option (Ayala *et al.,* 2023).

XIII. Marine Macroalgae As Sustainable Biomass Resources

In facilitating soil carbon storage and enhancing soil fertility to boost plant and total crop output, biochar significantly contributes to climate change mitigation, environmental sustainability, and agricultural productivity (Steiner*et al.,* 2007). The application of biochar, soil improvement, waste management, climate change mitigation, and energy are the four motivational goals outlined by (Lehmann and Stephan 2009). As shown in Fig. 1, these goals can help society, the economy, or both, either separately or in combination. (De *et al.,* 2014) talked about the idea of terra preta sanitation (TPS), which has been widely used in Amazonian civilization, and how biochar can improve soil fertility, support sustainable production, and lessen contamination of streams and groundwater. According to reports, TSP integrates soil fertility, food security, waste management, and renewable energy, making it a close-loop process that is advantageous for a sustainable lifestyle. The terra preta sanitation method, which is based on lactic acid fermentation and subsequent vermicomposting, involves diverting urine via a charcoal mixture. Lactofermentation was discovered to be a biological anaerobic process that produces no gas or odour (Steiner *et al.,* 2018)

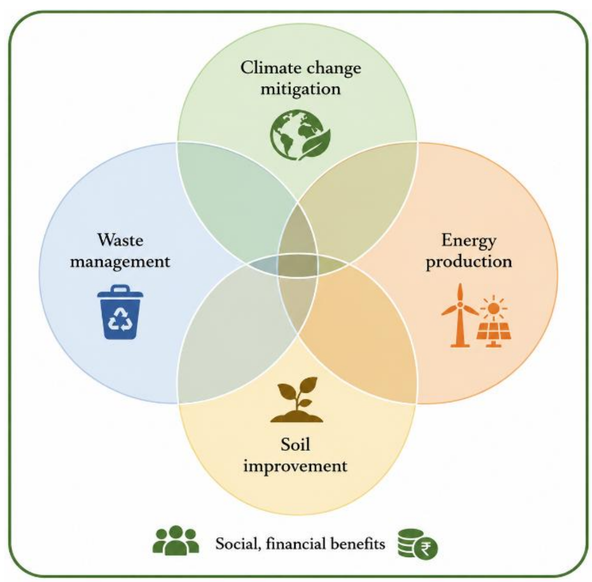

Fig: 1 Benefits of treated biochar for sustainable Environmental Remediation

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Plant Availability and Biochar Decomposition the availability of nutrients in biochar depends on their structural stability, which is influenced by the soil environment, manufacturing conditions, and type of feedstock (Asadullah*et al.,* 2010). The primary markers of biochar structural stability are the elemental ratios of H/C, O/C and C/N. Raising the pyrolysis temperature often lowers the H/C and O/C ratios while changing the structure of the biochar into a more stable arrangement both chemically and physiologically (Mohan *et al.,* 2014). On the other hand, a more stable biochar structure results from an increase in the C/N ratio as the pyrolysis temperature rises. Studies have revealed that biochar can partially disintegrate or mineralize due to biotic and abiotic elements of the natural environment, despite its strong resistance to chemical and biological breakdown (Cheng *et al.,* 2008). The biochar produced from perennial ryegrass shoot litter was labelled with 14°C to study its breakdown. In a lab incubator, biochar-added soil was kept at 20°C and 70% of its water-holding capacity for 1181 days. After being incorporated into the soil, biochar decomposes quite quickly in the first few months before slowing down as the partial decomposition continues (Kuzyakov *et al.,* 2009). It is unclear, nevertheless, if this mineralization is solely due to biochar or if it also includes the natural organic matter in the soil. A laboratory incubation experiment revealed a 13.5% increase in 14°C-labeled organic matter mineralization after adding commercial biochar. For the maize Stover biocharin 3.2-year incubation trial at 70% water holding capacity, a comparable mineralization rate (16% annually) was also noted 0.26% of the carbon in wood biochar produced at 350℃ and 0.72% of the carbon in maize biochar produced at 800°C calcified into CO_2 during a 60-day incubation trial (Hamer *et al.,* 2004).

XIV. Treatments And Experimental Design

A fully randomized design (CRD) with three replications of three (wheat varieties) × six (biochar rates) factorial combinations was employed in this study's pot experiment.

