© April 2026 | IJIRT | Volume 12 Issue 11 | ISSN: 2349-6002

Influence Of Sugarcane Bagasse as Bio-Absorbent on Remediation of Cadmium Poisoning in Aquatic Ecosystems

Preema Pradeep
Christ University, Bengaluru, Karnataka

***Abstract*—Heavy metal pollution, particularly Cadmium contmination in aquatic ecosystem has significant environmental and public health impact due to cadmium toxicity, their persistance in environment and ability to bioaccumulate in aquatic organisms and higher food chain. Effective and sustainable methods for the removal of cadmium from aquatic ecosystem are thus important as traditional methods such as chemical precipitation, ion exchange and filtrations are often costly and generated large amount of secondary wastes. This study investigates the influence of sugarcane bagasse biochar as a bio-absorbent for the cadmium metal remediation from aquatic ecosystem. The absorption potential of sugarcane bagasse biochar which is a modified form of bagasse was eveluated to understand their effectiveness in metal removal. Results indicate that biochar exhibits a high affinity for cadmium ions particularly when the biochar concentartion is higher as the surface area for absorption increases. This study highlights the benefits of utilizing sugarcane bagasse: as a sustainable and eco-friendly solution for reducing heavy metal pollution, adding value to agricultural wastes by converting them to functioning material.**

***Index Terms*—Cadmium contamination, aquatic ecosystem, sugarcane bagasse biochar, bio-absorbent, eco-friendly solution**

I. INTRODUCTION

Human activities contaminating aquatic ecosystems are a rising concern worldwide. Contamination leads to degradation of water quality and the spread of infectious diseases. Urbanization, industrialization, and agriculture are the primary reasons [1]. Heavy metals (Cadmium, mercury, lead), radioactive elements (strontium, cesium), industrial solvents (tri- and tetrachloroethylene, chlorofluorocarbons, benzene, xylene, formaldehyde), detergents, microfibers, plastics, agrochemicals (fertilizers and pesticides), and pharmaceuticals are among the wide range of contaminants that can pollute aquatic ecosystems which can even pose significant threats to human health and many productive activities [2], [3]. Both natural and anthropogenic activities cause the heavy metals to enter the aquatic ecosystem. Contamination can be directly through discharge or indirectly through atmospheric deposition or surface runoff. Volcanic activities and weathering of rocks are important natural sources of heavy metals as these are the natural constituents of rocks and salts. Slow leaching of metals from rocks and soils at low levels does not lead to any serious lethal effect on aquatic health [4]. The sharp rise in heavy metal pollution is mainly due to industry and agricultural practices which leads to the deposition of high levels of mercury, chromium, lead, cadmium, copper, zinc nickel, etc. Arsenic, cadmium, copper, mercury, and zinc have the most potential impact due to their high toxicity and persistence in the aquatic ecosystem [5]. Fertilizers are the major source of zinc and copper whereas arsenic, cadmium, and mercury are components of some fungicides and algaecides. The ecological significance of heavy metals is high as they are not removed from the water and also enter the food chain [6], [7]. At higher levels, the toxicity of metals can have harmful effects that interfere with the normal functioning of an organism. In lesser quantities, metals like Cu, Zn, Fe, Mn, Ca, Mg, Na, P, and S are necessary for the growth and survival of species. The toxicity brought on by non-essential metals like Cd, Hg, Cr, Pb, and As is extremely lethal even at lower concentrations[8]. Furthermore, aquatic species and invertebrates absorb these metal toxins, which have a variety of biological consequences, prolonged persistence, ability to accumulate in organisms, and their magnification in the food chain are attributed to toxicity[9], [10].

Cadmium is a non-essential heavy metal that is known to be extremely hazardous and carcinogenic to aquatic biota. 10% of total cadmium is derived from natural sources and 90% through anthropogenic activities, contributing to their entry into the food chain[11]. Cadmium is considered a xenobiotic due to its persistent and non-biodegradable nature in the aquatic ecosystem. It acts as a mitogen thus promoting cancer in many tissues by stimulating cell proliferation, inhibition in DNA repair, and apoptosis. Various structural and pathomorphological alterations in the organs primarily cause cadmium poisoning. Cadmium poses a significant health risk to humans. Cd toxicity can lead to multiple health problems, including renal toxicity, reproductive and fertility issues, and potential links to human diseases. Cd can enter the human body through inhalation or ingestion, and it can accumulate in the kidneys and liver. Monitoring human populations for early markers of Cd toxicity is crucial, as it can help identify and address potential health problems related to Cd exposure. Researchers have also explored new potential human health problems associated with Cd toxicity[12] [13]

Fishes absorb cadmium through gills, intestine, and transcutaneous uptake (skin). Fish livers and kidneys acquire large amounts of cadmium[14]. Recent studies on acute cadmium poisoning showed significant toxicity on major sites such as gill lamellae and kidney tubule in seabass (*Dicentrarchus labraxescens*). In the case of sub-chronic poisoning, the primarily affected organs appear to be the kidney and liver, and to a lesser extent in the gills[14], [15]. Cadmium induces cell death leading to kidney tissue damage thus affecting renal function at lower concentrations Cd causes apoptosis and in higher concentrations necrosis becomes evident. Fish absorb cadmium through various pathways, with the ionic form Cd (II) being the most common. Absorption through gills happens by passive diffusion or carrier-mediated transport while in the intestine occurs through endocytosis. Calcium channels may facilitate the entry of cadmium ions into chloride cells in the gills. Interaction with other metals, such as zinc, can increase the toxicity of water bodies. Higher calcium concentration may reduce cadmium toxicity by interacting with Cd^{2+} and minimizing its adverse effects [16]. It also exerts deleterious effects like nephrotoxic, cytotoxic, genotoxic, and immunotoxin. Cadmium enters the electron transport chain in mitochondria, leading to the production of superoxide radicals. Antioxidant enzymes such as SOD and CAT, which are involved in removing iron and copper from proteins, are impacted by cadmium exposure. Glutathione (GSH) levels in fish may vary based on factors such as fish species, duration of exposure, and specific chemicals involved [17]. According to a study by Kumar et al. from 2005, cadmium accumulates in carp tissues (*Cyprinus carpio*) in the following order: kidney, liver, and gills[18]. High levels of cadmium can accumulate in these tissues without immediate negative effects. Cadmium accumulation in tissues, especially the liver and kidney, can lead to pathological changes and may experience congestion, vascular hepatocyte degeneration, pancreatic cell necrosis, and altered peripancreatic lipids. The content of sex hormones in fish serum can be affected by sterol synthesis inhibition [19]. Damage to genesis and maturation of germ cells, reduction in sperm mobility, sperm count, and estrogen receptor expression [20], [21]. Zebrafish is a model animal that has been widely used in toxicity assessment. It was shown that, after the zebrafish were exposed to Cd solution, the gonad somatic index of the ovary and seminal gland significantly decreased. Cd mainly causes developmental abnormalities in zebrafish embryos [22].

In contemporary scenarios, a myriad of physicochemical and biological techniques has been employed for metal remediation. Despite their efficacy in mitigating metal pollution, certain conventional treatment technologies like chemical precipitation, electrochemical separation, membrane separation, reverse osmosis, ion exchange, and adsorption resins face limitations in terms of commercial feasibility [18]. Chemical precipitation involves adding chemicals (lime, sulphides) thus forming insoluble precipitates with metal ions which can be removed by filtration or sedimentation [23], [24]. Ion exchange relies on resin-based materials that bind to metal ions. This method is highly efficient for removing metals at trace levels and the possibility of metal recovery [24], [25]. Reverse osmosis is a type of membrane filtration process that separates dissolved metals by forcing through a semi-permeable membrane. However, this method is highly energy-intensive and has problems with membrane fouling thus reducing its efficiency [26]. Electrochemical treatment includes electrocoagulation, electrodeposition, and electro flotation using anodic and cathodic reactions[27], [28]. The addition of coagulants will stimulate the coalescence of colloidal material into smaller aggregates which under gentle agitation settle and are disposed of as sludge[29] [30]. Traditional methods have proven effective in certain situations, but they come with high operational costs, and inefficiencies at low concentration levels, and can lead to secondary pollution thus a large generation of harmful sludges. Such methods also involve large capital and are not effective in removing metal ions present in ppm levels [31]. These issues highlight the urgent need to explore new, sustainable, and environmentally friendly solutions. By utilizing more economical techniques, biosorption offers a workable and long-lasting solution for dealing with metal contamination in a range of industrial contexts. The trend toward utilizing commercially viable substitutes highlights the significance of maintaining an equilibrium between practical economic factors and ecological sustainability when searching for efficient metal removal techniques [32]. More advanced and recently developed treatment methods include adsorption (activated Carbon, polymeric materials, agricultural residue, industrial wastes, magnetic adsorbent), microbial fuel cells, nanotechnology, nanoparticles, and plant-mediated remediation of heavy metals [33]. Biosorption in cleaning metal pollution has attained considerable attention worldwide [34]. The inactive and non-living substances of biological origin assist in biosorption by absorbing metal ions from the aqueous solution even in very high or very dilute complex solutions. The biosorption process operated at a wide range of temperatures and pH, along with the low cost, the potential for regeneration of biosorbents, and minimum generation of toxic sludges have made it an environment-friendly approach in remediation. The surface property of biosorbent leads to the uptake of metal ions [35]. The biosorbents studied to date fall under two major classes: microbial-based and plant-based biomass. Plant-based biomass comes under the agricultural residues composed of hemicellulose, cellulose, lignin, and starch which aids in the adsorption capacity. Using biosorbents in their natural form has disadvantages related to low biosorption capacity and physical instability. These biosorbents can be modified to enhance their adsorption capacity and adaptability [36], [37]. The methods used for modification include physical pre-treatments such as heating, boiling, freezing, thawing, drying, autoclaving, and lyophilization. Various workers have identified several chemical treatments used for surface modification. These treatments include washing with detergents and alkaline solutions such as sodium hydroxide, calcium hydroxide, and sodium carbonate. Additionally, mineral and organic acid solutions are utilized, including hydrochloric acid, nitric acid, sulfuric acid, tartaric acid, citric acid, and thioglycolic acid. Other treatments involve organic compounds like ethylenediamine, formaldehyde, epichlorohydrin, and methanol, as well as the oxidizing agent hydrogen peroxide. Amination of the hydroxyl and carboxyl groups, carboxylation and phosphorylation of the hydroxyl group, saponification of the ester group, sulfonation, xanthanation, halogenation, oxidation, and other processes enhance biosorption efficiency [38]. Agricultural wastes like rice/ wheat husk, bran, fruit or vegetables, soybean hulls, sawdust of various trees, etc have shown great adsorption potential for heavy metal ions like Cd (II), Cu (II), Cr (III), Cr (VI), Pb (II), Hg (II), Zn (II). Physical, chemical, and ionic processes are involved in the sorption mechanism. Their adsorption processes are effective due to the involvement of different specific mechanisms like absorption, acid-base interaction, chelation, diffusion, and hydrogen bonding. Ion-exchange, hydrophobic interaction, electrostatic attraction, etc [34]. The metal ions undergo ionization, and there is a change in the solubility of the pH of the solution. Protonation and deprotonation occur in the biomass's functional groups due to changes in the acidity or basicity of the aqueous medium. The solubility of metal ions decreases due to an increase in pH thus resulting in precipitation. Irrespective of the biomass type and source, the maximum biosorption occurs depending on the speciation of the metal ions at that particular pH. Ni(II), Cd(II), Pb(II), and Zn(II) occur in their bivalent form at a pH greater than 6.5 [35] [39].

