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Using Sorghum Waste and Biomass Components to Remove Pollutants from Aquatic Environments (a Literature Review)

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Abstract: The review briefly summarizes literature information on the use of sorghum biomass components (stems, leaves, roots) and waste (husks, bagasse) as sorption materials to remove the ions of various metals (As(V), Cd^{2+}, Cr(III), Cr(VI), Cu^{2+}, Fe^{3+}, Mn(II), Ni^{2+}, Pb^{2+}, Tl^{+}, Zn^{2+}), dyes and other organic compounds from aqueous media. Brief information is provided on how sorghum biomass components and waste are used in various industries. The review presents the parameters of the above pollutants' adsorption process by sorghum biomass components and waste. It is shown that treating the latter with various chemicals improves their sorption characteristics for various pollutants. It was found that adsorption isotherms are described by various models, most often by those of Langmuir and Freundlich. In most cases, the process kinetics follows the pseudo-second-order model. It has also been shown that sorghum biomass components and waste are good precursors for activated carbons and carbonized production, which are also used to remove organic and inorganic pollutants from aquatic environments.

Keywords: Sorghum; biomass; waste; metal and metalloid ions; dyes; removal; adsorption models; process kinetics; activated carbon.

1. Introduction

The pollution of the World Ocean with various pollutants is currently one of the global environmental problems of our time. The main sources of pollutants entering water bodies include, as a rule, untreated or insufficiently treated wastewater from various processes, man-made accidents, and other factors.

There are various ways to treat wastewater and the water surface from various pollutants. However, it should be noted that the use of a particular treatment method depends on the composition of pollutants in the wastewater, which significantly complicates the equipment support of the process and the use of universal methods. However, a universal method allows removing almost all pollutants from aqueous media, regardless of the initial concentration of the latter, i.e., adsorption.

In industrial production, activated carbons (AC) produced from vegetable or mineral raw materials by thermal activation are often used as sorbents. However, the use of ACs is limited by high cost, abrasion, and the need for regeneration, which significantly increases the cost of wastewater treatment.

Given the above, work is currently underway to study wood biomass [1-6], agricultural raw materials [7-10], and natural mineral media [11-15] waste as sorption materials. Biomass components and agricultural raw materials waste are particularly interesting as sorption materials due to such positive aspects as high tonnage, annual formation, high efficiency, low cost, etc.

Cereals are worthy of attention as a food source for people and animals. After processing and separating the grains, straw, husk, husking bran, etc., are formed as waste. The volume of the latter is very huge and amounts to hundreds of thousands of tons. The question of grain crop waste recycling naturally arises.

One of the ways to use agricultural waste, including those of cereals, is using them as sorption materials to remove various pollutants from aqueous media. In particular, it was shown that the wastes of wheat [16], rice [17-21], barley [22], rye [23], mays [24, 25], and other cereals work well as reagents to remove a variety of pollutants from aqueous media.

A widespread grain crop worldwide is *Sorghum*, a genus of annual and perennial herbaceous plants of the grass or bluegrass family (*Poaceae*). It includes about 30 species that grow in Asia, Africa, South and North America, Europe, and Australia. A number of sorghum species are grown as cultivated plants — grain, technical, and fodder crops. The upright high stem can have a height of 0.5 m in dwarf forms and up to 7 m in some tropical varieties. There is no internal cavity. The inner part is filled with parenchyma. Cultivated forms of Sorghum usually have several stems. The root system is well developed, and its depth can reach 2-2.5 m. The leaf blade is lanceolate, and the edges are sharp. The inflorescence is a panicle, erect, spreading, drooping or bent. Normally, the panicle is from 10 to 70 cm long, in some cases longer. The seed grain, as a rule, is oval or ovoid and can be filmy or bare. The color is white, pink, red, or yellow. The weight of the grain is 5-32 mg. Sorghum is a thermophilic, heat- and drought-resistant crop. The optimal temperature for seed germination, plant growth, and development is +20...+30°C. Sorghum is not moisture-demanding. The amount of water required by sorghum seeds to swell is 35% of the total seed weight. Sorghum grains are processed into cereals, flour, starch, and alcohol. The green mass is used for livestock feed, including silage, but not any, since young plants of many sorghum species are poisonous [26].

The major sorghum producer is the USA. It is followed by Nigeria, Sudan, Mexico, Ethiopia, and India, among the main producers of Sorghum [26].

Because Sorghum is a low-maintenance crop that can thrive in arid, poor soils, it can be used for phytoremediation of sites contaminated by metal ions and petroleum hydrocarbons [27-31]. In addition, sorghum biomass after grain separation is recommended for the production of bioplastics [32], concrete [33], and chipboard [34]. Sorghum biomass can also be used to produce cellulose fibers [35, 36], antioxidant bio-colorant pigments [37], anthocyanidin and phenolic substances [38], and natural dyes [39]. It has also been found that bioethanol [40-42], methane [43], and hydrogen [44] can be produced from sorghum biomass, sucrose [45], xylitol [46], amylase [47], and protease [48] and other valuable organic compounds can be selected from it. There are a number of sources of literature on the production of such inorganic components as SiO_2 [49-51] silicon carbide [52] from sorghum biomass.

One of the ways to use sorghum grain processing biomass and waste is their use as sorption materials to remove metal ions, dyes, and other organic pollutants from aqueous media.

2. The Use of Sorghum Biomass Waste to Remove Metal Ions from Aqueous Media

The world literature contains a vast amount of information, including a review work [53] on using biomass components and sorghum processing waste to remove various metals from polluted water. In this review, metal ions are arranged alphabetically for convenience's sake.

As(V) ions, the biomass of sorghum components has been studied as a sorption material to remove As(V) ions from groundwater under dynamic conditions with varying pH values in the pH range = 2-10 [54-57]. It was found that the As(V) ions adsorption capacity at pH = 4.5 and t = 60 min of contact time was 8.43 mg/g and 6.99 mg/g for free and immobilized biomass of Sorghum, respectively [54]. After HCl treatment, As(V) ions were recovered in 91% and 95% of free and immobilized As(V) ions saturated biomass, respectively [55]. It was found that the adsorption isotherms were most accurately described by the Freundlich model [56]. Also, the effects of $CaCl_2$, $MgCl_2$, $FeSO_4$, $MgSO_4$, $Fe(NO_3)_3$, and humic substances on As(V) binding to sorghum biomass were evaluated. Among these compounds, only iron salts were found to positively increase the sorption of As(V) ions to sorghum biomass [57].

Cd(II) ions work was performed to study the adsorption of Cd^{2+} ions by native and NaOH-treated *Sorghum drummondii SB*. It was determined that the maximum sorption capacity of native SB was 1.52 mg/g, after treatment – 7.76 mg/g. Sorption mechanism and thermodynamic investigations suggested that Cd^{2+} ions removal by modified SB is a chemisorption and endothermic process, while Cd^{2+} ions removal by SB is predominantly physisorption and exothermic [58]. To improve sorption characteristics, it is proposed that sorghum husk be modified or carbonized. This made it possible to increase the maximum sorption capacity for Cd^{2+} ions to 54.9 mg/g and 58.9 mg/g, respectively). These results showed that the pseudo-second-order kinetic model best described the sorption process [59].

Cr(III) and Cr(VI) ions. There are several international publications on the study of the adsorption of Cr(III) and Cr(VI) ions by SB biomass. In particular, the adsorption of Cr(III) ions by sorghum straw was studied. First, sorghum straw sorption parameters were determined – the total surface area was 1.205 m^2/g, the pore volume was 0.0044 cm^3/g, and the average pore diameter was 13.54 nm. It was found that the maximum sorption capacity of sorghum straw for Cr(III) ions was 9.35 mg/g, and the main mechanism of the process is film diffusion [60] and ion exchange and complexation [61].

To improve the sorption characteristics of SB for Cr(III) ions, it was treated with urea under microwave radiation. It was found that treatment allows increasing the SB maximum sorption capacity from 7.03 mg/g to 16.36 mg/g. It was found that the Langmuir equation represented the adsorption process very well in both cases. It also was found that the process followed pseudo-second-order kinetics [62].

The adsorption of Cr(VI) ions by native Sorghum stems has also been investigated. It was determined that the maximum sorption capacity was 5.78 mg/g at pH = 1, and the sorbent dosage was 5 g/dm^3 and 200 rpm. It was found that the adsorption isotherms are more accurately described by the Langmuir model (R^2 = 0.959), and the kinetics of the process follow the pseudo-second-order model [63].

Also, the adsorption isotherms of this process were additionally calculated using two-parameter isotherm models (Harkins–Jura, Halsey, Smith, El-Awady, and Flory–Huggins) and three-parameter isotherm models (Redlich–Peterson and Sips). Also, the mechanism of adsorption has been studied using diffusion kinetic models (viz. liquid film diffusion, Dunwald–Wagner intra-particle diffusion model, and moving boundary model. It was determined that the Flory most accurately describes the adsorption isotherm–Huggins model (R^2 = 0.983), and the Moving boundary model is more suitable for describing the process mechanism [64].

Cu(II) ions, several publications on sorption purification of aqueous media from Cu^{2+} SB ions were found. Thus, there was a study of removing Cu^{2+} ions with the latter's initial concentration from 1 mg/dm^3 to 30 mg/dm^3 by biomass of various agricultural plants, including SB. It was found that the maximum Cu^{2+} ion removal was provided by the following process conditions: pH = 6, sorbent dosage – 1.5 g/dm^3, temperature – 30°C. It was determined that an increase in Cu^{2+} ion initial concentration decreased the efficiency of removing copper ions from 98% to 68% [65].

The removal of Cu^{2+} ions by native and heat-treated at 150°C sorghum stem biomass was also studied. At an initial concentration of copper ions of 50 mg/dm^3, the removal rate by native stems was 90%, and by thermally treated – 95% [66].

In another paper [66], native sorghum stems were also studied to remove Cu^{2+} ions from simulated solutions at various temperatures. The maximum sorption capacity was found to be 7.94 mg/g. On changing the initial concentration of Cu^{2+} from 35 to 200 mg/dm^3, the amount adsorbed increased from 1.42 to 5.92 mg/g. It was determined that the Freundlich model more accurately described the adsorption isotherms, the kinetics of the process were described by the pseudo-second-order model, and the Webers intraparticle diffusion model described the mechanism. The thermodynamic parameters of the process were calculated: ΔG = -1.30 - -7.21 kJ/mol at temperatures from 303K to 343K, ΔH = 43.44 kJ/mol, ΔS = 0.15 kJ/mol/K, which indicate physical adsorption [67].