Prior to the experiment, soil samples with pH values between 5.2 and 5.6 were randomly taken from 15 acidic farmland pits at a depth of 0 to 25 cm. These samples were then combined to create composite soil samples. Next, each experimental pot, measuring 40 cm in height and 27.0 cm in width, was filled with 12 kg of dry acidic soil combined with varying amounts of biochar. The dry weights of the potting soil were explained by the *P. Hysterophorus* biochar dosages of 0, 12.5, 16.0, 19.5, 23, and 26.5 t/ha. Thebiochar was simply placed into the acidic soil and the pots were left for two months with three-day intervals of 2000 mL watering for decomposition (Panahi *et al.,* 2020). Different amounts of biochar were applied according to treatments in a fully randomized design with three replications after the pots were prepared and filled with equal amounts of soil. The Ethiopia Agricultural Research Institute provided the tree wheat varieties Kekeba, Ogolcha, and Kingbird, which were utilized as test crops. The seeds were first cleaned with distilled water and sterilized for two minutes with 2% sodium hypochlorite before being sown. As a result, equal volumes of soil and varying dosages of biochar were added to pots, which were then divided into blocks. One of the treatments served as a control. Each germination pot was then regularly supplied with 2,000 mL of water once a day in the morning after 15 viable seeds were chosen and uniformly sown into each pot. Lastly, each wheat variety was harvested independently (Tamado *et al.,* 2006).Table 1. Carbon content increased from 34.38% in raw *S. wightii* to 68.21% after 60 minutes of pyrolysis at 300°C, nearly doubling the carbon concentration. Biochar produced under optimal conditions had the highest C/N ratio (37.27) and alkaline pH (9.9). Pyrolysis temperatures above 300°C caused progressive ash formation, lowering the quality of the biochar. The reported C/N ratio (37.27) was greater than the value (29) reported for Indonesian seaweed biochar by (Roberts *et al.,* 2015).

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TABLE 1. PHYSICOCHEMICAL CHARACTERISTICS OF *SARGASSUMWIGHTII* BIOCHAR PRODUCED UNDER DIFFERENT PYROLYSIS CONDITIONS

S. No	Pyrolysis Temperature (°C)	Residence Time (min)	Physical Appearance	Carbon Content (%)	Hydrogen Content	Sulphur Content	C/N Ratio	pH	Remarks
1.	Raw seaweed	–	Fresh seaweed biomass	34.38	Baseline	Baseline	–	–	Untreated biomass
2.	300	60	Well-formed biochar	**68.21**	Highest	Highest	**37.27**	**9.9**	Optimum condition with maximum carbon content
3.	350	60	Slight ash formation	Lower than 300°C	Decreased	Decreased	30–35	Alkaline	Partial ash formation observed
4.	400	60	Predominantly ash	Lower than 350°C	Further decreased	Further decreased	23.30–30.00	Alkaline	Excessive ash formation
5.	450	60	Complete ash	Very low	Very low	Very low	23.30	Alkaline	Unsuitable for biochar production

XV. CHROMIUM CONTAMINATION IN AGRICULTURAL SOILS

The intricate relationships between soil organic matter (SOM), mineralogy, and trace element geochemistry that collectively affect carbon stabilization mechanisms are what propel carbon sequestration in mangrove soils. Carbon stability is impacted by trace metals like chromium (Cr), manganese (Mn), nickel (Ni), copper (Cu), zinc (Zn), cadmium (Cd), and lead (Pb). Under the anoxic conditions found in mangrove soils, these elements can precipitate as insoluble compounds or form complexes with organic materials (Wu *et al.,* 2024). For example, Mn, Ni, and Cu catalyze microbial and enzymatic activities that impact carbon turnover, whereas Cr and Pb stabilize SOC by adsorption (Grey *et al.,* 2023). The atmospheric deposition, tidal inputs, and human activity, the geographical distribution of trace elements and elemental oxides in mangrove soils is highly stratified, with larger concentrations usually found in surface layers (0–1 m). Surface soils often have higher concentrations of elements like Cu, Zn, and Cd, but vertical leaching and redox-induced immobilization cause concentrations to decrease with depth (Rahman *et al.,* 2024).

Anthropogenic activities like shipping, urbanization, agricultural runoff, and industrial effluents have drastically changed the soil geochemistry of the damaged mangrove system in the Indian Sundarbans. Recent research emphasizes the effects of industrial and agricultural activities on trace metal enrichment, which includes Cr, Mn, Ni, Cu, Zn, Cd, and Pb. Complex carbon stabilization mechanisms are shown by higher concentrations of particular trace elements and their interactions with oxides like Fe2O3 and TiO2 (Li *et al.,* 2023).