Bagasse composed of lignin, pentose, and cellulose, is an agricultural solid waste from the sugar industry. The presence of different functional groups such as carboxylic, carbonyl, amino and hydroxyl helps in metal binding by cation exchange on the absorption site of biosorbent [40]. Sugarcane bagasse, a fibrous residue that remains after the crushing and extraction of juice from sugarcane stalks, is a cost-effective and widely available agro-industrial residue found in tropical regions, produced in large quantities as a by-product of sugar and bioethanol mills [41]. Cellulose, hemicellulose, lignin, ash, and a small amount of extractives form the sugarcane bagasse constituent. Sugarcane bagasse can efficiently remove a wide range of substances like toxic heavy metals, dyes [42], petroleum [43], phenolic compounds [44]and organic nutrients [45]. The unique functional group of bagasse helps bind metal ions to their surface. The sorption efficiency depends on the dosage, pollutant concentration, solution pH and temperature, contact time, and sorbent particle size [46]. The lignocellulosic matter of bagasse because of its numerous and varied functional groups (-OH, -COOH, $-NH_2$, $-CONH_2$, $-SH_2$, and $-OCH_3$) acts as a binding site. These binding sites attract metal ions either by replacing them with hydrogen ions, adsorption, or by donating electron pairs. The presence of these unique binding sites and high levels of silica make sugarcane bagasse and its derivatives effective at removing contaminants [43], [47]. The morphological organization of the sugarcane bagasse also contributes to their biosorption capacity. Sugarcane bagasse shows irregular structure and different levels of porosity which helps in their easy treatment and modification [48]. Both raw and modified forms of sugarcane bagasse can be used for the biosorption process. Sugarcane bagasse can be utilized in three main forms: raw bagasse, bagasse fly ash and bagasse-based activated carbon. Raw bagasse is used as a biosorbent without any chemical or physical treatments therefore is environmentally friendly. Sugarcane bagasse-based activated carbon and bagasse fly ash actively absorb various heavy metals, dyes, phenolic compounds, herbicides, and pesticides [46]. Many studies have revealed activated carbon as a more effective biosorbent than ash or raw sugarcane bagasse. Therefore, the present study aimed to provide a new solution for the remediation of metal contamination can potentially be provided by the use of biochar, a highly stable carbon-rich substance produced by several thermochemical methods of sugarcane bagasse. These methods include pyrolysis , gasification, hydrothermal carbonization, and torrefaction [49]. Key properties of biochar that enhance biosorption include high pH, cation exchange capacity, porous texture, large surface area, and active functional groups [50]. This research also aims to use sugarcane bagasse biochar as a cheap, environmentally friendly bioremediation agent and define methods for the remediation of cadmium metal contaminants from water solutions. The biochar's conversion rates are ascertained along with the physicochemical characteristics and morphology of the generated biochar.

II. OBJECTIVES

1. Identification and characterization of plant-based waste source as bio-adsorbent, i.e., Sugarcane bagasse
2. Production of char from the bagasse biomass to enhance the chelation.
3. Application of bio adsorbent into the artificial aquatic system and its toxicology studies.

III. REVIEW OF LITERATURE

Heavy metal pollution in aquatic habitats has a negative impact on organism health and biodiversity, making its repair a serious environmental concern. Cadmium (Cd) contamination is extremely hazardous due to its toxicity and persistence. In recent years, there has been an increasing interest in the efficient removal of heavy metals from contaminated water bodies using bio-absorbents derived from agricultural waste products. Sugarcane bagasse, a by-product of the sugar industry, has demonstrated significant potential as a bio-absorbent due to its abundance, high adsorption capacity, and cost [32].

In the modern world, water quality has become a significant concern. Various metals that contaminate water can be harmful and are dispersed through different pathways to various locations. The primary cause of water contamination is the rapid expansion and industrialization resulting from the growing global population. Increased concentrations of heavy metals and metalloids in lakes, rivers, groundwater, and other water sources are caused by several factors, including the discharge of mine tailings, the improper disposal of high-metal waste, the expansion of industrial areas, the use of leaded petrol and paints, fertilizers, animal manure, e-waste, sewage sludge, pesticides, wastewater irrigation, and coal. Exposure to heavy metals can lead to both chronic and acute toxicity.

Health issues associated with heavy metal exposure include developmental retardation, neurotoxicity, kidney damage, various types of cancer, liver and lung harm, and brittle bones. In extreme cases, exposure can even be fatal. [51].

Because of their extreme toxicity, persistence, and susceptibility to build over time, heavy metals are acknowledged as possible environmental toxicants. The weathering of metal-bearing rocks, volcanic eruptions, and human activities including mining, agriculture, industrial processes, and the extraction of minerals and metals are the main causes of heavy metal pollution in the environment. Among these sources, mining and agriculture are anthropogenic—that is, the products of human activity—while volcanic eruptions and rock weathering are natural occurrences. Due to these human activities, biogeochemical cycles are disrupted and heavy metals are transported into the environment. Heavy metal pollution of aquatic ecosystems can have detrimental consequences on human health and the environment. Heavy metals can build up in ecosystems and then make their way into food chains, which can lead to additional ecological and health issues because they are persistent toxicants [52].

The most dangerous metals and metalloids that have a negative impact on the aquatic ecosystem are Ni, Zn, Pb, Cr, Cu, Hg, As, Cd, and so on. They have the potential to negatively affect the aquatic ecosystem, particularly fish, and they also have a significant impact on the hydrological, geological, and eventually biological cycles. Retarded growth, physical abnormalities, decreased survival, and the extinction of aquatic plants and animals are all toxic impacts of heavy metals. Environmental scientists must assess and monitor the content of potentially harmful metals in aquatic resident biota because these heavy metals are tropically transported in flora and fauna through food chains and food webs [53].

Cadmium is extensively utilized in industries such as electroplating, batteries, television manufacturing, ceramics, photography, insecticides, electronics, metal finishing, and metallurgy. According to Hutchinson (1987), cadmium enters the environment through processes such as metal ore refining, using cadmium-containing pigments and alloys, and applying cadmium-containing phosphate fertilizers, among others. [54]. The toxic effects of cadmium are widespread in developing countries such as India. According to Atchinson et al. (1987), Al-Sabti (1986), and Crump and Trudeau (2009), cadmium is known to cause neurotoxic, genotoxic, and endocrinological effects in fish. Increased exposure to cadmium can cause a wide change in the ecological community and destroy fish species [55], [56], [57]. Fish is a major source of protein in many parts of the world. Therefore, heavy metal pollution in freshwater ecosystems is a significant concern for human health and the economy [58]. Many organs in fish tend to absorb heavy metals due to their affinity for these compounds. During this process, different heavy metals accumulate in various organs at different levels. The phenomenon known as "bioaccumulation" occurs when a chemical substance builds up in an organism at concentrations greater than what is found in its diet or environment. Several factors influence bioaccumulation, including elemental speciation, methods of active and passive absorption, tissue distribution and transit, growth dilution, and excretion [59], [60].

The absorption of nonessential trace elements by organisms is often related to the competitive uptake of similar nutrient ions and is highly dependent on their bioavailability. Bioavailability refers to the extent to which a metal can enter and impact a biological system. The most bioavailable—and therefore the most toxic—form of cadmium is the divalent ion. Exposure to this form triggers the production of a low molecular weight protein known as metallothionein, which can bind with cadmium and reduce its toxicity. This process typically occurs in the liver of both fish and humans. However, if the concentration of cadmium is too high, the metallothionein detoxification system can become overwhelmed, leaving excess cadmium available to cause toxic effects [61]. Bioaccumulation of cadmium can be through direct (contaminated medium exposure or consumption od cadmium-containing food) or indirect exposure. Fish primarily absorb cadmium (Cd) from the water in its free ionic form. They can also be exposed to Cd indirectly through their food when they consume lower trophic level species that have bioaccumulated metals. The gills serve as the main entry point for dissolved metals in freshwater fish. Additionally, the gastrointestinal tract plays a significant role in metal absorption. Metals that have organic ligands are absorbed in the intestine through a process called endocytosis, while metal ions are mainly absorbed either passively or via carrier-mediated transport through the gills. It has been suggested that the calcium channels in the chloride cells of the gills provide a route for Cd ions to enter the fish.

Cadmium is absorbed through the gills or intestinal walls and is then distributed via the bloodstream, bound to transport proteins, to various tissues in the body[62]. Once inside the body, cadmium (Cd) encounters various cytoplasmic elements, including enzymes and metallothioneins (MTs), which can lead to toxic effects. MTs are a group of small metal-binding proteins that play a critical role in cadmium metabolism, especially in its transport, detoxification, and storage. After absorption, cadmium binds to albumin and is transported to the liver [63]. Once processed in the liver, the cadmium bound to MTs is released into the plasma and carried into the glomerular filtrate. In the renal tubule, reabsorbed cells allow the Cd-MT complex to enter lysosomes. This facilitates the release of cadmium from the complex, allowing it to return to the tubular fluid for excretion in urine. Bioaccumulation—resulting from the balance of uptake, storage, and elimination—varies across different trophic levels[64].