The influence of the main components (cellulose, hemicellulose, and lignin) of the sweet sorghum stalk on radiation-induced grafting reaction and adsorption of Cu^{2+} ions from aqueous solution was investigated. Sweet sorghum stalk was grafted with acrylic acid induced by γ-irradiation. The results showed that the grafted stalk contained 1.6 mmol/g carboxyl groups, and its maximal adsorption capacity was 13.32 mg/g. The adsorption capacity of the grafted sweet sorghum stalk increased about five times, and the adsorption isotherm of the grafted materials conformed to the Langmuir model. The main mechanism for copper adsorption involved in ion exchange [68].

It was determined that sorghum leaves had a slightly higher maximum sorption capacity compared to native stems of the plant – 10.53 mg/g. Equilibrium data were well fitted to the Langmuir isotherm model and the pseudo-second-order kinetic model. The desorption of metal ions was also monitored by hydrochloric acid [69].

Reported a new biosorbent, the fermented sweet sorghum residues (FSSR), which is a byproduct of bioethanol production by fermentation of sweet sorghum straw, to remove Cu^{2+} ions from aqueous solution. It was found that fermentation contributes to an increase in the maximum sorption capacity from 0.83 mg/g to 1.94 mg/g. Also, the adsorption capacity of FSSR for Cu^{2+} ions was increased with the increase in pH. The adsorption process of Cu^{2+} by SSR and FSSR conformed to the Elovich kinetic model. The isothermal adsorption process conformed to the Freundlich and the Tempkin models [70].

Fe(III) ions, the biomass waste of bagasse sorghum, was utilized as an adsorbent to remove Fe^{3+} ions. Bagasse sorghum was modified using citric acid to enhance the adsorption of Fe^{3+} ions. The kinetics models fitted well to the pseudo-second-order model, indicating the adsorption mechanism of Fe^{3+} onto the modified bagasse sorghum was chemisorption supported by the Elovich model. The isotherm study was described well by the Freundlich model (R^2 = 0.941) with maximum adsorption of 45.872 mg/g [71].

Ni(II) ions. Investigate the use of unmodified and carbonized sorghum hull (размер пор – 150 µm and 250 µm) in the removal of Ni^{2+} ions from aqueous solution. The maximum adsorption for 150 µm and 250 µm were at 40 and 60 min. respectively (38.25 mg/dm^3 and 38.55 mg/dm^3, recpectivelly). Both pore sizes showed peak adsorption of Ni^{2+} at different adsorption times, respectively. These results showed that the pseudo-second-order kinetic model best describes the process, and the adsorption mechanism shows that both 150 µm and 250 µm were film diffusion-controlled [72].

Pb(II) ions. Sorghum stems were also studied as a sorption material to remove Pb^{2+} ions from simulated solutions. The effects of various experimental parameters, such as contact time, initial Pb^{2+} ion concentrations, pH, adsorbent dosage, and medium temperature, on the adsorption process were discussed. It was found that the maximum sorption capacity was 3.69 mg/g for a native sorghum stem sample. The adsorption isotherms are most accurately described by the Langmuir model, and the kinetics of the process more clearly follow Weber's intraparticle diffusion model. The thermodynamic parameters (ΔG = 1.32 - -1.61 kJ/mol at 303 – 343K, ΔH = 23.50 kJ/mol, ΔS = 0.07 J/mol-K) indicate physical adsorption [73].

To improve SB sorption characteristics for Pb^{2+} ions, SB was treated with thiourea under microwave radiation. It was found that such treatment (modification) makes it possible to increase the maximum sorption capacity from 6.29 mg/g to 17.82 mg/g. It was found that the adsorption isotherms are most accurately described by the Langmuir model, and the kinetics of the process correspond to the pseudo-second-order model [74].

Sorghum husk with particle sizes 150 and 250 microns was proposed to be treated with mercaptoacetic acid to improve its sorption characteristics for Pb^{2+} ions. It was found that the sorption capacity for lead ions after 80 minutes of contact was 39.09 mg/g. The authors determined that the kinetics of the process correspond to the pseudo-second-order model [75].

A modified NaOH sorghum bagasse (MSB) was used to adsorb Pb^{2+} ions from an aqueous solution. MSB shows smoother, increasing porosity and pore size (mesopore). The adsorption of Pb^{2+} by the adsorbents was optimum at pH = 5.0, contact time 15 min, adsorbent dosage 6 g/dm^3, and initial concentration 80 mg/dm^3. The pseudo-second-order model was suitable for describing the kinetics of the process with the diffusion model of the Elovich model. The adsorption isotherm model was suitable with the Langmuir model and gives a maximum adsorption capacity of 12.29 mg/g. The Gibbs free energy was negative, and the enthalpy was negative, indicating the adsorption was a spontaneous and exothermic [76].

Laboratory experiments were designed to identify the adsorption features of Pb^{2+} ions by sorghum vinasse under various conditions. The results showed that the adsorption capacity enhanced with the increasing pH and peaked (68.42 mg/g) when pH = 6. With the sorghum vinasse dosage ranging from 0.0250 to 0.2000 g, the adsorption capacity declined from 55.59 mg/g to 44.84 mg/g, and the Pb^{2+} ions removal rates increased from 13.52% to 91.14%. The pseudo-second-order kinetic and Langmuir model could well illustrate the adsorption process. The adsorption of Pb^{2+} ions on sorghum vinasse is a chemical and spontaneous process via monolayer adsorption involving physical absorption, ion exchange, surface complex with oxygen-containing functional groups, and chemical reactions [77].

Tl(I) ions, an adsorbent based on nitro-oxidized nanocellulose (NONC) extracted from sorghum stalks, was shown to be a highly effective Tl^{+} ions removal medium. The demonstrated NONC adsorbent exhibited high Tl^{+} removal efficiency (>90% at concentration < 500 ppm) and high maximum removal capacity Qmax = 1898 mg/g using the Langmuir model. The results indicate that adsorption occurs mainly due to electrostatic attraction between cationic Tl^{+} ions and anionic carboxylate groups on NONC, where the adsorbed Tl^{+} ions sites become nuclei for the growth of thallium oxide nanocrystals at high Tl^{+} ions concentrations. The mineralization process enhances the Tl^{+} removal efficiency, and the mechanism is consistent with the isotherm data analysis using the Freundlich model [78].

CN(I)- ions, Sorghum stems will be considered as an adsorbent for the removal of cyanide ions in aqueous solution. It is found that the pseudo-second-order kinetic model best described the experimental data with a high coefficient of determination and that the Langmuir isotherm model fitted better than the Freundlich and Temkin models. The Langmuir maximum adsorption capacity was 76.92 mg/g at 293 K. The thermodynamic study showed that the adsorption of cyanides on SSPs was endothermic and spontaneous and that it was chemisorption [79].

Multiple metal ions. As shown above, the values of the maximum sorption capacity of metal ions by sorghum biomass components vary significantly. This is due to the fact that experiments by different groups of authors were conducted under completely different conditions. Therefore, it is not entirely correct to compare the resulting data with each other. A comparative analysis of sorption characteristics is viable when adsorption experiments are carried out under the same conditions.

In this regard, the data on the study of various metal ions adsorption by components of sorghum biomass and its waste is analyzed below.

2 metal ions. Several papers have been found on the study of removing 2 metal ions from aqueous media by components and waste of sorghum biomass. In particular, Cd^{2+} and Cu^{2+} ions were removed from simulated solutions by sorghum biomass waste modified with thiourea under microwave exposure. Langmuir's model indicated that the maximum metal ion removal capacity of sorghum waste was 17.241 mg/g and 15.151 mg/g for Cd^{2+} and Cu^{2+} ions. Found that maximum removal of these toxic ions occurred in slightly acidic pH = 5-6 conditions, following a pseudo-second-order kinetic model. Boyd plots indicated that film dispersion mode was the rate-determining step [80].

Also, the adsorption behavior of sorghum husk with respect to Cd^{2+} and Pb^{2+} ions has been studied to consider its application to wastewater treatment. The optimum pH for Cd^{2+} and Pb^{2+} removals by sorghum husk were pH = 6 and pH = 5, respectively. Based on the Langmuir model, the maximum sorption capacity of sorghum husk for Cd^{2+} ions was calculated to be 6.99 mg/g, for Pb^{2+} ions - 58.82 mg/g. The data was best fitted with the Langmuir model [81].

Sorghum bicolor root powder was studied as a sorbent to remove Cr(VI) and Cu^{2+} ions from simulated solutions. It was found that the optimum pH and temperature for biosorption of both metals was found to be pH = 2 and T = 20°C, respectively. The maximum biosorption capacity for Cu^{2+} and Cr(VI) ions is 18.6 mg/g and 18.39 mg/g, respectively. The Langmuir model gave a better fit than the other two models. The kinetic studies indicated that the biosorption process of the metal ions followed a well pseudo-second-order model. The thermodynamic parameters were also calculated, and the values indicated that the biosorption process was exothermic, spontaneous, and feasible [82].

Also, the use of modified and unmodified sorghum hulls in the removal of Ni^{2+} and Cu^{2+} ions from aqueous solution should be investigated. The effect of pH, particle size, and chemical modification were investigated and reported. pH significantly affected the adsorption with maximum adsorption at pH = 10. Adsorption increased as chemical modification by thiolation with mercapto-acetic acid solution increased. The highest extent of removal was at pH = 10 for Ni^{2+} and Cu^{2+} ions. Ni^{2+} ions had 98.69%, while Cu^{2+} ions had 94.65% removal. The trend of metal ion removal was Ni^{2+} > Cu^{2+} ions [83].

Sorghum waste was found to be effective for the removal of Cu^{2+} and Zn^{2+} ions from aqueous solutions. The result obtained shows that the extent of metal ions removed increases with increasing contact time, increasing adsorbent doses, and increasing metal ion concentrations. It was determined that the maximum sorption capacity of sorghum waste for Cu^{2+} ions was 14.2 mg/g and for Zn^{2+} ions - 13.2 mg/g. It was determined that the adsorption isotherms of both metals corresponded to the Freundlich model ($R^2 > 0.998$). The kinetics of the adsorption process best fit the pseudo-second-order kinetic model. The adsorption of these metal ions from aqueous solution was consistent with the mechanism of physical adsorption [84].

Ions of 3 or more metals. Studies on the adsorption of three or more metal ions by components of sorghum biomass have been documented in international literature.