The contaminated soils have been managed using bioremediation, integrated remediation, and chemical and physical remediation techniques. Additionally, ligand-based composite hybrid materials (CMHs) and optical composite materials (OCMs) are being explored as possible materials for sustainable waste management. Das et al. state that biochar is a by-product of pyrolysis of feedstock derived from agricultural and forestry leftovers. Adding biochar to the soil is believed to have a high potential to improve C sequestration because the carbon (C) in biochar has an aromatic structure and is more intractable to the environment. Because biochar frequently has a high pH and cation exchange capacity (CEC), it can increase soil fertility (Sun *et al.,* 2020).

According to numerous writers, biochar is highly effective at eliminating chemicals from soils (Taraqqi *et al.,* 2021). An overview of current methods for reclaiming contaminated soils was given in this review study, along with information on how biochar affects the bioavailability and mobility of soil contaminants and how it removes pollutants from contaminated soils. Additionally, prospective research objectives addressing the application of biochar for the reclamation of polluted soils have been detailed, and the toxicity risks connected with adding biochar to unpolluted agricultural soils and its mitigation techniques are also explored (Cara *et al.,* 2020)

Applying biochar to soils may stabilize heavy metals through a variety of potential methods, as shown. Using Pb2+ as an example, the authors suggested a number of mechanisms for Pb2+ sorption by sludge-derived biochar, such as heavy metal exchange with Ca2+, Mg2+, and other cations associated with biochar, attributing to co-precipitation and inner sphere complexation with complexed humic matter and mineral oxides of biochar; surface complexation of heavy metals with various functional groups and inner sphere complexation with the free hydroxyl of mineral oxides and other surface precipitation; and physical adsorption and surface precipitation that help stabilize Pb2+. Depending on the kind of biochar and exchangeable cations (Na, Mg, K, and Ca) in acidic contaminated soils, some of these cations may be released during the sorption process with the heavy metal, which could enhance the stabilizing process. (Lu *et al.,* 2012) further showed that the primary mechanism responsible in their study was the heavy metal exchange with Ca2+, Mg2+, and other cations (Na+ and K+) associated with sludge-derived biochar; however, the contribution of monovalent (Na+ and K+) cations for heavy metal exchange was found to be negligible. The sorption mechanisms for metal-contaminated soils by biochar could therefore depend on the kind of soils and the cations present in both soils and biochar under realistic field conditions, with varying consequences for metal remediation in contaminated soils. Because these salts can precipitate with heavy metals and lower their bioavailability, the mineral components of biochar, such as phosphates and carbonates, are crucial in stabilizing heavy metals in soils (Jafarian *et al.,* 2023).

XVI. Marine Macroalgae As Sustainable Biomass

A variety of chemical components, including amino acids, fatty acids, carbohydrates, proteins, lipids, vitamins, minerals, micro and macronutrients, hormones, enzymes, growth factors such plant growth-promoting hormones, betaine, algin, etc., are abundant in marine macroalgae.

It can be employed in a variety of industries, including the dairy, pharmaceutical, agricultural, food and medicine, and polymer industries, due to the existence of such active phyco-constituents. The goal of this review study is to determine whether marine algae may be used as a biofertilizer (Hong *et al.,* 2007). This study examined various marine algae, their hormone, and the ways in which they affect plant growth. Biofertilizer made from marine macroalgae or its components has a number of positive benefits on plants. In terms of morphology (root and shoot parameters) and biochemical traits of pigment content, various marine macroalgae have been shown to stimulate plant growth. Numerous studies have documented the positive effects of seaweed on seed germination, plant growth, and soil health. (Zodape *et al.,*2008).

This exploratory study attempts to assess the economic potential of seaweed *Gracilaria sp.* biomass waste using a bio refinery approach based on the background and issues mentioned above. Based on data on seaweed biomass waste productivity and biomass components, this case study examines a typical seaweed production facility in Karawang, Indonesia. The findings of this initial investigation can be used as a foundation for more sophisticated laboratory research, techno-economic analysis, and lifecycle evaluation. It is hoped that this research would help spur the growth of bio-based and environmentally friendly seaweed companies with a wider range of useful goods (Filote *et al.,* 2021).