Nakayama et al. (2013) demonstrate that, compared to many other fish species, such as Serranochromis thumbergi, cadmium is relatively poorly accumulated in their tissues and is generally negatively correlated with trophic level. However, Croteau et al. (2005) indicate that despite lower tissue accumulation, the toxic effects of cadmium may increase with higher trophic position, revealing intricate dynamics in cadmium toxicity [65]. Cadmium exposure in fish disrupts various metabolic substrates, including glucose, glycogen, lactate, lipids, and proteins, as well as enzymes involved in protein metabolism [66]. Carp that were exposed to cadmium showed increased activities of glutamate aminoacyl transferase and alanine amino acyltransferase in their gills, liver, and kidneys, according to De Smet and Blust (2001) [67].

Environmental toxins harm fish behaviour, growth, and reproduction, with heavy metals like cadmium being particularly influential. These metals disrupt hormonal functions, neurotransmitter activity, and cellular processes. These findings underscore the need for effective remediation strategies to minimize cadmium exposure and its ecological and health impacts. According to Das and Banerjee. 1980, “Cadmium toxicity in fishes” air-breathing fish have stronger resistance than non-breathing fish in terms of survival and growth when exposed to a cadmium-containing environment. Though both species exhibit a clear stress response to cadmium exposure, the two anatomically distinct fish respond differently to carbohydrate metabolism, as evidenced by liver and muscle glycogen content, liver microsomal glucose-6-phosphatase activity, and serum glucose levels [68].

There is an increasing need to remove heavy metals from water due to various governmental and international standards designed to protect human health and the environment. These regulations impose limits on the allowable concentrations of heavy metals in drinking water and on their discharge into wastewater, necessitating proper treatment methods to ensure compliance [69]. A range of traditional and modern technologies is employed to remove heavy metals from aquatic ecosystems. Alkaline precipitation, filtration, electrochemical removal, ion exchange columns, and other technologies are used in the removal of heavy metals like cadmium. According to Bethke et al. (2018) and Kumar et al. (2021a), conventional treatment methods have several drawbacks, including the generation of hazardous sludge, high energy requirements, and inadequate removal effectiveness. Additionally, the technical and financial demands for installation, operation, and maintenance can pose significant challenges, often leading to the underutilization of these technologies, particularly in developing countries and decentralized settings. Therefore, there is a pressing need for solutions that are both efficient and environmentally friendly. Examples of such solutions include biological methods, nanotechnology, and biopolymer-based adsorption techniques [70], [71].

Bio adsorbents are gaining considerable popularity due to their eco-friendly approaches, broad applicability and improved functional and surface characteristics. The improved properties of modified adsorbents enhance their capacity to adsorb substances. Various mechanisms contribute to the removal process of biosorbents, including adsorption, ion exchange, chelation, surface precipitation, microbial absorption, physical entrapment, biodegradation, redox reactions, and electrostatic interactions. The specific biosorbent used and the type of pollutant being targeted can sometimes determine which mechanisms are employed. [72].

The methods by which sugarcane bagasse adsorbs heavy metals—especially cadmium—have been thoroughly studied in the literature in recent years. The adsorption capacity of sugarcane bagasse for heavy metals is mostly determined by its intrinsic properties, which include its porous structure and the presence of particular functional group [73].The porous structure of sugarcane bagasse increases its surface area and offers plenty of locations for metal binding. Because the material is porous, cadmium ions can more easily diffuse into the bagasse's interior structure, which enhances the effectiveness of adsorption. Its surface contains several functional groups, which are primarily responsible for its adsorption capabilities. Among the notable functional groups found in sugarcane bagasse are hydroxyl (OH), carboxyl (COOH), and phenolic moieties. These functional groups have active sites that can combine with cadmium ions to form complexes via electrostatic interactions, coordination, and ion exchange [74]. Research has indicated that the pH of the solution tends to affect the adsorption efficiency, An increase in the pH of the solution did not lead to an increase in the biomass removal efficiency of Cd(II) [32]. The initial concentration of cadmium in the solution and the contact time between the adsorbent and the metal ions are crucial parameters in determining adsorption efficiency. Studies have explored the adsorption kinetics and equilibrium isotherms to understand the relationship between initial metal concentration, contact time, and the overall adsorption process.

By optimizing pH and temperature conditions, researchers have been able to achieve maximum cadmium removal efficiency using sugarcane bagasse as a bio-absorbent. These results highlight how crucial it is to comprehend how environmental factors affect the adsorption process and offer insightful information for the creation of successful cadmium clean-up plans in aquatic environments. Studies have continuously demonstrated how well sugarcane bagasse extracts cadmium from aqueous solutions. Pseudo-second-order kinetics are generally followed by the adsorption process, suggesting that chemisorption is the main mechanism controlling cadmium uptake onto sugarcane bagasse surfaces. This implies that the active spots on the bio-absorbent material and cadmium ions have a robust chemical interaction [75]. Compared to a variety of other materials, sugarcane bagasse biochar has shown to be a very promising adsorbent for the removal of cadmium because of its porous structure and abundance of surface functional groups. Moubarik and Grimi (2015) observed a maximum capacity for removing Cd (II) of 96% when using sugarcane bagasse. This removal occurred at an initial Cd (II) concentration of 10 ppm in an aqueous solution with a pH of 7.0, and it required a contact time of 25 minutes. Karnitz et al. (2010) reported that chemically treated sugarcane bagasse demonstrated impressive adsorption capacities for Cu (II), Cd(II), and Pb(II) ions, achieving maximums of 92.6, 149.0, and 333.0 mg g^{-1}, respectively [76], [77].

Sugarcane bagasse biochar has comparable or greater adsorption capability than activated carbon. Because of its surface chemistry and structural properties, sugarcane bagasse biochar has an even higher potential to adsorb cadmium than biosorbents made from microorganisms or agricultural waste. Furthermore, studies that compare sugarcane bagasse biochar to clay minerals show that biochar has a competitive capacity for adsorbing cadmium, demonstrating the effectiveness of the biochar due to its high surface area and distinct functional groups. Under ideal circumstances, sugarcane bagasse biochar can match the effectiveness of metal oxides, which are recognized for their strong attraction to heavy metal ions. This is because of the synergistic interactions between the physical properties and surface functional groups. All things considered, sugarcane bagasse biochar shows promise as a substitute for conventional adsorbents in cadmium remediation, providing an efficient and long-lasting fix for environmental restoration projects [68], [78]

The practical use of bio-absorbents in heavy metal clean-up is strongly dependent on their regeneration and reusability. To recover the adsorption capability of discarded sugarcane bagasse, several regeneration procedures have been investigated, including thermal, chemical, and biological approaches. Thermal regeneration includes heating the used absorbent to remove adsorbed pollutants, whereas chemical regeneration uses desorbing agents such as acids or bases to liberate deposited metals. Biological regeneration is a newer technique that uses microorganisms to break down or alter absorbed pollutants, regenerating the bio-absorbent. The efficiency of bio-absorbent regeneration procedures is determined by several parameters, including the adsorbent's properties, the type of pollutant, the regeneration agent utilized, and the circumstances such as temperature and regeneration time. Thermal regeneration advantages from higher temperatures, which improve contaminant removal, whereas chemical regeneration provides greater flexibility in desorbing agent choices. Biological regeneration represents a viable route for environmentally benign and cost-effective in-situ remedial methods. Sugarcane bagasse showed acceptable reusability after regeneration, with negligible adsorption capacity loss over numerous cycles. However, the degree of reusability is determined on the regeneration procedure used and the qualities of the pollutants. To maximize the reusability potential of sugarcane bagasse for efficient heavy metal remediation, regeneration techniques must be properly characterized and optimized [79], [80], [81].

Sugarcane biochar's future as a bio adsorbent seems promising, with chances for innovation, integration, and long-term deployment in a variety of environmental remediation applications. Continued study, technological breakthroughs, and interdisciplinary collaborations will be critical in realizing sugarcane biochar's full potential for solving global environmental issues.

IV. MATERIALS AND METHODS

4.1. Materials required

4.1.1.Chemicals required

1) Cadmium chloride
2) Conc. Nitric acid
3) Conc. Hydrochloric acid
4) Distilled water
5) Methylene blue

4.1.2.Glasswares

1) Beakers
2) Glass funnel
3) Conical flask
4) Test tubes
5) Fishbowls
6) Glass rod
7) Petri dishes

4.1.3.Instruments required

1) Electronic weighing machine
2) Hot air oven
3) Muffle furnace
4) Hot plate
5) Atomic Absorption Spectrophotometer

4.1.4.Other materials

1) PP bottle
2) Whatman filter paper
3) Muslin cloth
4) Bagasse sample
5) Fish (Zebrafish)
6) Commercially available feed
7) Dissection kit

4.2. Collection and processing of bagasse

Sugarcane bagasse was collected from a juice shop near Christ University, Bengaluru. The samples were washed with distilled water several times to remove the juicy matter and cut into pieces approximately 5-10 cm long (fig8). These are then oven-dried at 60ºC for 60 minutes and ground into fine powder (fig9).

4.3. Preparation of biochar

Dried bagasse powder was converted into biochar in a laboratory muffle furnace to optimize the pyrolysis condition. Bagasse powder was taken in a crucible and pyrolyzed for 2 hours at 200ºC under oxygen-limited conditions until completely burnt (fig 10). The prepared biochar is passed through the sieve and the course particles are further powdered, and stored in an air-tight container for further analysis [82], [83].

4.4. Characterization of bagasse and biochar[84]

4.4.1.Moisture content:

Moisture content refers to the amount of water present in the sample, typically expressed as a percentage of the sample’s total weight. The sugarcane bagasse sample was weighed before drying (initial weight). Once the temperature is set, sample is placed in the oven (usually around 105°C) by using the following formula the moisture content can be calculated [85]:

$$\text{Moisture Content (\%)} = \frac{\text{initial weight- dry weight}}{\text{Initial weight}} \times 100$$

4.4.2.Biochar yield:

Biochar yield refers to the amount of biochar obtained after pyrolysis of the sugarcane bagasse which is expressed in percentage. The biochar yield was calculated as the mass of the biochar product divided by the mass of the biomass, using the following formula [86]

$$\text{Biochar yield (\%)} = \frac{\text{Mass of biochar} \times 100}{\text{Mass of biomass}}$$

4.4.3.Ash content:

Ash content is the amount of mineral matter left after burning the bagasse material at higher temperature. Ground sugarcane bagasse was weighed in a clean crucible container accurately with and without sample. The ground sample is then placed in a muffle furnace at higher temperature until all the organic matter is combusted. Weigh the remaining sample with crucible. Ash content can be determined by the formula

$$\text{Ash content (\%)} = \frac{\text{Weight of ash}}{\text{Weight of sample}} \times 100$$

4.5. Preparation of metal solution

Cadmium in the form of cadmium chloride in a solution is used as a cadmium source. 0.15 ppm concentration of Cadmium is used for the absorption studies. The water used for the experiment was taken from the aquaculture lab.