Proposed the adsorption characteristics of Cd^{2+}, Cu^{2+}, and Pb^{2+} onto *Sorghum bicolor* L. biomass from aqueous solutions. Maximum adsorption for all metal ions has taken place at pH = 5.0–6.0. Langmuir, Freundlich, Temkin, andDubinin–Radushkevich isotherm models in a nonlinear fashion were used to explain the phenomenon. The maximum adsorption capacity of *Sorghum bicolor* L. biomass was 7.87 mg/g, 4.34 mg/g, and 6.29 mg/g for Cd^{2+}, $Cu^{2+,}$ and Pb^{2+} ions, respectively. It was found that the process followed pseudo-second-order kinetics. The thermodynamic study indicated the process's favorability [85].

Also, the adsorption efficiency of sorghum waste for removing Cr(III), Cu^{2+}, and Ni^{2+} ions from aqueous solution using a batch process. It was found that after an 80-minute interaction time, the sorghum waste sorption capacity could be arranged in the following row according to the above ions: Cu^{2+} (14.2 mg/g) > Ni^{2+} (6.5 mg/g) > Cr(III) (3.0 mg/g). The adsorption of these metal ions from an aqueous solution is consistent with the physical adsorption mechanism; it is time, concentration, adsorbent dose, and pH-dependent. Its adsorption characteristics best fit the Freundlich model ($R^2 > 0.998$). The adsorption kinetic of the adsorbates agrees excellently with the pseudo-second-order kinetic models [86].

The adsorption of Cu^{2+}, Ni^{2+}, and Zn^{2+} ions by mercaptoacetic acid-treated sorghum biomass with particle sizes of 106 microns and 250 microns was studied. It was determined that sorption efficiency followed the trend Cu^{2+} (148.0 mg/g) > Ni^{2+} (90.9 mg/g) > Zn^{2+} (15.8 mg/g) for 106µm. Equilibrium sorption of the three metal ions on the adsorbents using the coefficient of determination (R^2) showed that sorption of Zn^{2+} followed Langmuir isotherm; sorption of Zn^{2+} ions - by Freundlich isotherm and sorption of Cu^{2+} ions - by Temkin isotherm [87].

Sorghumwaste in nature and chemically activated with phosphoric acid was used as a solid phase extraction material to determine Cd^{2+}, Cu^{2+}, Mn(II), and Pb^{2+} ions in aqueous solutions. The adsorption capacity of modified sorghum waste was determined by the batch method under the optimized conditions. The adsorption capacity of modified sorghum waste was found to be 9.53 mg/g, 11.77 mg/g, 11.64 mg/g, and 15.01 mg/g for Cd^{2+}, Cu^{2+}, Mn(II), and Pb^{2+} ions, respectively [88].

The removal of Cd^{2+}, Cr(III), Cu^{2+}, and Pb^{2+} ions by native and treated *Sorghum bicolor* biomass was also studied. The modification of sorghum biomass (SB) was successfully carried out using commercial urea (USB) and thiourea (TSB) as modifying agents under microwave irradiation. The optimum removal of metal ions by SB, USB, and TSB was found at slightly acidic pH. The Langmuir model showed a better fit to equilibrium data than other models. The values obtained in the case of TSB were the highest, showing its efficacy relative to SB and USB. Kinetic modeling of the equilibrium data showed that a pseudo-second-order mechanism governed the studied biosorption process, and boundary layer diffusion was the rate-determining step. Thermodynamic studies were also performed, which showed that biosorption of studied metal ions by SB, USB, and TSB was endothermic and spontaneous [62, 74, 80, 85, 89].

The analysis of the above data on the adsorption of various metal ions allowed us to conclude that the components of sorghum biomass have the greatest sorption capacity for Pb^{2+} ions. Slightly lower sorption characteristics are observed for Cu^{2+} and Ni^{2+} ions. The worst sorption rates are observed for Zn^{2+} and Cd^{2+} ions.

3. Using Sorghum Biomass Components to Remove Dyes from Aqueous Media.

There are international publications on the studies of dye sorption by \sorghum biomass components. The largest number of publications is devoted to removing methylene blue [90-]. In particular, one describes a study on removing this dye from simulated solutions of groundnut shell (GS) and sorghum husk (SH) under static conditions. It was found that at an initial dye concentration of 50 mg/dm^3, the sorghum husk sorption capacity was 0.69 mg/g [90]. In [91], the GS and SH were also used as adsorbents for Methylene blue (MB) dye adsorption. Langmuir, Freundlich, Temkin, and Harkins-Jura models were used to represent the equilibrium data. It was found that the Langmuir model was more adequate to represent the equilibrium data for MB with GS, whereas the Temkin model fitted well to both GS and SH for MB. The maximum adsorption capacity was found to be 7.052 mg/g and 15.3846 mg/g for GS and SH, respectively, with MB dye. It was seen that the pseudo-second-order kinetic equation could best describe the sorption kinetics for all the adsorption processes [91].

The removal of MB dyes from simulated solutions with crushed Sorghum stem biomass with varying process parameters was also studied under static conditions. At an initial dye concentration of 10-100 mg/dm^3, the recovery of methylene blue adsorption has been exceeded by 80%. The adsorption isotherm study shows that the adsorption isotherm of MB onto Sorghum raw stems follows the Langmuir model, and the maximum adsorption capacity corresponding was 27.78 mg/g at 313 K. The pseudo-second-order kinetic model adequately describes the kinetic data with a high determination coefficient (R^2=0.99). The estimated values for ΔG° were -2.56, -3.31and -3.78 kJ/mole at 295, 303, and 313 K, respectively. The enthalpy changes ΔH°, and entropy ΔS° of adsorption were 17.19 kJ/mole and 67.24 J/mole-K, respectively, indicating physical endothermic spontaneous absorption [92].

Sorghum stem sorption characteristics for MB dye can be improved by modifying the latter with various chemicals. In particular, a composite was obtained from waste of *Sorghum vulgare* coated with conducting polypyrrole (PPy) by in situ polymerization using potassium persulfate as a chemical oxidant. The adsorption capacity at neutral pH for uncoated Sorghum at an equilibrium concentration (Ce) of MB dye of 10 mg/dm^3 was 41.6 mg/g of Sorghum, and for sorghum/PPy composite was 68.4 mg/gram of composite, which is 1.6 times higher; however, the maxima adsorption capacities were 86.2 and 94.4 mg/g, respectively. It was also observed that at acidic pH for a Ce of 10 mg/dm^3, the adsorption capacity of the composite was 79.2 mg/g of composite, and the maximum adsorption capacity was 143.5 mg/g). The adsorption mechanism was well described by the Langmuir isotherm [93].

Besides, Sorghum stem modification with citric acid helps achieve a maximum sorption capacity of 534.76 mg/g for this dye [94]. Treating *Sorghum bicolor* stems with pyromellitic dianhydride provided a maximum sorption capacity of 568.18 mg/g. It is determined that the kinetics study showed that the adsorption processes followed the pseudo-second-order kinetic model, which confirms that the sorption rate is controlled by chemical adsorption. Equilibrium isotherms were analyzed using the Langmuir and Freundlich models. Langmuir model can be fitted better than the Freundlich model. It was found that with initial dye concentrations of 200-400 mg/dm^3, the degree of MB dye removal exceeds 99% [95].

Sorghum stem was used to become cellulose aerogel, which was then used as an MB dye absorbent. Cellulose was prepared by sorghum stem powder delignification using 6%w of NaOH solution. The ratio of powder and NaOH was varied at 1:12, 1:15, and 1:20. After this process, the powder was synthesized with NaOH/Urea to produce an aerogel by the freeze-drying method. The maximum sorption capacity evaluated with the result is 3.42, 11.55, 11.18, and 10.58 mg/g, respectively, for commercially activated carbon, 1:12, 1:15, and 1:20 aerogel. Sorption using Sorghum stem aerogel is better than activated carbon because the % removal using Sorghum stem aerogel is three times greater than activated carbon [96].

Studies have also been conducted on removing MB dyes from simulated solutions by sorghum processing waste under dynamic laboratory conditions. Obtained data indicated that to remove MB, the best operation conditions were obtained for a bed height of H=21cm, initial concentration MB of 100 mg/dm^3, and a flow of 6 sm^3/min. The characteristics of the breakthrough curves of the sorption process of MB with sorghum waste allow us to evaluate that the column operates with high efficiency since removals of methylene blue of up to 90.68% are achieved. Under these conditions, the Thomas model best represents the experimental data of the biosorption curves of MB with a sorption capacity of 18.97 mg/g [97].

Congo red dye was also removed using two sorption materials – Sorghum husk and groundnut shell. The initial dye concentration was 10-50 mg/dm^3. The maximum dye sorption capacity of sorghum husks was found to be 0.926 mg/g, and that of peanut shells was 0.937 mg/g. The studies show that for the adsorption of Congo red dye on sorghum husk and groundnut shell, Freundlich isotherm fit the experimental data well due to high R2 values of 0.983 and 0.9720, respectively. The Temkin binding energy (b_T) is positive for the two experiments, indicating that the process is endothermic [98]. Another group of authors used these two above-mentioned sorption materials to remove Congo red dye from simulated solutions. It was found that the maximum sorption capacity for the dye, determined from the Langmuir equation, was 4.37 mg/g in the case of groundnut shell and 4.92 mg/g in the case of sorghum husk. The pseudo-first and pseudo-second-order kinetic equations, power function, and Elovich models were used to model adsorption data. The pseudo-second-order kinetic equation best represented the sorption kinetics for all adsorption processes. Like in the previous case, the adsorption isotherm is more accurately described by the Freundlich model [99].

Erythrosine dye removal from an aquatic area using natural absorbents, namely Sorghum and Ziziphus nummularia pyrene, was also reviewed. The highest adsorption was achieved in the first 30 min of adsorbent-dye contact time. Also, most of the adsorption occurred at pH values of pH = 4- 8. Moreover, the highest amount of dye removal was observed in 20 mg/dm3 concentrations for the *Ziziphus nummularia pyrene* and 5 mg/dm^3 for the Sorghum. Both adsorbents showed a better agreement with the Langmuir model [100].