XVII. Marine Macroalgae As Promising Feedstocks For Biochar Production

The quick growth rates, abundance, and naturally high mineral content. Especially alkali and alkaline-earth metals like potassium, salt, calcium, and magnesium-marine macroalgae have become a promising charcoal feedstock. Seaweeds produce mineral-rich, high-ash biochar with unique surface reactivity and alkalinity because they have lower lignin content and larger proportions of polysaccharides than lignocelluloses biomass. Numerous researches have shown how well biochar made from seaweed works to purify water. *Sargassum* based biochar, for instance, have demonstrated a high adsorption affinity for heavy metals and cationic dyes due to electrostatic attraction and mineral-mediated interactions. *Sargassum* species are particularly interesting among marine macroalgae because of their frequent seasonal blooms and related disposal issues in coastal areas.According to earlier research, biochars made from *Sargassum* have high alkalinity, thermal stability, and reactive mineral phases, which enable uses in catalytic processes, dye adsorption, and nutrient removal (Hunget *et al.,* 2021).

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Additionally, seaweed-based biochar has been investigated as a soil supplement that enhances crop yield, soil water retention, and nutrient availability-all of which support SDG 2's food security goals. Nevertheless, current research frequently concentrates on single pyrolysis conditions or activated biochar, with little systematic assessment of how controlled pyrolysis temperature affects adsorption-relevant characteristics like surface charge, mineral phase distribution, functional group chemistry, and microstructural features. The temperature-dependent evolution of *Sargassum wightii* derived biochar physicochemical properties and how these properties relate to its suitability for adsorption-based water filtration are thus clearly lacking.Specifically, the impact of pyrolysis temperature on surface reactivity, charge behaviour and mineral enrichment-all important factors in the elimination of cationic pollutants including metal ions and pesticides has not been thoroughly examined. In order to clarify the impact of thermal treatment on biochar yield, surface chemistry, mineral content, and structural features, the current work examines the controlled pyrolysis of *Sargassumwightii* biomass at 350°C, 500°C and 600°C. To determine the significance of physicochemical parameters to practical water treatment effectiveness, extensive characterisation utilizing FTIR, SEM, BET, ICP-OES, XRD, and zeta potential investigations is combined with adsorption tests using pesticide-spiked water. The goal of the research is to determine the ideal pyrolysis conditions for creating mineral-rich seaweed biochar that can be used in environmentally friendly and sustainable water treatment applications (Zeghioud *et al.,* 2022).

XVIII. Marine Macroalgae As Natural Plant Biostimulants

Minerals, chemical compounds, and growth-promoting hormones (phytohormones) are all found in seaweed*Gracilaria sp*. and *Sargassum sp*. are the seaweeds that are typically utilized as source materials for organic fertilizers. These two macroalgae are now recognized as biostimulant plants that can boost crop yields by increasing plant growth and nutrients. Giberellin, auxins, and cytokinins are among the phytohormones found in it. While *Gracilaria*contains 10–47% protein, which can enhance organic compounds to stimulate plant growth, brown seaweeds, such as *Sargassum* are rich in alginate and fucoidan, which can stimulate plant root growth (Sedayu *et al.,* 2014). Organic fertilizer may stop land degradation and is good for the environment. There are two categories of organic fertilizer: liquid and solid.We can use the benefits of liquid organic fertilizer by simultaneously applying it to the roots and plants.

As a result, it can maintain soil moisture. Plants may absorb nutrients more easily with liquid organic fertilizer, which promotes plant growth. Because liquid organic fertilizer is 100% soluble, it is dispersed efficiently. Due to their high nutrient content and plant growth hormone, *Gracilaria sp*. and *Sargassum sp*. have the potential to be used as source materials for liquid organic fertilizer. *Gracilariasp*in contains 144 ppm auxin, 1,552 ppm gibberellin, and cytokinins, which include 65 ppm kinetin and 81 ppm zeatin. *Sargassum* also contains plant growth hormones, such as auxin (148 ppm), gibberellin (160 ppm), and cytokinins (71 ppm kinetin and 86 ppm zeatin). With auxin values of 130 ppm, gibberellin of 122 ppm, and cytokines of 61 ppm kinetin and 67 ppm zeatin, the growth hormone value is greater than that of commercial organic fertilizer (Raj *et al.,* 2018). The combination of seaweed *Gracilaria sp*. and *Sargassum sp*. through a fermentation process that is accelerated by bio activators from *Trichoderma sp*. and *Azospirillum sp*. A class of fungi called *Trichoderma sp*. controls pests and plant diseases in addition to breaking down organic debris. *Azospirillum sp.* is one aerobic bacterium that can increase nitrogen levels and establish relationships with plants. *Azospirillum sp.* can break down nitrogen in higher plants, including seaweed. In order to determine the characteristics of organic fertilizer created from different seaweed raw material compositions, this study compares *Gracilariasp*. and *Sargassum sp.* Liquid organic fertilizer formulations with different types of seaweed treatment have an impact on the amount of N, P, K, C organic, pH, and sensory testing (colour and aroma) of liquid organic fertilizers made to achieve the best attributes(Thaha*et al.,* 2020).