4.6. Experimental design

4.6.1.Absorption study:

0.15 ppm concentration of water is added to 4 bowls except for the control (fig11). Sugarcane bagasse biochar (0.1, 0.2, 0.3, 0.4 gm) is added to each bowl (fig12) and the solutions are incubated for 24 hours. The solution is then filtered to remove the biochar from the sample (fig 13). The clear solution is then used for the application purpose. Control is maintained with water taken from the aquaculture lab.

4.6.2.Application study:

Adult Zebra fishes (Danio rerio) were purchased from an aquarium shop. The fish were brought to the laboratory in a polythene bag filled with air. Methylene blue treatment to the fish was done to avoid infection and bacterial growth that could affect their health before transferring to the bowl. Fishes are then kept for acclimatization in a properly aerated tank one week prior to the experiment. All fish were fed with the commercially available pelleted feed daily. After a week the fish were transferred to all the bowls (10 each) (fig15). Mortality in each group was monitored on a daily basis (fig16). The experiment is continued for 96 hours [87].

Dead fish were stored at -120^{o}C in a sealed plastic bag for further analysis.

4.7. Acid digestion

Filtered bagasse biochar was oven-dried to remove the water content (fig14). Dried bagasse biochar and filtered water samples (after absorption study) and fishes were acid digested for the analysis. Fish were dissected and the tissue samples were taken mainly the organs and muscles.

HNO_3 and HCl were taken in the ratio of 3:1 in a beaker and heated in a hotplate (fig 17) until half the volume. 0.5 gm of the samples are added to the boiling acid and heated by continuous stirring to dissolve the sample. The samples are then added to a 10 ml volumetric flask and distilled water is added for dilution (fig 17) [88], [89].

4.8. Analytical measurement

The acid-digested solutions are then analyzed by AAS to determine the cadmium presence in each sample. Interpretation was done using graphical method.

V. RESULT

5.1. Bagasse and Biochar characterization

The experimental findings regarding the characterization of bagasse and biochar are systematically presented in Table 1. The moisture content of the biochar sample was evaluated by subjecting it to drying at a temperature of 105°C, yielding an average moisture content of 62.48±2.5%. This notably high moisture content in the bagasse poses significant challenges for its efficiency in thermal processes, such as pyrolysis. The presence of elevated moisture levels results in the necessity for additional energy to evaporate the water during thermal processing, which ultimately translates to a diminished yield of biochar.

In terms of ash content, which serves as an indicator of the inorganic residue left after the combustion of biomass, sugarcane bagasse exhibited a measured ash content of 8.0±1.7%. This moderate level of ash is generally considered advantageous, particularly for applications involving metal adsorption, making it a useful characteristic for various environmental remediation processes.

When it comes to the conversion efficiency, the biochar yield derived from the pyrolysis of sugarcane bagasse was calculated at 9.693±0.47%. This figure illustrates the overall effectiveness of transforming biomass into biochar. However, this relatively low yield can be predominantly attributed to the high moisture content inherent in the bagasse, emphasizing the need for moisture management in optimizing biochar production.

Table 1: Characterization of bagasse and biochar

S. No	Parameters	Average percentage values (%)	Standard deviation (%)
1	Moisture content	62.48	2.5
2	Ash content	8.0	1.7
3	Biochar yield	9.693	0.47

5.2. Absorption study of sugarcane bagasse biochar

The study investigated the impact of different dosages of bagasse biochar, specifically ranging from 0.1 g to 0.4 g, on the effectiveness of cadmium (Cd) removal from contaminated water sources (table 2). The findings revealed a distinct dose-dependent relationship, highlighting how varying amounts of biochar influence both the adsorption of cadmium and the residual concentration of cadmium found in the filtered water. Illustrated in Fig 1, the data shows that as the dosage of bagasse biochar increases, the amount of cadmium retained by the biochar also rises significantly. At the lowest dosage of 0.1 g (B2), the adsorbed cadmium concentration measured 0.08826 ppm. This amount increased to 0.0969 ppm when the dosage was raised to 0.2 g (B3), further climbing to 0.1197 ppm at 0.3 g (B4), and finally peaking at 0.139 ppm with the maximum dosage of 0.4 g (B5). This progressive increase in cadmium adsorption illustrates that higher biochar dosages provide a greater number of active adsorption sites, enhancing the material’s ability to capture and retain cadmium from the water. Consequently, this research underscores the potential of bagasse biochar as an effective adsorbent for the removal of harmful cadmium contaminants from aquatic environments.

In contrast, Figure 2 provides information on the cadmium concentration in the filtered water following treatment, revealing a clear trend of decreasing levels as the dosage of biochar increases. In the control bowl (B1), which contained only water and no adsorbent, the cadmium concentration was notably low at 0.003755 ppm. This minimal value highlights the inherent limitations of untreated water in removing contaminants. When 0.1 g of biochar was introduced into bowl B2, an unexpected increase in cadmium concentration was observed, rising to 0.05851 ppm. This rise may suggest that the initial addition of biochar was insufficient to effectively adsorb the cadmium ions or could indicate the process of desorption where cadmium ions were released into the water. As the biochar dosage was progressively increased, a significant decrease in cadmium concentration was recorded. At 0.2 g (B3), the cadmium level dropped to 0.04008 ppm, further declining to 0.02699 ppm at 0.3 g (B4). Notably, the most effective treatment occurred at 0.4 g (B5), where the cadmium concentration reached its lowest point at 0.02316 ppm. This outcome strongly suggests that a dosage of 0.4 g is optimal for the efficient removal of cadmium from contaminated water, demonstrating the effectiveness of biochar as an adsorbent in water treatment applications.

The analysis illustrated in the third graph reveals a significant inverse relationship between cadmium adsorption and the residual concentration of cadmium remaining in the water. This outcome further underscores the remarkable effectiveness of bagasse biochar as an adsorbent material. As the dosage of biochar increases, its capacity to adsorb cadmium also rises, resulting in a noticeable reduction of cadmium levels in the filtered water. These compelling findings enhance our understanding of bagasse biochar’s potential as a cost-effective and highly efficient solution for cadmium removal. The data suggest that increased dosages of biochar correspond to enhanced removal efficiency, with 0.4 grams emerging as the most effective amount for optimal performance. This study not only highlights the promise of bagasse biochar for addressing cadmium contamination in water but also paves the way for further investigations into its capabilities for removing other heavy metals and its performance under diverse environmental conditions. The implications for water treatment applications are significant, suggesting that with continued research, bagasse biochar could play a vital role in improving water quality and safeguarding environmental health.

Table 2: Cadmium concentration after AAS analysis of biochar and water sample after treatment.

S. No	Bowl	Biochar concentration (gm)	Cadmium absorbed by filtered bagasse biochar (ppm)	Cadmium remaining in water after absorption (ppm)
1	B1	0	0	0.003755
2	B2	0.1	0.08826	0.05851
3	B3	0.2	0.0969	0.04008
4	B4	0.3	0.1197	0.02699
5	B5	0.4	0.139	0.02316

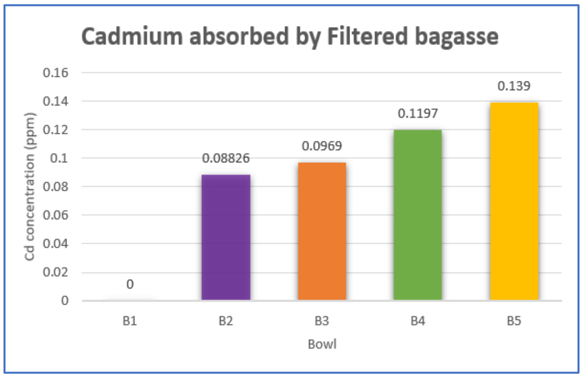

Fig1: The cadmium adsorbed on the bagasse biochar after filtration in each bowl

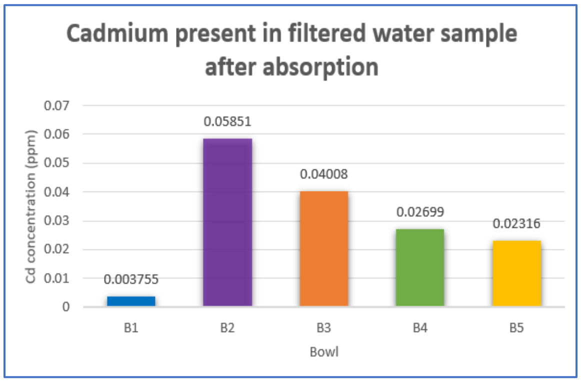

Fig 2: cadmium content remaining in the treated water sample after adsorption

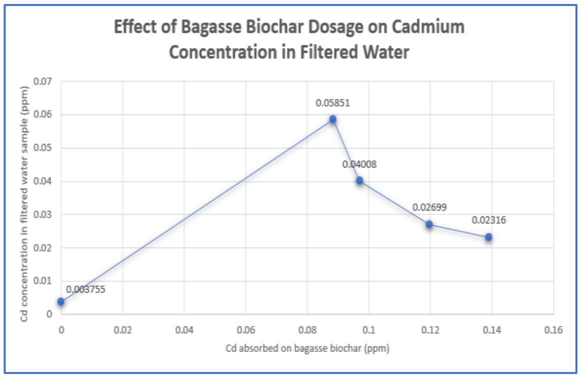

Fig 3: Comparison between the cadmium concentration in biochar and water sample after absorption study.