In [101], the efficacy of using HCl-modified malted sorghum mash to remove basic fuchsin dye from aqueous solution was investigated through batch adsorption studies. The quantity of fuchsin dye removed by the adsorbent increased with an increase in contact time, and optimum adsorption was achieved in 30 min. The adsorption process depended on the aqueous solution's pH, with optimum removal of dye occurring between pH = 4 and pH = 9. It was found that the absorption of dye by the adsorbent increased with an increase in initial dye concentration but decreased with an increase in the adsorbent dose. The Langmuir (R^2 = 0.992) and Temkin (R^2 = 0.983) models described the experimental data. The maximum adsorption capacity of HCl-modified malted sorghum mash was 58.48 mg/g at 304 K. The pseudo-second-order model yielded a much better fit than the other kinetic models. The free energy of adsorption (ΔG°) was evaluated as -22.54 kJ/mol. The negative value of ΔG° confirmed the feasibility of the process and the spontaneous nature of adsorption [101].

Starch produced from sorghum biomass was used to remove the Maxilon red GRL dye from simulated solutions. It was found that the maximum sorption capacity for this dye was 16.75 mg/g. It was also determined that the highest dye removal rate was provided at pH = 10 [102].

For example, in the case of metal ions, it isn't easy to compare the data obtained by groups of authors on the sorption characteristics of dyes under different conditions. Several articles have been found on using sorghum biomass components to remove the two dyes under identical experimental conditions.

In particular, there was a study of methylene blue and Congo red removal from sorghum husk simulated solutions. Response surface methodology (RSM) optimization was carried out using Box-Behnken design of design expert software. Effects of contact time, pH, and adsorbent dosage on the biosorbent performance on the dye removal were investigated. Optimization of the process variables gave optimum contact time of 138.05 min, pH = 3.00, and adsorbent dosage of 4.00 g/dm^3 with percentage removal of 94.22 % for methylene blue and 88.63 % for Congo red [103].

Also, a magnetically tuned biosorbent was prepared from sorghum husks using in situ co-precipitation of Fe_3O_4. The biosorbent was then used to remove methylene blue and crystal violet dyes from aqueous solutions in a batch process. The response surface method was used to optimize adsorption using Box–Behnken experimental design. A pseudo-second-order kinetic model with a correlation coefficient (R2)>0.9 was the most appropriate for both dyes. The equilibrium data were best fitted with Langmuir isotherm with maximum adsorption capacity (Qmax) of 18.87 and 30.00 mg/g for Methylene blue and Crystal violet dyes, respectively. The thermodynamic parameters for the adsorption processes showed that it was spontaneous, endothermic, and random systems with free energy changes less than zero, enthalpy changes ΔH = +49.81 and +51.18 kJ/mol, entropy changes (ΔS) = +178.39 and +177.34 J/mol·K for Methylene blue and Crystal violet dyes, respectively. Optimization studies revealed that 95% of the dyes are removable at 1.0 g adsorbent dosage and pH = 4.05 at 50°C with an initial dye concentration of 50 mg/dm^3 [104].

Sorghum bicolor L. was modified by means of phthalic anhydride for the enhanced removal of reactive dies. Alizarin red S (ARS) and Bromophenol blue (BPB) were used as a substrate for removal. The observed optimum values were 1 g/500 ppm for ARS and 1 g/300 ppm for BPB at neutral pH within 25-30 min at room temperature. The equilibrium statistics fitted well in the Langmuir equilibrium model with maximum adsorption capacities of 285.71 and 65.78 mg/g for ARS and BPB, respectively. The kinetic data was followed by the pseudo-second-order rate equation. The thermodynamics study revealed that the process was exothermic and spontaneous [105].

Also, *Sorghum bicolor* and white clover (*Trifolium repens*) extracts as plant coagulants can be used for wastewater treatment instead of chemical coagulants. It was found that in the optimum treatment conditions of 100 mg/dm^3 coagulant dose and pH = 7, high turbidity (81.34%) and COD reduction (62%) (compared with alum and $FeCl_3$) were obtained. The percentage of COD reduction is higher in white clover than the Sorghum coagulant, and the turbidity reduction percentage is higher in *Sorghum bicolor* [106].

4. Production of Activated Carbons from Sorghum Biomass Components and Using the Former for Purification of Aquatic Environments from Various Pollutants.

One of the applications of sorghum biomass is to produce activated carbons or carbonized substances and use them to remove various pollutants from aqueous media. Thus, in particular, we looked at four varieties of sweet Sorghum and processed their bags into biochars at low (350°C) and high temperatures (700°C). Several physicochemical and adsorptive properties were also determined to ascertain their potential use as either adsorbents. It was determined that the total surface area of carbonizates produced at 350°C was 0.73-2.49 m^2/g and that of activated carbons produced at 700°C – from 116 m^2/g to 216 m^2/g. It was also determined that the average volume of micropores was 1.3 m^2/g (350°C) and 99.1 m^2/g (700°C) [107].

Sorghum straw activated with phosphoric acid was used to produce activated carbon at 450°C. It was determined that the total area of activated carbon was more than 600^{m2}/g. It was found that the sorption capacity for the Methylene blue dye was 662 mg/g, for iodine – 667 mg/g [108].

The *Sorghum durra* stalk was employed as a novel precursor for forming high surface area activated carbons (ACs) by utilizing $ZnCl_2$ as an activating agent followed by pyrolysis in a flow of N_2 gas. The formation of ACs has been investigated at different pyrolysis temperatures (400, 500, and 600°C) and different $ZnCl_2$ impregnation concentrations. The results indicated that the AC could be formed with high carbon contents, good thermal stability, large specific surface areas in the 1200–1817 m2/g range, and nanostructured in graphene-like layers of 5-6 nm thick. In addition, the textural flexibility (in terms of super-micro/meso porosity) of the produced ACs can be fine-tuned by pyrolysis conditions. The potential application of ACs was tested for the removal of dye methylene blue (MB) in aqueous media. The adsorption isotherms and kinetics of dye on ACs were examined at 25°C. The ACs showed a high adsorption capacity, as high as 386 mg dye/g. The adsorption of MB was better described by the Langmuir isotherm model and followed the pseudo-second-order equation [109].

Two biomass carbon adsorbents were synthesized by a KOH activation and carbonization route using sorghum stem and root as carbon precursors. Compared with the samples without KOH activation, the pore structure of the KOH-activated carbon has been dramatically improved. The findings show that the specific surface areas of the adsorbents by sorghum stem (S1) and sorghum root (R1) were 948.6 and 168.1 m^2/g, respectively. Meanwhile, the abundant −OH and –C(O)O− groups on the surface of these adsorbents endow them with negative polarity, thereby exhibiting excellent adsorption performance for removing methylene blue (MB) and Pb^{2+} ions from wastewater. The adsorption amount and removal rate of sorghum stem was 98.1 mg/g and 98.08%, respectively, for dye, whereas those of sorghum root was 197.6 mg/g and 98.82% for the Pb^{2+} ions, respectively [110].

It also discusses the results of the study of the adsorption of methylene blue dye on activated carbon, derived from cheap and abundantly available agro-residue of *Sorghum bicolor* stalk on suitable heat and acid treatment. The batch studies revealed optimum values of adsorption parameters such as pH, adsorbent dosage, agitation speed, grain size, temperature, and contact time. The adsorption isotherm data were best described by the Langmuir isotherm model with a maximum adsorption capacity of 176.05 mg dye/g activated carbon at 30 °C [111].

Modified sweet Sorghum-derived biochar using bentonite clay was prepared for its adsorption behavior towards removing the cationic dye Malachite green. A clay biochar composite was prepared by combining clay and biochar in a ratio of 1:5. The composite showed an improvement in the adsorption capacity for the dye removal compared to the biochar. It was found that the maximum sorption capacity of coal for the dye was 9.84 mg/g, of composite – 12.13 mg/g. The kinetic studies revealed that the adsorption fits both pseudo-first-order (R^2 – 0.9864) and pseudo-second-order kinetic models (R^2 – 0.9975), which indicates both physisorption and chemisorption mechanisms for the interaction between adsorbent and adsorbate molecules. The adsorption isotherm indicated that the Freundlich model best describes the adsorption mechanism [112].

Also, the composite was prepared using a 1:5 mass ratio of bentonite to biomass, which subsequently underwent fast pyrolysis. Isotherm and kinetic models were used to assess each of the adsorbents' capacity to remove Cr(VI) and Zn^{2+} ions. Bentonite and biochar showed a high adsorption affinity toward Zn^{2+} ions (Qe = 14.536 mg/g and Qe = 14.063 mg/g, respectively) and a poor adsorption capacity for the removal of Cr(VI) ions (Qe = 0.291 mg/g and Qe = 0.529 mg/g respectively). The prepared composite had a lower adsorption capacity for both metals (Qe = 0.572 mg/g and Qe = 10.897 mg/g for Cr(VI) and Zn^{2+} ions, respectively) compared to the control group [113].

The sorghum straw biochar was prepared by pyrolysis of sorghum powder with particle sizes ranging from 40 to 120 mesh under an oxygen-limited condition at 550°C for 1 h. A novel method has been developed for the simultaneous removal of one of the organic arsenic forms, roxarsone (4-hydroxy-3-nitrobenzene arsonic acid) and As(III/V) ions using the modified sorghum straw biochar. The removal performance of biochar for roxarsone, arsenite [As(III)], and arsenate (As(V)) was investigated using batch experiments. At pH = 5, the arsenic concentration of 1.0 mg/dm^3, the adsorbent dose of 1.0 g/dm^3, the maximum adsorption capacities of roxarsone, As(III) ions, and As(V) ions were 12.4 mg/g, 5.3 mg/g, and 23.0 mg/g, respectively. The adsorption behaviors fit well with the Langmuir and the pseudo-second-order rate model [114].

Activated carbon produced from sorghum biomass was studied to determine the ability to remove Cr(III) and Ni^{2+} ions from simulated solutions. The experiments were carried out with varying process parameters (pH, initial concentration of metal ions, dosage of adsorbent, contact time). It was found that the maximum sorption capacity calculated based on the Langmuir equation was 25.64 mg/g for Cr(III) ions and 47.62 mg/g. It was found that the adsorption isotherm for the Cr(III) ion is more accurately described (R^2 = 0.980) by the Langmuir model for Ni^{2+} ions by the Freundlich model (R^2 = 0.977). The process kinetics in both cases is described by the pseudo-second-order model [115].

Batch adsorption experiments were carried out to study the influencing factors and adsorption mechanisms of ammonium ions onto sorghum straw biochar (SSB). The results showed that the adsorption capacity of biochar was much higher than sorghum straw's. The biochar pyrolyzed at 300°C had the highest adsorption capacity. The favorable pH was 6–10, and the optimal dosage was 2.5 g/dm^3. The adsorption process and behavior conformed to the pseudo-second-order kinetic and Langmuir isotherm adsorption models. The maximum ammonium adsorption capacity of SSB at 45°C was 7.09 mg/g. The ammonium adsorption of biochar was mainly chemical adsorption. The regeneration test indicated SSB had good regeneration performance after three adsorption-regeneration cycles [116].

