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Components of Millet Biomass as Sorption Materials to Remove Various Pollutants from Aqueous Media (a Brief Literature Review)

Ildar G. Shaikhiev [1], Natalia V. Kraysman [2,*], Svetlana V. Sverguzova [3]

[1] Department of Engineering Ecology, Institute of Chemical Engineering and Technology, Kazan National Research Technological University, Kazan, Russian Federation; ildars@inbox.ru;
[2] Department of Foreign Languages for Professional Communication, Institute of Innovation Management, Kazan National Research Technological University, Kazan, Russian Federation; n_kraysman@mail.ru;
[3] Department of Industrial Ecology, Institute of Chemical Engineering and Technology, Belgorod State Technological University named after V.G. Shukhov, Belgorod, Russian Federation; pe@intbel.ru;
* Correspondence: n_kraysman@mail.ru;

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Abstract: The paper provides literature data on using millet biomass components (straw, husk, and bran) as sorption materials to remove various metal ions and dyes from aqueous media. It also presents data on the sorption capacity of millet biomass components for various pollutants. The analysis revealed that the adsorption isotherms, in most cases, are more accurately described by the Langmuir and Freundlich models, and the process kinetics most often follows the pseudo-second-order model. It has also been shown that millet biomass components can be used as precursors to produce activated carbons and carbonizates, which are also effective sorbents to remove various pollutants from simulated and real wastewater.

Keywords: millet straw; husk and bran; metal ions; dyes; adsorption; modification; activated carbon.

1. Introduction

Chemical pollution of the environment has become threatening at the moment. The main pollutants in poorly treated wastewater due to man-made accidents are oil and petrochemical products, various metal ions, dyes, pesticides, antibiotics, and other medicines etc.

The choice of the purification method to remove various pollutants from wastewater and natural water depends on the nature of the pollutant, its physical state, solubility in water, and other parameters. This requires a selective approach to removing or disposing of pollutants from aquatic environments, which entails the sophistication of the natural and wastewater treatment equipment.

However, an all-purpose method allows the removal of various pollutants from water with any initial concentration to almost zero residual concentrations, i.e., adsorption. However, activated carbons used in water treatment are expensive and require the regeneration of sorbed pollutants, which further contributes to the increase in the cost of the process.

A solution to this issue may be a new innovative trend currently developing globally – using lignocellulose waste and wood, shrub, and grass biomass components as chemicals to

remove various pollutants from aquatic environments. Of particular interest are the components of biomass and agricultural raw materials waste. They offer the benefits of cheapness, annual generation, large amounts, often high efficiency, and a number of other advantages.

The largest amount of waste is generated across the globe during grain biomass processing. Wastes, including straw, husks, bran, and glume, are formed during processing. The latter has been widely studied as a sorption material for removing various pollutants from aquatic media. In particular, it has been shown that wheat [1-3], rice [4-6], barley [7-9], oats [10-12], rye [13-15], and buckwheat [16, 17] straws are effective sorption materials to remove various pollutants from aqueous media. It has also been shown that wheat [18, 19], rice [4, 20-22], barley [23, 24], rye [13, 25, 26], oats [27, 28], buckwheat [16, 29, 30] and other cereals' husks effectively remove various chemicals from wastewater and simulated water.

One of the cereals cultivated by man since ancient times is millet. Up to 442 millet varieties grow in Asia, America, Africa, and Europe, and proso millet (*Panicum miliaceum*) is mainly grown for grain, which is currently unknown in its wild form. The plant has a panicled inflorescence with long branches. Root fibrous. Spikelets compressed from the back, convex on one side and flat on the other, ovate-pointed. Three papyraceous glumes with prominent veins, the lower one shorter than the next two. In the sinus of the third glume, a fourth one usually develops, belonging, like the third, to an underdeveloped flower. Flower scales are cartilaginous after flowering. Three stamens. Stigmas pinnate. Fruit free caryopsis [31-33].

In addition to proso millet, other millet varieties are cultivated in the world, such as pearl millet (*Cenchrus americanus* or *Pennisetum typhoides*), African millet (*Pennisetum glaucum)* [33], etc.

The UN General Assembly declared 2023 the International Year of Millets (IYM 2023). This time, millet attracted attention as a drought-resistant, low-maintenance, and nutritious crop, which is relevant in the context of climate change [34, 35].

Millet grain is used to produce cereals and flour, malt, and alcohol; grain, husk, and straw are used for livestock feed. Millet biomass processing product is straw, which, in most cases, is burned or plowed into the ground, which is economically unjustified.

The composition of millet straw was determined: total carbohydrates - 53.98 ± 0.50%, cellulose - 36.68 ± 0.40%, hemicellulose - 17.31 ± 0.16 %, lignin - 19.38 ± 0.21%, total nitrogen - 0.55 ± 0.02%, ash - 4.50 ± 0.03%, moisture - 15.64 ± 0.69% [36]. The total content of chemical elements was as follows: C- 85.8 ± 0.28%, N – 0.33 ± 0.02%, S – 228.9 ± $0.8 \cdot 10^{-4}$%. Also, in millet straw composition were identified, mg/kg: Co – 0.1412 ± 0.012, Cu – 0.1315 ± 0.114, Fe – 1.1955 ± 0.011, Mn – 0.0781 ± 0.019, Zn – 0.4039 ± 0.014 [37].