5.3. Application Study

After the treatment of the water samples, a comprehensive study to assess the biological effects of residual cadmium levels on zebrafish (Danio rerio), a widely recognized model organism in aquatic toxicity research was conducted. In this experiment, ten healthy zebrafish were carefully placed in separate bowls containing the treated water samples, and mortality rates were monitored over a 96-hour observation period, as summarized in Table 3. In conjunction with monitoring mortality rates, the accumulation of cadmium in the tissues of these zebrafish to evaluate the potential for bioaccumulation was measured, with findings presented in Table 4. The results demonstrated significant variability in the effectiveness of the water treatment across different samples. Higher residual cadmium concentrations were associated with increased mortality rates among the zebrafish. This observation underscores a concerning correlation between cadmium levels in the water and the resultant toxicity experienced by the fish, as illustrated in Figure 4. For instance, bowls treated with biochar that exhibited lower cadmium adsorption capacities, such as bowl B2, displayed increased mortality rates alongside elevated cadmium accumulation in the zebrafish tissues (as illustrated in Figures 5 and 6). In contrast, bowls containing water treated with biochar samples like B5, which achieved the highest levels of cadmium adsorption, showed significantly lower mortality rates and minimal cadmium accumulation in the zebrafish. A thorough analysis of cadmium levels within the zebrafish tissues, including muscle and organs, revealed distinct degrees of accumulation directly correlated with the residual cadmium concentrations in the treated water. These findings highlight the substantial health risks associated with insufficient cadmium removal from aquatic environments. In conclusion, this research emphasizes the critical necessity of optimizing biochar treatment methods to enhance cadmium removal efficacy while minimizing ecological and biological impacts. The results affirm biochar's effectiveness as an adsorbent for cadmium and underscore the importance of comprehensive post-treatment monitoring to protect the health of aquatic ecosystems.

Table 3: Mortality rate of fishes in each bowl

S. No	Bowl	Mortality rate (96 hour)	% of Mortality
1	B1	2	20%
2	B2	7	70%
3	B3	5	50%
4	B4	4	40%
5	B5	2	20%

Table 4: Cadmium concentration present in fish

S. No	Bowl	Cadmium content in fish muscle (ppm)	Cadmium content in fish organs (ppm)
1	B1	0.00036	0.003395
2	B2	0.00256	0.06073
3	B3	0.00225	0.03783
4	B4	0.00214	0.02485
5	B5	0.00147	0.02169

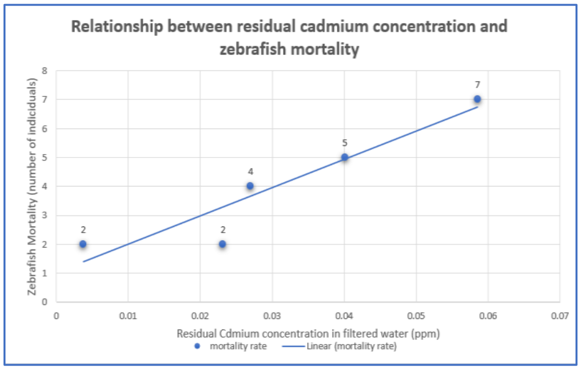

Fig 4: Scatter plot showing the relationship between residual cadmium concentration and zebrafish mortality

To investigate the relationship between fish mortality rates and cadmium levels in treated water samples, SPSS software was employed for statistical analysis. The findings revealed a compelling Pearson correlation coefficient (r) of 0.937, accompanied by a p-value of 0.019. This indicates a robust and positive correlation between the concentration of cadmium in the water and the rates of fish mortality. The p-value being less than 0.05 further underscores the statistical significance of this correlation.

A scatter plot (Figure 4) effectively visualizes the connection between cadmium concentration in filtered water and the mortality rates of zebrafish. The plot reveals a clear and direct positive correlation between these two variables, illustrating that as cadmium levels rise, the mortality rates of zebrafish also increase. Notably, in instances where cadmium concentrations fell below a specific threshold, fish mortality remained relatively low. However, a dramatic escalation in the fatalities of zebrafish was evident as cadmium concentrations became more pronounced. This observation highlights the severe toxic effects that cadmium exerts on aquatic organisms, even when present at seemingly low concentrations, thereby raising concerns about water quality and its impact on marine life.

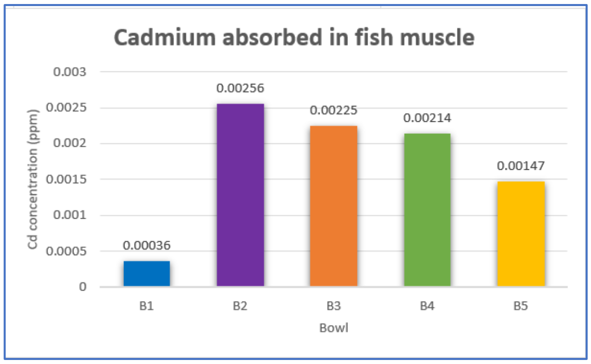

Fig 5: Cadmium accumulation on muscles of zebrafish

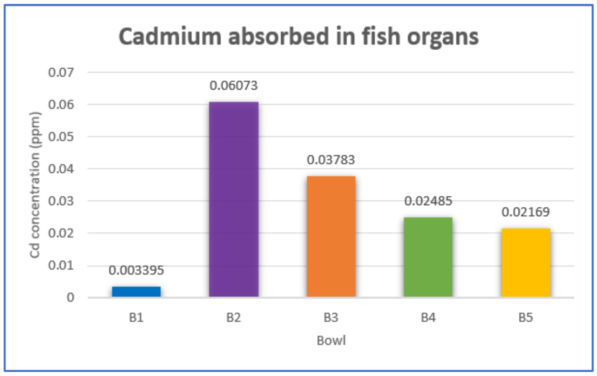

Fig 6: Cadmium accumulation on zebrafish organs

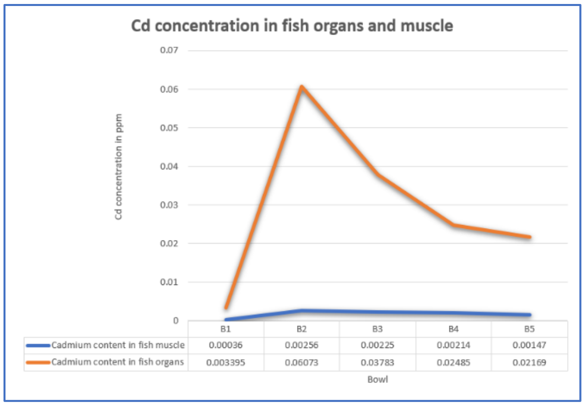

Fig 7: Comparison on the cadmium absorption rate in different parts of fish

Figure 7 provides a comprehensive analysis of cadmium (Cd) concentration in fish muscle and various organs across five distinct samples, labelled B1 to B5. The data highlights a significant difference in cadmium accumulation between these tissues. Notably, cadmium levels in muscle tissue remain consistently low across all samples, with the highest concentration recorded in sample B2, measuring 0.00256 ppm. While there is a slight downward trend in cadmium levels from B1 to B5, the overall changes are subtle and not particularly pronounced. In contrast, the cadmium levels found in fish organs are considerably higher, with the highest concentration also found in sample B2, which measures 0.06073 ppm. Following sample B2, there is a gradual decline in organ cadmium levels, especially between samples B3 and B5, highlighting the variability in accumulation among these tissues. This significant difference in cadmium accumulation suggests that fish organs are more prone to retaining this toxic metal, likely due to their vital roles in filtering and storing harmful substances. The elevated cadmium concentration in sample B2 raises concerns about potential environmental contamination, which may result from industrial discharge, agricultural runoff, or even natural sources of cadmium. If these fish are consumed, there are alarming health implications to consider, including the risk of kidney damage, bone disorders, and various other toxic effects associated with cadmium exposure.

VI. DISCUSSION

The study provides a comprehensive examination of the significant potential of sugarcane bagasse biochar as an environmentally friendly and economically beneficial solution for the remediation of cadmium in aquatic ecosystems. This innovative approach utilizes biochar derived from sugarcane bagasse, a by-product of sugar production, to address the pressing issue of cadmium pollution in water bodies. Key findings from the cadmium absorption study reveal a dose-dependent relationship, indicating that as the amount of biochar increases, its effectiveness in absorbing cadmium also improves. The increase in biochar dosage results in a higher availability of active sites, enhancing the overall capacity for cadmium removal from water. This critical insight underscores the importance of optimizing biochar application rates in remediation efforts. These findings are consistent with prior research indicating that the structural characteristics of biochar—specifically its high surface area and porous nature—play a vital role in its adsorption capabilities. Previous studies, including those conducted by Bayar et al. (2024) and Chen et al. (2020), have also corroborated the strong correlation between biochar dosage and absorption efficiency. The trends observed are not limited to cadmium; they extend to the absorption of various heavy metals, such as lead, copper, chromium, and mercury. Overall, this research positions sugarcane bagasse biochar as a promising tool for tackling cadmium contamination and supports its broader application in environmental remediation strategies, highlighting its dual benefits for both ecological preservation and economic sustainability [90] [91].

A significant challenge highlighted in the study is the high moisture content present in sugarcane bagasse, which poses considerable difficulties in energy consumption for drying and subsequent thermal processing. This elevated moisture content directly affects the efficiency of biochar production, leading to a low yield of only 9.693%. Such a low yield underscores the necessity for implementing effective pre-treatment methods. These methods may include air-drying, which allows moisture to evaporate naturally, freeze-drying, which removes moisture through sublimation at low temperatures, or various chemical treatments that can help to reduce moisture levels and prepare the biomass for thermal processing. Moreover, comparative studies have emphasized the critical role of pyrolysis temperature in enhancing the properties of biochar. Research indicates that biochar produced at elevated temperatures showcases a marked increase in carbon content, which is pivotal for its effectiveness as a soil amendment and a carbon sequestration agent. Furthermore, higher pyrolysis temperatures correspond to a decrease in ash content, which can negatively impact the quality of the biochar. Additionally, the adsorption properties of biochar are enhanced at these elevated temperatures, making it more effective in capturing nutrients and contaminants. Specifically, operating at temperatures above 500°C has been shown to significantly improve the structural stability and functional diversity of biochar. This increase in temperature not only fosters the formation of more aromatic structures within the biochar but also enhances its capability to adsorb metal ions. As a result, higher temperature pyrolysis could be a key strategy in optimizing the production of biochar from sugarcane bagasse, ultimately enhancing its utility in various applications, including soil improvement and environmental remediation.[92].

The biological assessment conducted using zebrafish (Danio rerio) generated valuable insights into the ecological consequences of residual cadmium exposure in aquatic environments. The analysis revealed a strong positive correlation ($r = 0.937$) between the concentration of cadmium in the treated water and the mortality rate of zebrafish. This significant statistical relationship underscores the severe impact that incomplete removal of cadmium can have on fish populations. Additionally, the study highlighted the potential for bioaccumulation of cadmium in aquatic organisms. Specifically, it was noted that cadmium concentrations were markedly higher in the tissues of zebrafish, especially within vital organs such as the liver, kidneys, and gills, compared to the muscle tissue. This finding is particularly concerning, as bioaccumulation can lead to increased toxicity over time, affecting the health and survival of fish. Furthermore, the results of this study are consistent with previous research by Vadlamani et al. (2017), who documented the tendency of cadmium to accumulate in various organs of fish. Their research emphasized that the storage of cadmium in the liver, kidneys, and gills can cause extensive physiological and biochemical alterations, adversely impacting the overall well-being of aquatic organisms. Such alterations may disrupt metabolic processes, impair growth, and reduce reproductive success, posing significant risks to aquatic ecosystems and their biodiversity.[93].