Also, chemically activated biochars prepared from grain from sorghum distillers using two base activators (NaOH and KOH) were investigated for their adsorption properties with respect to ammonium nitrogen from aqueous solution. The results showed that the alkali-activated biochar exhibited significantly enhanced adsorption capacity by 2.93 and 4.74 times, respectively, compared with the pristine biochar. Although the NaOH-activated biochar possessed a larger specific surface area (132.8 and 117.7 m^2/g for the NaOH- and KOH-activated biochars, respectively), the KOH-activated biochar had higher adsorption capacity owing to its much higher content of functional groups. The biochar had a maximum adsorption capacity of 14.34 mg/g at 45°C. The adsorption process followed pseudo-second-order kinetics, and chemical adsorption was the rate-controlling step. The equilibrium data were consistent with the Freundlich isotherm, and the thermodynamic parameters suggested that the adsorption process was endothermic and spontaneous [117].

A biochar composite was prepared with sorghum straw and sewage sludge as raw materials by modification with Na_2CO_3 to remove sulfamethoxazole from water. The specific surface area and total pore volume were 519 m^2/g and 0.210 cm^3/g, respectively. At pH = 3-6, neutral sulfamethoxazole molecule adsorption was mainly through hydrophobic action. When pH > 7.0, the adsorption of anionic sulfamethoxazole species mainly depended on the negative charge-assisted hydrogen bond. The Langmuir model showed the best consistency with experimental data, and the maximum adsorption capacity of sulfamethoxazole on biochar at pH 6.0 and 20°C was calculated to be 139.8 mg/g [118].

Sorghum straw carbon (SSC) treated in NH_3 atmosphere was employed for surface modification of Bi_2WO_6 photocatalyst prepared by a hydrothermal method. It is found that when the mass ratio of N-containing sorghum straw carbon/Bi_2WO_6 is 1.5%, the sample manifests excellent visible light activity. The photocatalytic decontamination rate constant of phenol on the 1.5% N-containing sorghum straw carbon/Bi_2WO_6 is 8-fold that on the single Bi_2WO_6. The photocatalytic reduction efficiency for Cr(VI) ions on the 1.5% sample is 37.8% after 120 min under visible light photocatalysis, and the photocatalytic reduction rate constant of Cr(VI) ions over the 1.5% sample is 1.8-fold of that on the neat Bi_2WO_6 [119].

5. Conclusions

This review summarizes the literature data on the use of sorghum biomass components (stem, leaves, root) and processing waste (grain husk, bagasse) as sorption materials to remove various metals and metalloids (As(V), Cd^{2+}, Cr(III), Cr(VI), Cu^{2+}, Fe^{3+}, Mn(II), Ni^{2+}, Pb^{2+}, Tl^{+}, Zn^{2+}), dyes, and other organic compounds from aqueous media. It also briefly describes the ways to use sorghum processing waste in various production industries. The parameters of certain pollutant adsorption by sorghum biomass and processing waste are given. It is shown that treatment with various chemicals improves sorghum biomass components and waste sorption characteristics for various pollutants. It was found that adsorption isotherms are described by various models, most often by those of Langmuir and Freundlich. In most cases, the process kinetics follows the pseudo-second-order model. It is also shown that sorghum components and processing waste are good precursors for activated carbons and carbonizate production, which can also be used to remove various organic and inorganic pollutants from aquatic environments.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Babu, R.S.; Prasanna, K.; Kumar, P.S. A censorious review on the role of natural lignocellulosic fiber waste as a low-cost adsorbent for removal of diverse textile industrial pollutants. *Environ. Res*. **2022**, *215*, 114183, https://doi.org/10.1016/j.envres.2022.114183.
2. Bilal, M.; Ihsanullah, I.; Shah, M.U.H.; Reddy, A.V.B.; Aminabhavi, T.M. Recent advances in the removal of dyes from wastewater using low-cost adsorbents. *J. Environ. Manag*. **2022**, *321*, 115981, https://doi.org/10.1016/j.jenvman.2022.115981.
3. Ho, S. Low-Cost Adsorbents for the Removal of Phenol/Phenolics, Pesticides, and Dyes from Wastewater Systems: A Review. *Water* **2022**, *14*, 3203, https://doi.org/10.3390/w14203203.
4. Topare, N.S.; Wadgaonkar, V.S. A review on application of low-cost adsorbents for heavy metals removal from wastewater. *Mater. Today: Proceedings* **2023**, *77*, 8-18, https://doi.org/10.1016/j.matpr.2022.08.450.
5. Shaikhiev, I.G.; Kraysman, N.V.; Sverguzova, S.V. Review of pistachio (*Pistacia*) shell use to remove pollutants from aqua media. *Biointerface Res. Appl. Chem*. **2023**, *13*, 1-11, https://doi.org/10.33263/BRIAC134.389.
6. Shaikhiev, I.G.; Kraysman, N.V.; Sverguzova, S.V. Review of peach (*Prúnus pérsica*) shell use to remove pollutants from aquatic environments. *Biointerface Res. Appl. Chem*. **2023**, *13*, 1-14, https://doi.org/10.33263/BRIAC135.459.
7. Varsha, M.; Kumar, P.S.; Rathi, B.S. A review on recent trends in the removal of emerging contaminants from aquatic environment using low-cost adsorbents. *Chemosphere* **2022**, *287*, 132270, https://doi.org/10.1016/j.chemosphere.2021.132270.
8. Ungureanu, E.L.; Mocanu, A.L.; Stroe, C.A.; Panciu, C.M.; Berca, L.; Sionel, R.M.; Mustatea, G. Agricultural byproducts used as low-cost adsorbents for removal of potentially toxic elements from wastewater: A comprehensive review. *Sustainability* **2023**, *15*, 5999, https://doi.org/10.3390/su15075999.
9. Nayagam, J.O.P.; Prasanna, K. Utilization of shell-based agricultural waste adsorbents for removing dyes: A review. *Chemosphere* **2022**, *291*, 132737, https://doi.org/10.1016/j.chemosphere.2021.132737.
10. Chakraborty, R.; Asthana, A.; Singh, A.K.; Jain, B.; Susan, A.B.H. Adsorption of heavy metal ions by various low-cost adsorbents: a review. *Int. J. Environ.l Analyt. Chem*. **2022**, *102*, 342-379, https://doi.org/10.1080/03067319.2020.1722811.
11. Kinoti, I.K.; Karanja, E.M.; Nthiga, E.W.; M'thiruaine, C.M.; Marangu, J.M. Review of clay-based nanocomposites as adsorbents for the removal of heavy metals. *J. Chem*. **2022**, *2022*, 7504626, https://doi.org/10.1155/2022/7504626.
12. Dhar, A.K.; Himu, H.A.; Bhattacharjee, M.; Mostufa, M.G.; Parvin, F. Insights on applications of bentonite clays for the removal of dyes and heavy metals from wastewater: a review. *Environ. Sci. Pollut. Res*. **2023**, *30*, 5440-5474, https://doi.org/10.1007/s11356-022-24277-x.

13. Novikau, R; Lujaniene, G. Adsorption behaviour of pollutants: Heavy metals, radionuclides, organic pollutants, on clays and their minerals (raw, modified and treated): A review. *J. Environ. Manag*. **2022**, *309*, 114685, https://doi.org/10.1016/j.jenvman.2022.114685.
14. Ewis, D.; Ba-Abbad, M.M.; Benamor, A.; El-Naas, M.H. Adsorption of organic water pollutants by clays and clay minerals composites: A comprehensive review. *Appl. Clay Sci.* **2022**, *229*, 106686, https://doi.org/10.1016/j.clay.2022.106686.
15. Ayalew, A.A. A critical review on clay-based nanocomposite particles for application of wastewater treatment. *Water Sci. Technol*. **2022**, *85*, 3002-3022, https://doi.org/10.2166/wst.2022.150.
16. Farooq, U.; Kozinski, J.A.; Khan, M.A.; Athar, M. Biosorption of heavy metal ions using wheat based biosorbents–a review of the recent literature. *Bioresource Technol*. **2010**, *101*, 5043-5053, https://doi.org/10.1016/j.biortech.2010.02.030.
17. Lata, S., Samadder, S.R. Removal of heavy metals using rice husk: a review. *Int. J. Environ. Res. Develop*. **2014**, *4*, 165-170.
18. Chuah, T.G.; Jumasiah, A.; Azni, I.; Katayon, S.; Choong, S.T. Rice husk as a potentially low-cost biosorbent for heavy metal and dye removal: an overview. *Desalination* **2005**, *175*, 305-316, https://doi.org/10.1016/j.desal.2004.10.014.
19. Sandeep, C. Rice husk as a potential adsorbent for removal of metal ions-a review. *Der Chemica Sinica*, **2015**, *6*, 90-93.
20. Syuhadah, N.; Rohasliney, H. Rice husk as biosorbent: a review. *Health Environ. J*. **2012**, *3*, 89-95.
21. Shamsollahi, Z.; Partovinia, A. Recent advances on pollutants removal by rice husk as a bio-based adsorbent: A critical review. *J. Environ. Manag*. **2019**, *246*, 314-323, https://doi.org/10.1016/j.jenvman.2019.05.145.
22. Ahmed, M.J.; Hameed, B.H.; Hummadi, E.H. Insight into the chemically modified crop straw adsorbents for the enhanced removal of water contaminants: A review. *J. Molec. Liquids* **2021**, *330*, 115616, https://doi.org/10.1016/j.molliq.2021.115616.
23. Shaikhiev, I.G.; Sverguzova, S.V.; Shaikhieva, K.I.; Deberdeev, T. R. Using rye (Secale cereale) processing wastes as sorption materials for removing pollutants from aquatic environments. *Polymer Sci. Series D* **2023**, *16*, 651-656, https://doi.org/10.1134/S1995421223030346.
24. Sharma, A.; Tomer, A.; Singh, J.; Chhikara, B.S. Biosorption of metal toxicants and other water pollutants by Corn (Maize) plant: A comprehensive review. *J. Integr. Sci. Technol.* **2019**, *7*, 19-28.
25. Ahmed, M.J.; Danish, M.; Anastopoulos, I.; Iwuozor, K.O. Recent progress on corn (Zea mays L.)-based materials as raw, chemically modified, carbonaceous, and composite adsorbents for aquatic pollutants: A review. *J. Analyt. Appl. Pyrolysis* **2023**, *172*, 106004, https://doi.org/10.1016/j.jaap.2023.106004.
26. Tonapi, V.A.; Talwar, H.S.; Are, A.K.; Bhat, B.V.; Reddy, C.R.; Dalton, T.J. Sorghum in the 21st century: Food, fodder, feed, fuel for a rapidly changing world; Springer: **2020**.
27. De Voogt, P.; Cavieres, M.F.; Gunther, F.A. Reviews of environmental contamination and toxicology; Springer: **2016**.
28. Jadia, C.D.; Fulekar, M.H. Phytotoxicity and remediation of heavy metals by fibrous root grass in soil - vermicompost media. *J. Appl. Biosci*. **2008**, *10*, 491-499.
29. Koohkan, H.; Mortazavi, M.S.; Golchin, A.; Saraji, F.; Akbarzadeh-Chomachaei, G. Comparison of native bacterial and fungal bioaugmentation in the removal of petroleum from soil in the presence of Sorghum. *Water, Air, Soil Pollut.* **2023**, *234*, 309, https://doi.org/10.1007/s11270-023-06298-5.
30. Hamvumba, R.; Mataa, M.; Mweetwa, A.M. Evaluation of sunflower (*Helianthus annuus* L.), Sorghum (*Sorghum bicolor* L.) and chinese cabbage (*Brassica chinensis*) for phytoremediation of lead contaminated soils. *Environ. Pollut*. **2014**, *3*, 65, https://doi.org/10.5539/ep.v3n2p65.
31. Angelova, V.R.; Ivanova, R.V.; Delibaltova, V.A.; Ivanov, K.I. Use of sorghum crops for in situ phytoremediation of polluted soils. *J. Agricult. Sci. Technol. A* **2011**, *1*, 693-702.
32. Sani, H.A.; Yauri, A.U.B.; Muhammad, A.; Yahayya, Y.; Salau, M. Preparation and characterization of bioplastic from sorghum husk. *American J. Polymer Sci. Technol*. **2020**, *6*, 14-20, https://doi.org/10.11648/j.ajpst.20200602.12.
33. Tijani, M.A.; Ajagbe, W.O.; Agbede, O.A. Recycling sorghum husk and palm kernel shell wastes for pervious concrete production. *J. Clean. Product*. **2022**, *380*, 134976, https://doi.org/10.1016/j.jclepro.2022.134976.