A 12-PR/400 series 8B furnace (Hobersal, Barcelona, Spain) equipped with a temperature programmer was used to carry out the biochar production pyrolysis. For each biochar, 200g of beach-cast seaweed was put in a 20-cm-diameter stainless-steel receptacle and added to the furnace. The temperature was raised at a rate of 3°C per minute until the required pyrolysis temperature was attained. Tests were conducted at two temperatures (300 and 600°C) and two residence times (1 and 3 hours). Before being characterized, the beach-cast seaweed and the resulting BCs were sieved to a size of 2 mm. (Ciesielski *et al.,* 1997)

XIX. Biochar Production From Sustainable Biomass: Applications In Chromium Remediation

Most biochar is made from terrestrial ligno-cellulosic feedstocks, or "woody" plants, which create biochar with a high fixed carbon content (usually more than 70%) but poor direct nutritional value.

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On the other hand, it has recently been shown that seaweed may be used to make biochar, which has a number of distinctive qualities for use in a variety of industries (Bird *et al.,* 2011). Compared to ligno-cellulosic feedstock, seaweed frequently produces larger amounts of biochar. Although seaweed biochar typically has a lower carbon content than ligno-cellulosic biochar, it has a higher exchangeable nutrient content and Cation Exchange Capacity (CEC)2. Because of its high CEC, seaweed biochar is excellent at retaining nutrients in agricultural soils. It also turns seaweed charcoal into an effective metal biosorbent from waste water effluents. After that, it can be modified to increase its affinity for problematic oxyanionic pollutants, such as selenium (Se), which would normally have a low affinity for passive biosorbents (Roberts *et al.,* 2015). Although seaweed biochar has several applications, few studies have looked at the production of biochar from a range of seaweed feedstocks. Studies on seaweed biochar have concentrated on seaweeds from non-commercial sources and bioremediation methods; seaweeds cultivated commercially will need to be converted in order to make seaweed biochar on a large scale (Kidgell*et al.,* 2014).

The importance of underutilized biomass sources for the manufacture of biochar, such as invasive plant species, forestry products, and agricultural wastes, has been highlighted by research. A very invasive species of global importance is *Partheniumhysterophorus*. It is a poisonous weed that reduces biodiversity, causes significant agricultural losses, and poses health risks to people and animals. Its low economic worth and quick growth make it a perfect choice for conversion into charcoal. *Parthenium* environmental impact is reduced and a sustainable adsorbent material is produced by turning it into biochar. Research has shown that different types of biochar can use surface complication, ion exchange, and electrostatic attraction to sequester harmful metals like lead (Bashar *et al.,* 2021).

Globally, the effectiveness of Cr removal treatment systems varies and is negligible (Kosek *et al.,* 2020). Inadequately treated wastewater is a major factor in the leather industry's struggle to achieve green and sustainable development. Cr concentration has already been subject to a strict quality standard. For example, the maximum amount of Cr that can be found in drinking water is 0.05 mg/L, while the amount of Cr that should be released into bodies of water is 50 mg/L (Aigbe and Osibote 2020). Therefore, it is morally and legally essential to remove Cr from wastewater in order to prevent damage of the environment and public health. However, the traditional wastewater treatment plant's performance for removing Cr is still difficult and inefficient.