An initial increase in the concentration of cadmium observed at the lowest biochar dosage of 0.1 grams raises important questions about the dynamics of adsorption and the potential effects of desorption on this process. This phenomenon can be attributed to the insufficient availability of active sites for cadmium adsorption at lower biochar dosages, a limitation that has been acknowledged in previous studies examining competitive ion exchange processes during adsorption dynamics. The implications of these findings highlight the critical importance of determining an optimal biochar-to-pollutant ratio in order to achieve effective treatment outcomes for cadmium contamination.

Furthermore, addressing these challenges, researchers have explored the potential of utilizing functionalized or chemically modified biochars, such as those impregnated with iron oxides or activated through specific chemical processes. These modified biochars have been reported to significantly enhance adsorption capacities, thereby mitigating the limitations associated with standard biochar applications. By improving the availability of active sites and overall adsorption efficiency, these specialized biochars present a promising avenue for more effective remediation of cadmium and possibly other heavy metal contaminants in various environmental settings.

VII. CONCLUSION

The research presents compelling evidence regarding the substantial potential of biochar derived from sugarcane bagasse as a highly effective and environmentally sustainable adsorbent for the extraction of cadmium (Cd) from contaminated water sources. A thorough characterization of both the bagasse and the resulting biochar provided vital insights into their structural and chemical properties. One notable finding was the remarkably high moisture content of 62.48% in the bagasse, a factor that poses significant challenges during the pyrolysis process, as it necessitates additional energy to evaporate this excess moisture. This elevated moisture not only complicates the production process but also results in a diminished yield of biochar, which was measured at only 9.69%. Consequently, there is a critical need for improved strategies to manage moisture levels during biochar production to optimize yields. Despite this particular challenge, the biochar demonstrated an ash content of 8.0%, indicating it possesses beneficial characteristics for metal adsorption and, therefore, holds promise as a remediation tool in environmental applications.

The absorption studies conducted revealed a clear dosage-dependent relationship, wherein increasing quantities of biochar led to enhanced cadmium removal efficiencies. The optimal adsorption results were achieved using a dosage of 0.4 g, which successfully reduced cadmium levels to 0.139 ppm, with a corresponding residual concentration of 0.02316 ppm remaining in the water. This observation highlights the vital role that higher concentrations of biochar play in improving adsorption performance, primarily due to the increased availability of active sites that facilitate the adsorption process. Notably, a comparative analysis revealed a statistically significant negative correlation between cadmium absorption and its residual concentrations in water, effectively confirming the capability of biochar from sugarcane bagasse to remove cadmium from aquatic environments. These findings indicate that the strategic optimization of biochar dosages can lead to a significant reduction in cadmium contamination, thereby providing a cost-effective and efficient method for its removal.

In a further exploration of the biochar's efficacy, a biological experiment was conducted using zebrafish as a model organism. This investigation provided additional validation of the biochar treatment's effectiveness. The data indicated a robust positive correlation between the residual cadmium concentration in the treated water and the mortality rates of the zebrafish, with a calculated Pearson correlation coefficient of 0.937 and a p-value of 0.019, both indicating a statistically significant relationship. The results revealed that zebrafish exposed to elevated cadmium concentrations experienced higher mortality rates and demonstrated substantial accumulation of cadmium in their tissues, particularly in organs where cadmium was found to accumulate more significantly than in muscle tissue. This finding underscores the serious toxicological consequences of cadmium exposure on aquatic organisms, even at relatively low concentrations. Importantly, water treated with 0.4 g of biochar exhibited the lowest residual cadmium concentration along with the lowest mortality rates, further underscoring the essential role that optimized biochar dosages can play in alleviating cadmium toxicity.

This research confirms that sugarcane bagasse biochar is not only a highly effective material for the removal of cadmium from water but also represents a sustainable approach to addressing heavy metal contamination. It offers a cost-effective, environmentally friendly solution for mitigating such contamination while simultaneously minimizing the ecological and biological risks associated with heavy metal presence in aquatic systems. The study emphasizes the importance of optimizing both the production and application methods for biochar to enhance its performance and efficiency. Moreover, it lays a crucial foundation for investigating the potential use of biochar in the removal of other heavy metals and pollutants, thus opening new opportunities for its practical implementation in water treatment technologies. With continued research and methodological refinements, sugarcane bagasse biochar could emerge as a pivotal resource in the protection of aquatic ecosystems and the enhancement of water quality, outcomes that are integral to promoting human health and safeguarding environmental integrity.

Fig 8: Dried Sugarcane bagasse

Fig 9: Powdered bagasse

Fig 10: Sugarcane bagasse biochar after pyrolysis

Fig 11: 0.15 ppm Metal solution

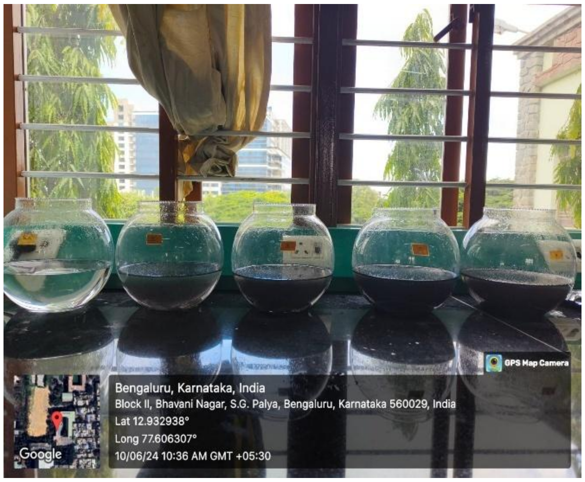

Fig 12: Different concentartaion of biochar added to each bowl containing same concentration of cadmium and a control bowl

Fig 13: Filtration of treated water to separate biochar after absorption

Fig 14: Separated biochar oven dried for acid digestion

Fig 15: Application study with zebrafishes

Fig 16: Dead fish for acid digestion

Fig 17: Acid digestion of filtered water sample and biochar to determine cadmium concentration

REFERENCES

[1] D. Mendil and Ö. D. Uluözlü, "Determination of trace metal levels in sediment and five fish species from lakes in Tokat, Turkey," Food Chemistry, vol. 101, no. 2, pp. 739–745, Jan. 2007, doi: 10.1016/j.foodchem.2006.01.050.

[2] M. Hampel, J. Blasco, and H. Segner, "Molecular and cellular effects of contamination in aquatic ecosystems," Environmental Science and Pollution Research, vol. 22, no. 22, pp. 17261–17266, Nov. 2015, doi: 10.1007/s11356-015-5565-5.

[3] S. R. Hughes, P. Kay, and L. E. Brown, "Global synthesis and critical evaluation of pharmaceutical data sets collected from river systems," Environmental Science & Technology, vol. 47, pp. 661–677, 2013.

[4] A. Rashid et al., "Environmental and socioeconomic factors induced blood lead in children: An investigation from Kashmir, India," Environmental Monitoring and Assessment, vol. 191, no. 2, p. 76, Jan. 2019, doi: 10.1007/s10661-019-7220-y.

[5] I. Bashir et al., "Concerns and threats of contamination on aquatic ecosystems," in Bioremediation and Biotechnology, Cham: Springer, 2020, pp. 1–26, doi: 10.1007/978-3-030-35691-0_1.

[6] K. Loska and D. Wiechuła, "Application of principal component analysis for the estimation of sources of heavy metal contamination in surface sediments," Chemosphere, vol. 51, no. 8, pp. 723–733, Jun. 2003, doi: 10.1016/S0045-6535(03)00187-5.

[7] C. A. Harguinteguy, A. F. Cirelli, and M. L. Pignata, "Heavy metal accumulation in aquatic plant Stuckenia filiformis and its relationship with sediment and water," Microchemical Journal, vol. 114, pp. 111–118, May 2014, doi: 10.1016/j.microc.2013.12.010.

[8] S. Stankovic, P. Kalaba, and A. R. Stankovic, "Biota as toxic metal indicators," Environmental Chemistry Letters, vol. 12, no. 1, pp. 63–84, Mar. 2014, doi: 10.1007/s10311-013-0430-6.

[9] V. Velma and P. B. Tchounwou, "Chromium-induced biochemical, genotoxic and histopathologic effects in liver and kidney of goldfish (Carassius auratus)," Mutation Research, vol. 698, no. 1–2, pp. 43–51, Apr. 2010, doi: 10.1016/j.mrgentox.2010.03.014.

[10] S. Gheorghe et al., "Metals toxic effects in aquatic ecosystems: Modulators of water quality," in Water Quality, InTech, 2017, doi: 10.5772/65744.

[11] P. Kumar et al., "Levels of cadmium and lead in tissues of freshwater fish (Clarias batrachus) and chicken in Western UP, India," Bulletin of Environmental Contamination and Toxicology, vol. 79, no. 4, pp. 396–400, Oct. 2007, doi: 10.1007/s00128-007-9263-y.

[12] G. Genchi et al., "The effects of cadmium toxicity," International Journal of Environmental

Research and Public Health, vol. 17, no. 11, p. 3782, May 2020, doi: 10.3390/ijerph17113782.

[13] S. Kumar and A. Sharma, “Cadmium toxicity: Effects on human reproduction and fertility,” Reviews on Environmental Health, vol. 34, no. 4, pp. 327–338, Dec. 2019, doi: 10.1515/reveh-2019-0016.

[14] S. Thophon et al., “Histopathological alterations of white seabass (Lates calcarifer) under cadmium exposure,” Environmental Pollution, vol. 121, no. 3, pp. 307–320, Mar. 2003, doi: 10.1016/S0269-7491(02)00270-1.

[15] M. Yousuf and E. Shahawi, “Trace metals in Lethrinus lentjan fish from Arabian Gulf,” vol. 62, pp. 293–300, 1999.

[16] P. Kumar, “Cadmium toxicity in fish: An overview,” GERF Bulletin of Biosciences, vol. 1, no. 1, pp. 41–47, 2010.