34. Mohite, A.S.; Jagtap, A.R.; Avhad, M.S., More, A.P. Recycling of major agriculture crop residues and its application in polymer industry: A Review in the context of waste to energy nexus. *Energy Nexus* **2022**, *7*, 100134, https://doi.org/10.1016/j.nexus.2022.100134.
35. Reddy, N.; Yang, Y. Structure and properties of natural cellulose fibers obtained from sorghum leaves and stems. *J. Agric. Food Chem*. **2007**, *55*, 5569-5574, https://doi.org/10.1021/jf0707379.
36. Reddy, N.; & Yang, Y. Biofibers from agricultural byproducts for industrial applications. *Trends Biotechnol*. **2005**, *23*, 22-27, https://doi.org/10.1016/j.tibtech.2004.11.002.
37. Kayodé, A.P.P.; Bara, C.A.; Dalodé-Vieira, G.; Linnemann, A.R.; Nout, M.J.R. Extraction of antioxidant pigments from dye sorghum leaf sheaths. *LWT-Food Sci. Technol*. **2012**, *46*, 49-55, https://doi.org/10.1016/j.lwt.2011.11.003.
38. Kayodé, A.P.; Nout, M.R.; Linnemann, A.R.; Hounhouigan, J.D.; Berghofer, E.; Siebenhandl-Ehn, S. Uncommonly high levels of 3-deoxyanthocyanidins and antioxidant capacity in the leaf sheaths of dye sorghum. *J. Agric. Food Chem*. **2011**, *59*, 1178-1184, https://doi.org/10.1021/jf103963t.
39. Wizi, J.; Wang, L.; Hou, X.; Tao, Y.; Ma, B.; Yang, Y. Ultrasound-microwave assisted extraction of natural colorants from sorghum husk with different solvents. *Ind. Crops Prod.* **2018**, *120*, 203-213, https://doi.org/10.1016/j.indcrop.2018.04.068.
40. Xiao, M.Z.; Sun, Q.; Hong, S.; Chen, W.J.; Pang, B.; Du, Z.Y.; Yang, W.; Sun, Z.; Yuan, T.Q. Sweet Sorghum for phytoremediation and bioethanol production. *J. Leather Sci. Eng*. **2021**, *3*, 1-23, https://doi.org/10.1186/s42825-021-00074-z.
41. Chen, C. Alternative pretreatment of sorghum bagasse for bio-ethanol production; Master's Theses, Louisiana State University and Agricultural & Mechanical College: **2011**, https://doi.org/10.31390/gradschool_theses.2338.
42. Foglia, F.E. Evaluation of effectiveness of tannin removal by alkaline pretreatment on Sorghum for ethanol production blended with corn. A thesis for the degree of Master of Science. *Clemson University* **2018**, 93 p, https://open.clemson.edu/all_theses/2948/.
43. Cao, W.; Sun, C.; Li, X.; Qiu, J.; Liu, R. Methane production enhancement from products of alkaline hydrogen peroxide pretreated sweet sorghum bagasse. *RSC Advances* **2017**, *7*, 5701-5707, https://doi.org/10.1039/c6ra25798d.
44. Saratale, G.D.; Kshirsagar, S.D.; Saratale, R.G.; Govindwar, S.P.; Oh, M.K. Fermentative hydrogen production using sorghum husk as a biomass feedstock and process optimization. *Biotechnol. Bioprocess Eng*. **2015**, *20*, 733-743, https://doi.org/10.1007/s12257-015-0172-3.
45. Cheng, M.H.; Dien, B.S.; Lee, D.K.; Singh, V. Sugar production from bioenergy sorghum by using pilot scale continuous hydrothermal pretreatment combined with disk refining. *Bioresource Technol*. **2019**, *289*, 121663, https://doi.org/10.1016/j.biortech.2019.121663.
46. Sene, L.; Arruda, P.V.; Oliveira, S.M.M.; Felipe, M.G.A. Evaluation of sorghum straw hemicellulosic hydrolysate for biotechnological production of xylitol by *Candida guilliermondii*. *Brazili. J. Microbiol*. **2011**, *42*, 1141-1146.
47. Adefila, O.A.; Bakare, M.K.; Adewale, I.O. Characterization of an α-amylase from Sorghum (Sorghum bicolor) obtained under optimized conditions. *J. Inst. Brewing* **2012**, *118*, 63-69, https://doi.org/10.1002/jib.11.
48. Garg, G.K., Virupaksha, T.K. Acid protease from germinated Sorghum: 1. Purification and characterization of the enzyme. *Eur. J. Biochem*. **1970**, *17*, 4-12, https://doi.org/10.1111/j.1432-1033.1970.tb01124.x.
49. Bello, M.O.; Abdus-Salam, N.; Adekola, F.A. Utilization of Guinea corn (*Sorghum vulgare*) husk for preparation of bio-based silica and its characterization studies. *Int. J. Environ. Agric. Biotechnol*. **2018**, *3*, 670-675, https://doi.org/10.22161/ijeab/3.2.48.
50. Athinarayanan, J.; Jaafari, S.A.A.H.; Periasamy, V.S.; Almanaa, T.N.A., Alshatwi, A.A. Fabrication of biogenic silica nanostructures from *Sorghum bicolor* leaves for food industry applications. *Silicon* **2020**, *12*, 2829-2836, https://doi.org/10.1007/s12633-020-00379-4.
51. Akaleme, M.C.; Hassan, I.O.; Olawuyi, B.J. Preparation and characterization of nanosilica from sorghum husk ash by chemical method. *IOP Confer. Series: Mater. Sci. Eng.* **2020**, *805*, 012023, https://doi.org/10.1088/1757-899X/805/1/012023.
52. Qadri, S.B.; Gorzkowski, E.P.; Imam, M.A.; Fliflet, A.; Goswami, R.; Kim, H.; Caldwell, J.D., Klemm, F.; Rath, B.B. Production of nanoscale particles and nanorods of SiC from sorghum leaves. *Ind. Crops Products* **2013**, *51*, 158-162, http://dx.doi.org/10.1016/j.indcrop.2013.09.004.