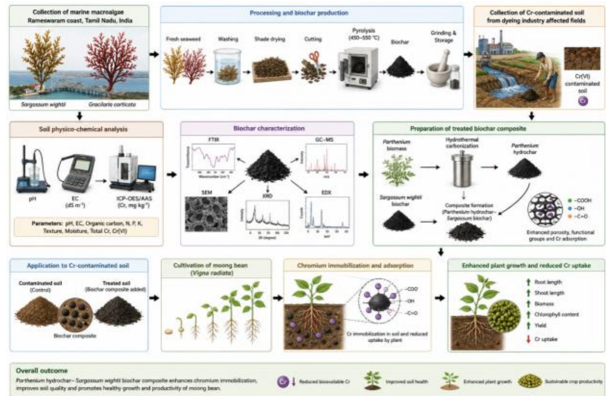

Fig: 2 Characterizations, and Application of Treated Seaweed Biochar for Chromium-Contaminated Agricultural Soil Remediation

Potential mechanism of heavy metal remediation by biochar

Because of its porous architecture, wide surface areas, and functional groups, biochar is an excellent sorbent or amendment for heavy metals in polluted soil(Feng and Zhu 2018).Changing the pH of the soil to promote or induce ionic exchange, surface adsorption, and potential precipitation, as well as generally enhancing soil characteristics, can explain the mechanistic pathways for metal immobilization using biochar. Because micromesopores are widely distributed, biochar is also said to have an adequate surface area. According to, the capacity of surface area and surface sites on which metals can swiftly adhere increases with the number of microspores. Additionally, the elimination of Cr is due to biochar capacity to complex and interact electrostatically with heavy metals (Li *et al.,*2017)

XX. Improvement Of Soil Physicochemical Properties Of Biochar

When added to soil, biochar can enhance its physicochemical characteristics because of its alkaline nature. Biochar is an effective soil supplement that is crucial to the cleanup of soils contaminated with heavy metals. In real-world applications, its alkalinity aids in raising soil pH levels, reducing soil acidification and fostering a plant-friendly growth environment (Dong *et al.,* 2024). Furthermore, biocharplethora of functional groups and porous structure improve the soil's ability to absorb and retain nutrients, lowering nutrient loss. When used properly, biochar potent water-retention capacity can also improve the soil's capacity to hold water, reducing drought stress and guaranteeing enough hydration for plant growth (Edwin *et al.,* 2024).

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XXI. Risk Of Chromium To Human Health From Chromium-Contaminated Agricultural Soil

The permanence, mobility, and toxic consequences of chromium pollution in agricultural soil have made it a significant environmental and public health concern. Hexavalent chromium [Cr (VI)] is the more mobile, highly soluble, and poisonous of the two main oxidation states compared to trivalent chromium [Cr(III)]. Chromium can enter food crops through agricultural soils contaminated by industrial processes such leather tanning, electroplating, textile dyeing, mining, and metal processing, causing major health concerns to people through the food chain. Oxidative stress, DNA damage, cellular apoptosis, and disruption of regular metabolic processes have all been linked to long-term exposure to Cr(VI) through contaminated food, drinking water, soil particles, or inhalation. Long-term chromium exposure raises the risk of lung, stomach, and gastrointestinal malignancies, liver and kidney malfunction, respiratory conditions, skin lesions, immune system damage, and reproductive toxicity, according to epidemiological research. The chemical form, concentration, length of exposure, and individual physiological characteristics like age, gender, and nutritional status all affect how harmful chromium is. The United States Environmental Protection Agency (USEPA), the World Health Organization (WHO), and the Agency for Toxic Substances and Disease Registry (ATSDR) are among the international organizations that acknowledge Cr(VI) as a human carcinogen and have set guideline values to reduce human exposure. Therefore, in order to lower the dangers to human health, guarantee food safety, and encourage sustainable agricultural output, chromium-contaminated agricultural soils must be effectively remedied (Zhang *et al.,* 2014).

XXII. Effects Of Seaweed Biochar And Partheniumbiochar On Chromium-Contaminated Agricultural Soil

In each pot, 1 kg of contaminated soil was well mixed with BC300, BC400, BC500, BC600 and BC700 at varying doses of 0, 5, 10, 20, and 30 g kg-1. The biochar dosage group served as the control group. To maintain the soil field water capacity, a suitable quantity of distilled water was added to each pot. Each pot was filled with forty rye seeds following two weeks of balancing. Twenty seedlings with the same growth state were maintained in each pot after the seeds were trimmed one week after emergence.Throughout the time, the soil field water capacity remained constant. Under natural light, the experimental temperature was kept between 10 and 25°C. Destructive samples were collected after 30 days of plant growth in order to identify the physiological markers of plant growth. Every treatment group underwent three repetitions (Beesley *et al.,* 2011).