[17] M. Sevcikova, H. Modra, A. Slaninova, and Z. Svobodova, “Metals as a cause of oxidative stress in fish: A review,” Veterinarni Medicina, vol. 56, no. 11, pp. 537–546, Nov. 2011, doi: 10.17221/4272-vetmed.

[18] N. Aruna, N. Bagotia, A. K. Sharma, and S. Kumar, “A review on modified sugarcane bagasse biosorbent for removal of dyes,” Chemosphere, vol. 268, p. 129309, Apr. 2021, doi: 10.1016/j.chemosphere.2020.129309.

[19] C. Amutha and P. Subramanian, “Cadmium alters reproductive endocrine disruption and growth in Oreochromis mossambicus,” Fish Physiology and Biochemistry, vol. 39, no. 2, pp. 351–361, Apr. 2013, doi: 10.1007/s10695-012-9704-3.

[20] V. J. Nesatyy, A. A. Ammann, B. V. Rutishauser, and M. J. F. Suter, “Effect of cadmium on interaction of 17β-estradiol with the rainbow trout estrogen receptor,” Environmental Science & Technology, vol. 40, no. 4, pp. 1358–1363, Feb. 2006, doi: 10.1021/es051346i.

[21] C. S. Vergilio, R. V. Moreira, C. E. V. Carvalho, and E. J. T. Melo, “Evolution of cadmium effects in testis and sperm of Gymnotus carapo,” Tissue and Cell, vol. 47, no. 2, pp. 132–139, Apr. 2015, doi: 10.1016/j.tice.2015.02.001.

[22] J.-L. Zheng, L.-B. Peng, L.-P. Xia, J. Li, and Q.-L. Zhu, “Effects of cadmium exposure on reproductive and circadian systems in female zebrafish,” Chemosphere, vol. 282, p. 130879, Nov. 2021, doi: 10.1016/j.chemosphere.2021.130879.

[23] K. Singh, N. A. Renu, and M. Agarwal, “Methodologies for removal of heavy metal ions from wastewater: An overview,” Interdisciplinary Environmental Review, vol. 18, no. 2, p. 124, 2017, doi: 10.1504/IER.2017.10008828.

[24] A. Azimi, A. Azari, M. Rezakazemi, and M. Ansarpour, “Removal of heavy metals from industrial wastewaters: A review,” Chemical and Biochemical Engineering Reviews, vol. 4, no. 1, pp. 37–59, Feb. 2017, doi: 10.1002/cben.201600010.

[25] T. A. Kurniawan, G. Y. S. Chan, W.-H. Lo, and S. Babel, “Physico-chemical treatment techniques for wastewater containing heavy metals,” Chemical Engineering Journal, vol. 118, no. 1–2, pp. 83–98, May 2006, doi: 10.1016/j.cej.2006.01.015.

[26] M. Mohebi, M. G. Parashkoohi, and A. Mohammadi, “Comparison of biofilm and suspension methods for chromium removal using microalgae,” Results in Engineering, vol. 24, p. 103397, Dec. 2024, doi: 10.1016/j.rineng.2024.103397.

[27] H. I. Maarof, W. M. A. W. Daud, and M. K. Aroua, “Recent trends in removal and recovery of heavy metals by electrochemical technologies,” Reviews in Chemical Engineering, vol. 33, no. 4, 2017, doi: 10.1515/revce-2016-0021.

[28] P. Drogui, J.-F. Blais, and G. Mercier, “Review of electrochemical technologies for environmental applications,” Recent Patents on Engineering, vol. 1, no. 3, pp. 257–272, Nov. 2007, doi: 10.2174/187221207782411629.

[29] C. Y. Teh, P. M. Budiman, K. P. Y. Shak, and T. Y. Wu, “Recent advancement of coagulation–flocculation in wastewater treatment,” Industrial & Engineering Chemistry Research, vol. 55, no. 16, pp. 4363–4389, Apr. 2016, doi: 10.1021/acs.iecr.5b04703.

[30] C. Zamora-Ledezma et al., “Heavy metal water pollution: Hazards and remediation methods,” Environmental Technology & Innovation, vol. 22, p. 101504, May 2021, doi: 10.1016/j.eti.2021.101504.

[31] U. Wingenfelder, C. Hansen, G. Furrer, and R. Schulin, “Removal of heavy metals from mine waters by natural zeolites,” Environmental

Science & Technology, vol. 39, no. 12, pp. 4606–4613, Jun. 2005, doi: 10.1021/es048482s.

[32] C. Phaenark, T. Jantrasakul, P. Paejaroen, S. Chunchob, and W. Sawangproh, “Sugarcane bagasse and corn stalk biomass as sorbents for Pb (II) and Cd (II) removal,” Trends in Sciences, vol. 20, no. 2, p. 6221, Dec. 2022, doi: 10.48048/tis.2023.6221.

[33] G. Crini, E. Lichtfouse, L. D. Wilson, and N. Morin-Crini, “Conventional and non-conventional adsorbents for wastewater treatment,” Environmental Chemistry Letters, vol. 17, no. 1, pp. 195–213, Mar. 2019, doi: 10.1007/s10311-018-0786-8.

[34] S. Singh et al., “Current advancement and future prospects of biosorbents for bioremediation,” Science of the Total Environment, vol. 709, p. 135895, Mar. 2020, doi: 10.1016/j.scitotenv.2019.135895.

[35] V. K. Gupta, A. Nayak, and S. Agarwal, “Bioadsorbents for remediation of heavy metals: Current status and future prospects,” Environmental Engineering Research, vol. 20, no. 1, pp. 1–18, Mar. 2015, doi: 10.4491/eer.2015.018.

[36] D. Castro et al., “Chemical modification of agro-industrial waste-based bioadsorbents for Zn (II) removal,” unpublished, 2018.

[37] W. S. Wan Ngah and M. A. K. M. Hanafiah, “Removal of heavy metal ions from wastewater by modified plant wastes: A review,” Bioresource Technology, vol. 99, no. 10, pp. 3935–3948, Jul. 2008, doi: 10.1016/j.biortech.2007.06.011.

[38] R. H. Vieira and B. Volesky, “Biosorption: A solution to pollution?” International Microbiology, vol. 3, no. 1, pp. 17–24, Mar. 2000.

[39] V. K. Gupta, A. Nayak, B. Bhushan, and S. Agarwal, “Efficiency of activated carbons from low-cost precursors for heavy metal removal,” Critical Reviews in Environmental Science and Technology, vol. 45, no. 6, pp. 613–668, Mar. 2015, doi: 10.1080/10643389.2013.876526.

[40] E. Khoramzadeh, B. Nasernejad, and R. Halladj, “Mercury biosorption using sugarcane bagasse,” Journal of the Taiwan Institute of Chemical Engineers, vol. 44, no. 2, pp. 266–269, Mar. 2013, doi: 10.1016/j.jtice.2012.09.004.

[41] T. C. Sarker, S. M. G. G. Azam, and G. Bonanomi, “Advances in sugarcane industry by-product valorization,” Waste and Biomass Valorization, vol. 8, no. 2, pp. 241–266, Mar. 2017, doi: 10.1007/s12649-016-9665-3.

[42] B. C. S. Ferreira, F. S. Teodoro, A. B. Mageste, L. F. Gil, R. P. de Freitas, and L. V. A. Gurgel, “Carboxylate-functionalized sugarcane bagasse for dye removal: Kinetic and thermodynamic studies,” Industrial Crops and Products, vol. 65, pp. 521–534, Mar. 2015, doi: 10.1016/j.indcrop.2014.10.020.

[43] H. T. Boni, D. de Oliveira, A. A. Ulson de Souza, and S. M. A. G. Ulson de Souza, “Bioadsorption using sugarcane bagasse for oil and grease removal,” International Journal of Environmental Science and Technology, vol. 13, no. 4, pp. 1169–1176, Apr. 2016, doi: 10.1007/s13762-016-0962-y.

[44] M. A. A. Akl, “Removal of phenol using sugarcane bagasse-based activated carbon,” Journal of Analytical & Bioanalytical Techniques, vol. 5, no. 2, 2014, doi: 10.4172/2155-9872.1000189.

[45] D. Diriba, A. Hussen, and V. M. Rao, “Removal of nitrite from aqueous solution using agricultural waste,” Bulletin of Environmental Contamination and Toxicology, vol. 93, no. 1, pp. 126–131, Jul. 2014, doi: 10.1007/s00128-014-1297-3.

[46] T. C. Sarker, S. M. G. G. Azam, A. M. A. El-Gawad, S. A. Gaglione, and G. Bonanomi, “Sugarcane bagasse as a low-cost biosorbent for removal of hazardous materials,” Clean Technologies and Environmental Policy, vol. 19, no. 10, pp. 2343–2362, Dec. 2017, doi: 10.1007/s10098-017-1429-7.

[47] G. J. de Moraes Rocha, V. M. Nascimento, A. R. Gonçalves, V. Silva, and C. Martín, “Influence of mixed sugarcane bagasse composition on physicochemical properties,” Industrial Crops and Products, vol. 64, pp. 52–58, 2015, doi: 10.1016/j.indcrop.2014.10.022.

[48] A. A. Abdelhafez and J. Li, “Removal of Pb (II) from aqueous solution using biochars derived from sugarcane bagasse and orange peel,” Journal of the Taiwan Institute of Chemical Engineers, vol. 61, pp. 367–375, Apr. 2016, doi: 10.1016/j.jtice.2016.01.005.

[49] K. O. Iwuozor et al., “Thermochemical conversion of sugarcane bagasse into biochar: A

review," Cleaner Materials, vol. 6, p. 100162, Dec. 2022, doi: 10.1016/j.clema.2022.100162.

[50] S. Singh et al., "Role of biochar in soil biogeochemistry and remediation: A review," Journal of Soil Science and Plant Nutrition, vol. 23, no. 3, pp. 2981–2997, Sep. 2023, doi: 10.1007/s42729-023-01370-9.

[51] A. Singh et al., "Heavy metal contamination of water and its toxic effects on living organisms," in The Toxicity of Environmental Pollutants, IntechOpen, 2022, doi: 10.5772/intechopen.105075.

[52] D. Kapoor and M. P. Singh, "Heavy metal contamination in water and its sources," in Heavy Metals in the Environment, Elsevier, 2021, pp. 179–189, doi: 10.1016/B978-0-12-821656-9.00010-9.