53. Naseem, K.; Farooqi, Z.H.; Ur Rehman, M.Z.; Ur Rehman, M.A.; Begum, R.; Huma, R.; Shahbaz, A.; Najeeb, J.; Irfan, A. A systematic study for removal of heavy metals from aqueous media using *Sorghum bicolor*: an efficient biosorbent. *Water Sci. Technol*. **2018**, *77*, 2355-2368, http://dx.doi.org/10.2166/wst.2018.190.
54. González-Acevedo, Z.I.; Cano-Aguilera, I.; Aguilera-Alvarado, A.F. Removal and recovery of arsenic from aqueous solutions by sorghum biomass. In Natural Arsenic in Groundwater; CRC Press: **2005**; pp. 271-278.
55. Haque, N; Morrison, G. M; Perrusquía, G; Gutierréz, M ; Aguilera, A.F.; Cano-Aguilera, I; Gardea-Torresdey, J.L Characteristics of arsenic adsorption to sorghum biomass **. 2007** Jun 25;145(1-2):30-5. doi: 10.1016/j.jhazmat.2006.10.080. Epub 2006 Nov 1.
56. Haque, M.N.; Morrison, G.M.; Perrusquia, G.; Gutierrez, M.; Aguilera, A.F.; Cano-Aguilera, I.; Gardea-Torresdey, J.L. Characteristics of arsenic adsorption to sorghum biomass. *J. Hazard. Mater*. **2007**, *145*, 30-35, http://dx.doi.org/10.1016/j.jhazmat.2006.10.080.
57. Cano-Aguilera, I.; Haque, N.; Morrison, G.M.; Aguilera-Alvarado, A.F.; Gutierrez, M.; Gardea-Torresdey, J.L.; De La Rosa, G. Use of hydride generation-atomic absorption spectrometry to determine the effects of hard ions, iron salts and humic substances on arsenic sorption to sorghum biomass. *Microchem. J*. **2005**, *81*, 57-60, http://dx.doi.org/10.1016/j.microc.2005.01.014.
58. Saraeian, A.; Hadi, A.; Raji, F.; Ghassemi, A.; Johnson, M. Cadmium removal from aqueous solution by low-cost native and surface modified *Sorghum x drummondii* (Sudangrass). *J. Environ. Chem. Eng*. **2018**, *6*, 3322-3331, https://doi.org/10.1016/j.jece.2018.05.018.
59. Imaga, C.; Abia, A.A. Kinetics and mechanisms of cadmium (II) ion sorption using carbonized and modified sorghum (*Sorghum bicolor*) hull of two pore sizes (CMSH 150µm and 250µm). *Int. J. Chem. Process Eng. Res*. **2015**, *2*, 44-58.
60. Garcia-Reyes, R.B.; Rangel-Mendez, J.R. Adsorption kinetics of chromium (III) ions on agro-waste materials. *Bioresource Technol*. **2010**, *101*, 8099-8108, http://dx.doi.org/10.1016/j.biortech.2010.06.020.
61. Garcia-Reyes, R.B.; Rangel-Mendez, J.R.; Alfaro-De la Torre, M.C. Chromium (III) uptake by agro-waste biosorbents: chemical characterization, sorption–desorption studies, and mechanism. *J. Hazard. Mater*. **2009**, *170*, 845-854, http://dx.doi.org/10.1016/j.jhazmat.2009.05.046.
62. Salman, M.; Athar, M.; Farooq, U.; Nazir, H.; Noor, A.; Nazir, S. Microwave-assisted urea-modified sorghum biomass for Cr (III) elimination from aqueous solutions. *Korean J. Chem. Eng*. **2013**, *30*, 1257-1264, http://dx.doi.org/10.1007/s11814-013-0054-3.
63. Prasanthi, M.R.; Jayasravanthi, M.; Nadh, R.V. Kinetic, thermodynamic and equilibrium studies on removal of hexavalent chromium from aqueous solutions using agro-waste biomaterials, *Casuarina equisetifolia* L. and *Sorghum bicolor*. *Korean J. Chem. Eng*. **2016**, *33*, 2374-2383, http://dx.doi.org/10.1007/s11814-016-0078-6.
64. Mokkapati, R.P.; Ratnakaram, V.N.; Mokkapati, J.S. Utilization of agro-waste for removal of toxic hexavalent chromium: surface interaction and mass transfer studies. *Int. J. Environ. Sci. Technol*. **2018**, *15*, 875-886, https://doi.org/10.1007/s13762-017-1443-7.
65. Rizzuti, A.M.; Winston, R.J.; Orr, I.S. Biosorption of copper from aqueous solutions utilizing agricultural wastes. *Remediation J.* **2021**, *31*, 39-46, http://dx.doi.org/10.1002/rem.21674.
66. Fomina, E.V.; Sverguzova, S.V.; Sapronova, Z.A.; Kozhukhova, M.I. Obtaining sorption material from Sorghum for aqueous solutions purification from heavy metals. *IOP Conf. Series: Mater. Sci. Eng*. **2020**, *945*, 012016, http://dx.doi.org/10.1088/1757-899X/945/1/012016.
67. Mokkapati, R.P.; Mokkapati, J.; Ratnakaram, V.N. Kinetic, isotherm and thermodynamics investigation on adsorption of divalent copper using agro-waste biomaterials, *Musa acuminata*, *Casuarina equisetifolia* L. and *Sorghum bicolor*. *Polish J. Chem. Technol*. **2016**, *18*, 68-77, http://dx.doi.org/10.1515/pjct-2016-0031.
68. Dong, J.; Hu, J.; Wang, J. Radiation-induced grafting of sweet sorghum stalk for copper (II) removal from aqueous solution. *J. Hazard. Mater*. **2013**, *262*, 845-852, http://dx.doi.org/10.1016/j.jhazmat.2013.09.060.
69. Shajahan, A.; Vijayakanth, D.; Basha, K.A.; Basha, A.S. Kinetic, thermodynamic and adsorption isotherms studies on removal of copper (II) ions from aqueous solutions using Jumbo grass (*Sorghum Bicolur Sorghum Sudanefe*). *Asian J. Chem*. **2015**, *27*, 3387-3393, http://dx.doi.org/10.14233/ajchem.2015.18840.
70. Wu, J.; Dong, J.; Wang, J. Adsorptive removal of Cu (II) from aqueous solution by fermented sweet sorghum residues as a novel biosorbent. *J. Molec. Liquids* **2022**, *367*, 120362, https://doi.org/10.1016/j.molliq.2022.120362.

71. Widyaningrum, B.A.; Matilda, T.; Ningrum, R.S.; Pramasari, D.A. Utilization of sorghum bagasse modified with citric acid for Fe (III) adsorption: kinetics and isotherm studies. *Agrointek: J. Teknol. Ind. Pertanian* **2022**, *16*, 646-655.
72. Imaga, C.C.; Abia, A.A.; Igwe, J.C. Adsorption kinetics and mechanisms of nickel (II) ion sorption using carbonized unmodified sorghum (*Sorghum bicolor*) hull of two pore sizes (150µm and 250µm). *J. Chem. Pharm. Res*. **2015**, *7*, 89-101.
73. Mokkapati, R.P.; Ratnakaram, V.N.; Mokkapati, J. Mass transfer, kinetic, equilibrium, and thermodynamic study on removal of divalent lead from aqueous solutions using agrowaste biomaterials, *Musa acuminata*, *Casuarina equisetifolia* L., and *Sorghum bicolor*. *Theoret. Found. Chem. Eng*. **2019**, *53*, 578-590, https://doi.org/10.1134/S0040579519040249.
74. Salman, M.; Athar, M.; Farooq, U.; Rauf, S.; Habiba, U. A new approach to modification of an agro-based raw material for Pb (II) adsorption. *Korean J. Chem. Eng*. **2014**, *31*, 467-474, https://doi.org/10.1007/s11814-013-0264-8.
75. Imaga, C.C.; Abia, A.A. Kinetics and mechanisms of sorption of lead (II) ions using carbonized and mercapto-Acetic acid modified sorghum (*Sorghum bicolor*) hull of two pore sizes. *J. Multidisciplin. Eng. Sci. Technol*. **2015**, *2*, 316-323.
76. Afandi, A.Y.; Kurniawan, Y.D.; Widyaningrum, B.A.; Matilda, T.; Indriani, D.W.; Putri, D.I.M.; Darmokoesoemo, H.; Kusuma, H.S. Potentials of NaOH modified agricultural waste of sorghum bagasse for lead (II) removal from aqueous solution: kinetics, isotherm and thermodynamic studies. *Chem. Ecology* **2023**, *39*, 506-524, https://doi.org/10.1080/02757540.2023.2206395.
77. Zhao, T.; Dai, G.; Gu, H.; Sun, R. Adsorption characteristics of lead ion by sorghum vinasse. *Polish J. Environ. Stud*. **2022**, *31*, 3447-3454, https://doi.org/10.15244/pjoes/146008.
78. Chen, H.; Sharma, P.R.; Sharma, S.K.; Alhamzani, A.G.; Hsiao, B.S. Effective thallium(I) removal by nanocellulosebBioadsorbent prepared by nitro-oxidation of sorghum stalks. *Nanomaterials* **2022**, *12*, 4156, https://doi.org/10.3390/nano12234156.
79. Chergui, S.; Yeddou, A.R.; Chergui, A.; Halet, F.; Nadjemi, B.; Ould-Dris, A. Removal of cyanide from aqueous solutions by biosorption onto sorghum ttems: kinetic, equilibrium, and thermodynamic studies. *J. Hazard. Toxic Radioact. Waste* **2022**, *26*, 04021037, https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000647.
80. Salman, M.; Rehman, R.; Farooq, U.; Tahir, A.; Mitu, L. Biosorptive removal of cadmium (II) and copper (II) using microwave-assisted thiourea-modified Sorghum bicolor agrowaste. *J. Chem*. **2020**, 8269643, https://doi.org/10.1155/2020/8269643.
81. Tatah, V.S.; Otitoju, O.; Ezeonu, C.S.; Onwurah, I.N.E.; Ibrahim, K.L.C. Characterization and adsorption isotherm studies of Cd (II) and Pb (II) ions bioremediation from aqueous solution using unmodified sorghum husk. *J. Appl. Biotechnol. Bioeng*. **2017**, *2*, 113-120, http://dx.doi.org/10.15406/jabb.2017.02.00034.
82. Choudhary, S.; Goyal, V.; Singh, S. Removal of copper (II) and chromium (VI) from aqueous solution using sorghum roots (*S. bicolor*): a kinetic and thermodynamic study. *Clean Technol. Environ. Policy* **2015**, *17*, 1039-1051, https://doi.org/10.1007/s10098-014-0860-2.
83. Imaga, C.C., Abia, A.A. Assessment of chemical modification, pH and pore size of Sorghum (*Sorghum bicolor*) hull in sorption of Ni^{2+} and Cu^{2+}. *Sci. J. Pure Appl. Chem*. **2014**, 1-9.
84. Essien, N.B.; Essien, U.B.; Ibuot, A.A. Sorghum waste as an efficient adsorbent for the removal of Zn^{2+} and Cu^{2+} from aqueous medium. *Commun. Physical Sci*. **2010**, *5*, 51-61.
85. Salman, M.; Athar, M.; Farooq, U.; Nazir, S.; Nazir, H. Insight to rapid removal of Pb (II), Cd (II), and Cu (II) from aqueous solution using an agro-based adsorbent *Sorghum bicolor* L. biomass. *Desalin. Water Treat*. **2013**, *51*, 4390-4401, https://doi.org/10.1080/19443994.2012.749186.
86. Essien, N.B.; Odoemelam, S.; Essien, U.B. Sorghum waste as an adsorbent for the removal of nickel, copper and chromium ions from aqueous solution. *Chem. Res. J*. **2018**, *3*, 74-83.
87. Imaga, C.; Abia, A.A.; Igwe, J.C. Adsorption isotherm studies of Ni (II), Cu (II) and Zn (II) ions on unmodified and mercapto-acetic acid (MAA) modified sorghum hulls. *Int. Res. J. Pure Appl. Chem*. **2015**, *5*, 318-330, http://dx.doi.org/10.9734/IRJPAC/2015/13510.
88. Uçar, G.; Bakircioglu, D.; Kurtulus, Y.B. Determination of metal ions in water and tea samples by flame-AAS after preconcentration using Sorghum in nature form and chemically activated. *J. Analyt. Chem*. **2014**, *69*, 420-425, https://doi.org/10.1134/S1061934814050098.