XXIII. Role Of Seaweed Biochar In Enhancing Plant Growth Under Chromium Contamination

The impact of biochar on the fresh weight of rye roots and leaves. As the amount of *Enteromorphaporifera*biochar grew, so did the fresh weight of rye. The fresh weight of the leaf and root increased by 53.5–65.8% and 71.6–96.3%, respectively, when the dose of biochar was 30 g kg-1. The explanation could be that chromium stress hindered rye's metabolism and decreased biomass, whereas the addition of biochar reduced chromium stress and increased biomass; the impact was more pronounced the more biochar was added. Furthermore, it was more evident that biochar promoted root growth than leaf growth. This could be due to the fact that the roots had a certain trapping effect on chromium, which decreased the transfer of chromium to the leaves. When biochar was added to the soil, chromium was reduced and fixed, relieving the roots of chromium stress. Out of all the types of biochar, BC400 and BC600 boosted rye biomass the greatest and lessened the impact of the soil heavy metal chromium on rye development (Sizmur *et al.,* 2017).The use of Enteromorpha prolifera charcoal boosted chlorophyll a and chlorophyll b levels in rye under chromium stress. The maximum chlorophyll levels were seen at 30 g kg^{-1}, with BC400 demonstrating the largest improvement, followed by BC600. These findings show that biochar substantially reduced chromium toxicity and improved photosynthetic activity in rye plants (Kalinke *et al.,* 2017).

XXIV. Chromium In Industrial Effluents Environmental Risks And Remediation Approaches

Waste streams from a variety of industries, including mining, metal cleaning, plating, dyeing, and metal processing, frequently contain chromium, a hazardous heavy metal. The highest permissible limit for total chromium is 0.05 mg/L, under the World Health Organization's (WHO) drinking water recommendations (Mohammed*et al.,* 2024). The most common type of chromium in natural water is trivalent chromium. Hexavalent chromium pollution is almost entirely caused by human activity. Compared to trivalent chromium, hexavalent chromium is more poisonous, mobile, and an immediate carcinogen.

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In order to reduce water pollution, hexavalent chromium is therefore more crucial than trivalent chromium. Finding workable economic and environmental solutions that enable maintaining the levels of this polluting agent in the allowable range becomes essential when one considers the need to lessen the detrimental effects on the environment caused by residuals contaminated with chromium (VI) and their potential effects on public health. From an economic and energy consumption perspective, the conventional physico-chemical methods of removing heavy metals from liquid effluents-such as chemical precipitation, electrochemical oxidation reduction, and treatments-are typically not feasible, particularly when the concentrations of heavy metals are low. Because of this, the viability of using the biosorption technique to extract heavy metals from industrial effluents is examined (Zeffa *et al.,* 2019).

TABLE-2 EFFECT OF *ENTEROMORPHAPROLIFERA* BIOCHAR ON CHLOROPHYLL CONTENT OF RYE UNDER CHROMIUM STRESS

S.No	Treatment	Biochar Dose (g/ kg⁻¹)	Chlorophyll a	Chlorophyll b	Overall Effect
1.	Control	0	Lowest	Lowest	High Cr stress
2.	Biochar	10–20	Moderate	Moderate	Improved growth
3.	Biochar	30	**4.9–7.7**	**1.7–2.0**	Maximum effect
4.	BC400	30	**4.4–6.7**	Increased	Best performance
5.	BC600	30	**3.5–5.6**	Increased	High performance

XXV. CONCLUSION

Parthenium-derived and seaweed-derived biochar are sustainable, low-cost, and ecologically benign materials with high potential for chromium remediation in agricultural soils. Their distinct physicochemical features, such as high surface area, numerous functional groups, porous structure, and mineral-rich composition, improve chromium immobilization, soil fertility, and promote green gram development and productivity (*Vigna radiata*). The combination of *Parthenium* and seaweed biochar is a viable technique for converting invasive and marine biomass into value-added products while also promoting sustainable agriculture and environmental preservation. However, more research is needed to optimize biochar production settings, understand the long-term mechanisms of chromium stabilization, and test the efficacy of *Parthenium*-modified seaweed biochar under field circumstances in order to ease its widespread agricultural application.

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