[53] A. Sharma, A. S. Grewal, D. Sharma, and A. L. Srivastav, "Heavy metal contamination in water: Impacts on human health and environment," in Metals in Water, Elsevier, 2023, pp. 39–52, doi: 10.1016/B978-0-323-95919-3.00015-X.

[54] T. C. Hutchinson and K. M. Meema, Lead, Mercury, Cadmium and Arsenic in the Environment. Chichester, U.K.: John Wiley & Sons, 1987, pp. 279–303.

[55] G. J. Atchison, M. G. Henry, and M. B. Sandheinrich, "Effects of metals on fish behavior: A review," Environmental Biology of Fishes, vol. 18, no. 1, pp. 11–25, Jan. 1987, doi: 10.1007/BF00002324.

[56] K. Al-Sabti, "Comparative micronucleated erythrocyte induction in cyprinids by mutagenic chemicals," Cytobios, vol. 47, pp. 147–154, 1986.

[57] K. L. Crump and V. L. Trudeau, "Mercury-induced reproductive impairment in fish," Environmental Toxicology and Chemistry, vol. 28, no. 5, pp. 895–907, May 2009, doi: 10.1897/08-151.1.

[58] K. Mondal, S. Ghosh, and S. Haque, "Contamination and toxic effects of cadmium, mercury and lead in freshwater fishes: A review," International Journal of Zoology Studies, vol. 3, pp. 153–159, 2018.

[59] J. A. Arnot and F. A. Gobas, "Bioconcentration and bioaccumulation factors for organic chemicals in aquatic organisms," Environmental Reviews, vol. 14, no. 4, pp. 257–297, Dec. 2006, doi: 10.1139/A06-005.

[60] H. Karadede, S. A. Oymak, and E. Ünlü, "Heavy metals in mullet and catfish from Atatürk Dam Lake, Turkey," Environment International, vol. 30, pp. 183–188, 2004, doi: 10.1016/S0160-4120(03)00169-7.

[61] D. A. Wright and P. Welbourn, "The science of environmental toxicology: Concepts and definitions," in Environmental Toxicology. Cambridge, U.K.: Cambridge University Press, 2002, pp. 21–69, doi: 10.1017/CBO9780511805998.004.

[62] P.-E. Olsson, P. Kling, and C. Hogstrand, "Mechanisms of heavy metal accumulation and toxicity in fish," in Metal Metabolism in Aquatic Environments. Boston, MA, USA: Springer, 1998, pp. 321–350, doi: 10.1007/978-1-4757-2761-6_10.

[63] M. Nordberg and G. F. Nordberg, "Toxicological aspects of metallothionein," Cellular and Molecular Biology, vol. 46, no. 2, pp. 451–463, Mar. 2000.

[64] A. Annabi, I. Messaoudi, A. Kerkeni, and K. Said, "Cadmium accumulation and histological lesions in Gambusia affinis under exposure," International Journal of Environmental Research, vol. 5, pp. 745–756, 2011.

[65] S. Nakayama et al., "GIS-based source estimation of copper pollution and accumulation in Oreochromis species," Archives of Environmental Contamination and Toxicology, vol. 64, pp. 119–129, 2013, doi: 10.1007/s00244-012-9815-7.

[66] J. A. Almeida, E. L. B. Novelli, M. Dal Pai Silva, and R. Alves Júnior, "Metabolic responses of Nile tilapia to environmental cadmium exposure," Environmental Pollution, vol. 114, no. 2, pp. 169–175, Sep. 2001, doi: 10.1016/S0269-7491(00)00221-9.

[67] D. Smet and H. Blust, "Stress responses and protein metabolism changes in carp during cadmium exposure," Ecotoxicology and Environmental Safety, vol. 48, pp. 255–262, 2001, doi: 10.1006/eesa.2000.2012.

[68] K. K. Das and S. K. Banerjee, "Cadmium toxicity in fishes," Hydrobiologia, vol. 75, no. 2, pp. 117–121, Oct. 1980, doi: 10.1007/BF00007424.

[69] M. K. Hussain et al., "Bio-adsorbents for efficient heavy metal removal in water purification," Journal of Water Process Engineering, vol. 64, p.

105705, Jul. 2024, doi: 10.1016/j.jwpe.2024.105705.

[70] K. Bethke et al., “Functionalized cellulose for water purification and antimicrobial applications,” Advanced Functional Materials, vol. 28, no. 23, p. 1800409, Jun. 2018, doi: 10.1002/adfm.201800409.

[71] A. Kumar et al., “Metal tolerance mechanisms in edible plants: A physiological perspective,” in Handbook of Bioremediation. Elsevier, 2021, pp. 23–47, doi: 10.1016/B978-0-12-819382-2.00003-X.

[72] A. Saravanan, S. Karishma, P. S. Kumar, P. Thamarai, and P. R. Yaashikaa, “Mechanisms of modified bio-adsorbents for environmental remediation,” Environmental Pollution, vol. 339, p. 122720, Dec. 2023, doi: 10.1016/j.envpol.2023.122720.

[73] P. L. Homagai, K. N. Ghimire, and K. Inoue, “Adsorption behavior of heavy metals onto modified sugarcane bagasse,” Bioresource Technology, vol. 101, no. 6, pp. 2067–2069, Mar. 2010, doi: 10.1016/j.biortech.2009.11.073.

[74] U. Garg, M. P. Kaur, G. K. Jawa, D. Sud, and V. K. Garg, “Removal of cadmium (II) from aqueous solution using agricultural waste biomass,” Journal of Hazardous Materials, vol. 154, no. 1–3, pp. 1149–1157, Jun. 2008, doi: 10.1016/j.jhazmat.2007.11.040.

[75] M. Khai Nguyen, M. Trang Hoang, T. Thuy Pham, and B. Van der Bruggen, “Performance of modified sugarcane bagasse for Cd (II) removal,” Journal of Renewable Materials, vol. 7, no. 5, pp. 415–428, 2019, doi: 10.32604/jrm.2019.04371.

[76] A. Moubarik and N. Grimi, “Valorization of olive stone and sugarcane bagasse as biosorbents for cadmium removal,” Food Research International, vol. 73, pp. 169–175, Jul. 2015, doi: 10.1016/j.foodres.2014.07.050.

[77] O. Karnitz Júnior, L. V. A. Gurgel, and L. F. Gil, “Removal of Ca (II) and Mg (II) using modified sugarcane bagasse,” Carbohydrate Polymers, vol. 79, no. 1, pp. 184–191, Jan. 2010, doi: 10.1016/j.carbpol.2009.07.048.

[78] M. Haghighatjou and M. Shirvani, “Sugarcane bagasse biochar: Preparation and zinc sorption characteristics,” Communications in Soil Science and Plant Analysis, vol. 51, no. 10, pp. 1391–1405, May 2020, doi: 10.1080/00103624.2020.1763383.

[79] P. S. Kumar, C. Vincent, and V. Uthayakumar, “Adsorption of cadmium ions using sugarcane bagasse biochar: Equilibrium and kinetics,” Bioresource Technology Reports, vol. 5, pp. 295–304, 2019.

[80] V. K. Gupta, I. Ali, T. A. Saleh, M. N. Siddiqui, S. Agarwal, and M. R. H. Siddiqui, “Regeneration of adsorbents,” in Handbook of Materials for Wastewater Treatment. Elsevier, 2021, pp. 409–428.

[81] S. Tehreem et al., “Role of biochar in heavy metal remediation and adsorption kinetics,” Journal of Saudi Chemical Society, vol. 26, no. 5, p. 101518, Sep. 2022, doi: 10.1016/j.jscs.2022.101518.

[82] Anjali et al., “Physico-chemical characterization of biochar from lignocellulosic biomass,” International Journal of Applied Biology, vol. 6, no. 2, pp. 186–212, Dec. 2022, doi: 10.20956/ijab.v6i2.23265.

[83] F. Ronsse, S. van Hecke, D. Dickinson, and W. Prins, “Production and characterization of biochar: Influence of feedstock and conditions,” Global Change Biology Bioenergy, vol. 5, no. 2, pp. 104–115, Mar. 2013, doi: 10.1111/gcbb.12018.

[84] O. D. Nartey and B. Zhao, “Biochar preparation and adsorptive capacity: An overview,” Advances in Materials Science and Engineering, vol. 2014, pp. 1–12, 2014, doi: 10.1155/2014/715398.

[85] P. C. Jain and P. Singh, “Moisture determination of jaggery using microwave oven,” Sugar Tech, vol. 2, no. 3, pp. 51–52, Sep. 2000, doi: 10.1007/BF02945760.

[86] S. Sadaka et al., “Characterization of biochar from switchgrass carbonization,” Energies, vol. 7, no. 2, pp. 548–567, Jan. 2014, doi: 10.3390/en7020548.

[87] S. Azad, I. Liaqat, R. Iqbal, and U. Rafi, “Histopathological effects of cadmium on tissues of Labeo rohita,” Journal of Innovative Sciences, vol. 8, no. 1, 2022, doi: 10.17582/journal.jis/2022/8.1.01.07.

[88] A. H. Uddin et al., “Comparison of digestion methods for elemental analysis using AAS,” Journal of Analytical Science and Technology, vol. 7, no. 1, 2016, doi: 10.1186/s40543-016-0085-6.

[89] I. Bankaji et al., “Comparison of digestion methods for metal analysis in plants,” Separations, vol. 10, no. 1, p. 40, Jan. 2023, doi: 10.3390/separations10010040.

[90] J. Bayar et al., “Biochar-based adsorption for heavy metal removal: A sustainable approach,” Environmental Geochemistry and Health, vol. 46, no. 11, p. 428, Sep. 2024, doi: 10.1007/s10653-024-02214-w.

[91] G. Chen et al., “Removal of cadmium ions using biochars derived from different raw materials,” Journal of Water Process Engineering, vol. 35, p. 101223, Jun. 2020, doi: 10.1016/j.jwpe.2020.101223.

[92] M. Uchimiya, L. H. Wartelle, K. T. Klasson, C. A. Fortier, and I. M. Lima, “Influence of pyrolysis temperature on biochar properties and metal sorption,” Journal of Agricultural and Food Chemistry, vol. 59, no. 6, pp. 2501–2510, Mar. 2011, doi: 10.1021/jf104206c.

[93] S. K. Vadlamani et al., “Cadmium accumulation and toxicity in fish fry of Labeo rohita and Cyprinus carpio,” Journal of Environmental Biology, vol. 39, no. 4, pp. 500–506, Jul. 2018, doi: 10.22438/jeb/39/4/mrn-644.