89. Salman, M. USE OF ECO-FRIENDLY MODIFIED LIGNOCELLULOSIC MATERIAL FOR DETOXIFICATION OF METAL CONTAMINATED WATERS. Doctoral dissertation, Institute of Chemistry, University of the Punjab. **2016**.
90. Sunday, K.; Amarachi, E.I. Adsorption Isotherm of Methylene blue dye on Sorghum husk and ground nut shell. *ChemRxiv. Cambridge: Cambridge Open Engage* **2022**, 1-19, https://doi.org/10.26434/chemrxiv-2022-xwn8t.
91. Hammari, A.M.; Abubakar, H.; Misau, M.I.; Aroke, U.O.; Hamza, U.D. Adsorption equilibrium and kinetic studies of methylene blue dye using groundnut shell and sorghum husk biosorbent. *J. Environ. Bioremediat. Toxicol.* **2020**, *3*, 32-39, https://doi.org/10.54987/jebat.v3i2.556.
92. Sifoun, N.; Yeddou, A.R.; Nouri, L.H.; Chergui, A.; Nadjemi, B. Kinetic and thermodynamic studies of methylene blue adsorption on Sorghum stems. *Algerian J. Environ. Sci. Technol.* **2020**, *6*, 1526-1536.
93. Ovando-Medina, V.M.; Díaz-Flores, P.E.; Martínez-Gutiérrez, H.; Moreno-Ruiz, L.A.; Antonio-Carmona, I.D.; Hernández-Ordoñez, M. Composite of cellulosic agricultural waste coated with semiconducting polypyrrole as potential dye remover. *Polymer Composites* **2014**, *35*, 186-193, https://doi.org/10.1002/pc.22649.
94. Li, F.; Chen, J.; Yua, X. Removal of methylene blue dye from aqueous solutions by using modified grain sorghum stalk as a new adsorbent. *Energy Procedia*, **2011**, *11*, 646-3652, https://doi.org/10.1016/j.egypro.2011.10.738.
95. Li, F.Y.; Zhang, S.H.; Chen, J.Y. The study of the modified grain sorghum stalk to remove Methylene blue dye from aqueous solution. *Adv. Mater. Res*. **2012**, *430*, 197-201, http://dx.doi.org/10.4028/www.scientific.net/AMR.430-432.197.
96. Septiani, E.L.; Prastuti, O.P.; Kurniati, Y.; Fauziyah, M.A.; Widiyastuti, W.; Setyawan, H.; Wahyudiono; Kanda, H.; Goto, M. Sorption efficiency in dye removal and thermal stability of Sorghum stem aerogel. *Mater. Sci. Forum* **2019**, *966*, 175-180, https://doi.org/10.4028/www.scientific.net/MSF.966.175.
97. Rives, Y.C.; Galindo, M.H.B.; Jimenez, I.J.T.; Rico, I.L.R.; Carrazana, R.J.C. Application of mathematical models to breakthrough curves of methylene blue removal using agricultural waste of Sorghum (AWS). *Int. J. Adv. Eng. Res. Sci*. **2019**, *6*, 7, https://dx.doi.org/10.22161/ijaers.6739.
98. Sunday, K.; Nyankwon, M.Y. Adsorption isotherms of Congo red dye on groundnut shell and sorghum husk. *Chemrxiv* **2022**, 1-18.
99. Hammari, A.M.; Misau, M.I.; Aroke, U.O.; Hamza, U.D.; Yusuf, A.A. Adsorption equilibrium and kinetics studies of Congo red dye using groundnut shell and sorghum husk biosorbent. *J. Biochem., Microbiol. Biotechnol*. **2021**, *9*, 29-36, https://doi.org/10.54987/jobimb.v9i1.573.
100. Yahyaei, N.; Mousavi, J.; Parvini, M.; Mohebi, P. Comparison and analysis of two natural adsorbents of *Sorghum* and *Ziziphus nummularia* pyrene for removal of Erythrosine dye from aquatic environments. *Adv. Environ. Technol*. **2016**, *2*, 71-76, http://dx.doi.org/10.22104/aet.2016.381.
101. Oyelude, E.O.; Frimpong, F.; Dawson, D. Studies on the removal of basic fuchsin dye from aqueous solution by HCl treated malted sorghum mash. *J. Mater. Environ. Sci*. **2015**, *6*, 1126-1136.
102. Irinislimane, H.; Belhaneche-Bensemra, N. Extraction and characterization of starch from oak acorn, Sorghum, and potato and adsorption application for removal of Maxilon red GRL from wastewater. *Chem. Eng. Commun*. **2017**, 897-906, http://dx.doi.org/10.1080/00986445.2017.1325739.
103. Hamza, U.D., Datugun, P.; Ahmed, S.I. Response surface methodology optimization of Methylene blue and Congo red dyes adsorption on sorghum husk. *ABUAD J. Eng. Res. Develop*. **2019**, *2*, 49-58, http://dx.doi.org/10.1088/1757-899X/959/1/012010.
104. Adeogun, A.I.; Akande, J.A.; Idowu, M.A.; Kareem, S.O. Magnetic tuned sorghum husk biosorbent for effective removal of cationic dyes from aqueous solution: isotherm, kinetics, thermodynamics and optimization studies. *Appl. Water Sci*. **2019**, *9*, 1-17, https://doi.org/10.1007/s13201-019-1037-2.
105. Akram, M.; Salman, M.; Farooq, U.; Saleem, U.; Tahir, S.; Nazir, H.; Arsalan, H.M. Phthalate-functionalized Sorghum bicolor L.; an effective biosorbent for the removal of Alizarin Red S and Bromophenol blue dyes from simulated wastewater. *Desalin. Water Treat*. **2020**, *190*, 383-392, https://doi.org/10.5004/dwt.2020.25724.
106. Mirbolooki, H.; Parsa, M.; Moghadami, S.; Ghanbari, F.; Ostovar, F. Use of plant-based coagulants *Sorghum Bicolor* and *Trifolium Repens* as future alternatives for textile wastewater treatment based on computational model. *J. Computat. Cognitive Eng*. **2024**, *5*, 106-113, http://dx.doi.org/10.61360/BoniGHSS242016120301.

107. Lima, I.; Bigner, R.; Wright, M. Conversion of sweet sorghum bagasse into value-added biochar. *Sugar Technol*. **2017**, *19*, 553-561, https://doi.org/10.1007/s12355-017-0508-8.
108. Lori, J.A.; Lawal, A.O.; Ekanem, E.J. Adsorption characteristics of active carbons from pyrolysis of bagasse, Sorghum and millet straw in ortho phosphoric acid. *J. Environ. Sci. Technol*. **2008**, *1*, 124-134, https://doi.org/10.3923/jest.2008.124.134.
109. Khalil, K.M.; Allam, O.A.; Khairy, M.; Mohammed, K.M.; Elkhatib, R.M.; Hamed, M.A. High surface area nanostructured activated carbons derived from sustainable sorghum stalk. *J. Molec. Liq*. **2017**, *247*, 386-396, https://doi.org/10.1016/j.molliq.2017.09.090.
110. Hou, J.; Liu, Y.; Wen, S.; Li, W.; Liao, R.; Wang, L. Sorghum-waste-derived high-surface area KOH-activated porous carbon for highly efficient methylene blue and Pb (II) removal. *ACS Omega* **2020**, *5*, 13548-13556, https://doi.org/10.1021/acsomega.9b04452.
111. Dod, R.; Banerjee, G.; Saini, D.R. Removal of methylene blue (MB) dye from water environment by processed Jowar Stalk [Sorghum bicolor (L.) Moench] adsorbent. *Clean Technol. Environ. Policy* **2015**, *17*, 2349-2359, https://doi.org/10.1007/s10098-015-0977-y.
112. Fosso-Kankeu, E.; Waanders, F.; Potgieter, J. Enhanced adsorption capacity of sweet Sorghum derived biochar towards malachite green dye using bentonite clay. **2016**; pp. 24-25.
113. Fosso-Kankeu, E.; Waanders, F.B.; Steyn, F.W. The preparation and characterization of clay-biochar composites for the removal of metal pollutants. **2015**; pp. 54-57.
114. Zang, S.; Zuo, Y.; Wang, J.; Liu, X.; Gomez, M.A.; Wei, L. Adsorption removal of roxarsone, arsenite (III), and arsenate (V) using iron-modified sorghum straw biochar and its kinetics. *Acta Geochimica* **2021**, *40*, 409-418, https://doi.org/10.1007/s11631-021-00466-2.
115. Adewoye, L.T.; Mustapha, S.I.; Adeniyi, A.G.; Tijani, J.O.; Amoloye, M.A.; Ayinde, L.J. Optimization of nickel (ii) and chromium (iii) removal from contaminated water using Sorghum bicolor. *Nigerian J. Technol*. **2017**, *36*, 960-972, https://doi.org/10.4314/njt.v36i3.41.
116. Xu, H.; Wang, B.; Zhao, R.; Wang, X.; Pan, C.; Jiang, Y.; Zhang, X.; Ge, B. Adsorption behavior and performance of ammonium onto sorghum straw biochar from water. *Sci. Reports* **2022**, *12*, 5358, https://doi.org/10.1038/s41598-022-08591-5.
117. Hsu, D.; Lu, C.; Pang, T.; Wang, Y.; Wang, G. Adsorption of ammonium nitrogen from aqueous solution on chemically activated biochar prepared from sorghum distillers grain. *Appl. Sci*. **2019**, *9*, 5249, https://doi.org/10.3390/app9235249.
118. Niu, Y.; Huang, Z.; Huang, J.; Qin, D.; Tang, L.; Hu, W.; Dong, K.; Wang, D. Highly effective removal of sulfamethoxazole by Na_2CO_3-modified biochar derived from sorghum straw and sewage sludge. *Environ. Sci. Water. Res. Tech*. **2023**, *9*, 2355-2367, https://doi.org/10.1039/D3EW00120B.
119. He, Y.; Chen, Y.; Lei, S.; Zhong, J.; Li, M. Rich oxygen vacancies facilitated visible light-driven removal of phenol and Cr (VI) over Bi_2WO_6 decorated by sorghum straw carbon. *Colloids Surf. A: Physicochem. Eng. Aspects* **2022**, *641*, 128534, https://doi.org/10.1016/j.colsurfa.2022.128534.