The high content of hydrocarbons contributes to the use of millet straw as a secondary material resource in a variety of industries. Thus, in particular, bioethanol [38], biooil [39], and biogas [40] can be produced from millet straw. Also, crushed millet straw can be used as a filler for polymer compounds [41], litter, animal feed [42], and other industries.

Millet grains are covered with lignocellulose husks, which are peeled off before using the grains. Tons of agricultural waste are generated annually, most of which is incinerated, which results in the release of large amounts of greenhouse gas. This is environmentally unfriendly and economically impractical. The main advantages of post-harvest millet waste include its accessibility, biodegradability, ease of renewal, and environmental friendliness. During the processing of millet grains, waste is generated in the form of husks and bran.

The proximate analysis of pearl millet biomass revealed that the contents were moisture (8±0.32 %), ash (6.27±0.08 %), total solids (92 ±0.14%), water extractives (6.43±0.12%),

ethanol extractives (5.72±0.34), cellulose (41.6±0.01%) hemicellulose (22.32±0.65%), glucan (28.47±2.88%), galactan (2.12±2.46%), arabinan (3.78±0.04%), xylan (17.24±0.62%), acid-soluble lignin (16.32±0.49%) and acid soluble lignin (5.49±0.08%). The chemical composition of pearl millet is comparable to and even superior to that of the other major cereals [43]. Apparently, the husks of millet grains have a similar composition.

The husks of millet grains are widely used in various industries: as a filler in brick manufacture [44], concrete [45], various polymeric materials [46-48], for the production of paper [49], bioethanol [50], furfural [51], and other valuable products.

One of the ways to use millet biomass is by its application as a sorption material to remove various pollutants from aqueous media.

2. The Use of Millet Biomass as Sorption Materials to Remove Metal Ions from Aqueous Media

It was studied on finger millet (*Eleusine coracana*) husk as an alternative adsorbent for the removal of Cu^{2+} ions from electroplating effluents. Batch experiments were conducted at room temperature - 28°C to determine the various parameters such as contact time, adsorbent dosage, pH, and initial concentration. The maximum removal efficiency of Cu^{2+} ions was 86.86% for 20 g/dm^3 of millet husk at pH = 2.0 and an equilibrium contact time of 4 h with an initial concentration of 6.24 mg/dm^3. The data fit well with Langmuir isotherms, and the kinetics of the process correspond to a pseudo-second-order model [52].

Also, the efficacy of millet husks was tested for the removal of Cu^{2+} and Fe^{2+} ions from aqueous solution. The millet husks were found to be effective for removing the targeted metal ions. The results of the FTIR analysis showed the presence of OH, C-H, NH, and C=O groups, which indicates tendencies for metal binding. Moreover, the results showed that millet husk has the removal capacity of Cu^{2+} ions of 84.5 % (67.6 mg/g). The amount of Fe^{2+} ions was found to be 91.5 % (73.2 mg/g) [53].

The ability of the chaff of millet to adsorb Cu^{2+} and Pb^{2+} ions from aqueous solution was investigated in a fixed-bed column. The Thomas model was applied to the adsorption of Cu^{2+} and Pb^{2+} ions at different flow rates and different influent concentrations to predict the breakthrough curves and determine the column's characteristic parameters useful for process design. Furthermore, the efficiency of adsorption is high. When the flow rate was 3.6 sm^3/min and the influent concentration of Cu^{2+} and Pb^{2+} ions was 14.82 mg/dm^3 and 50.12 mg/dm^{3,} respectively, the equilibrium adsorption biomass reached 1.98 mg/g and 6.72 mg/g, respectively. The competitive adsorption for Pb^{2+} and Cu^{2+} ions was studied. Moreover, the total adsorbing capability of chaff did not decrease when both Cu2+ and Pb2+ ions were in solution [54].

Millet (*Eleusine coracana*) husk was investigated as an alternative adsorbent for removing Ni^{2+} ions from wastewater. Batch experiments were conducted at room temperature - 28°C to determine the various parameters such as contact time, adsorbent dosage, pH, and initial concentration. The maximum removal efficiency of Ni^{2+} ions was 99.98% for 18 g/dm^3 of millet husk at pH = 8.0. The data fitted well to both Langmuir and Freundlich isotherms. The present study showed that millet husk was capable of removing Ni^{2+} ions from aqueous solutions [55].

Millet (*Pennisetum typhoideum*) husk has been tried and tested for the removal of Cr(VI) and Mn(VII) ions from the aqueous system. The exciting results indicate that it could be used to remove heavy metal ions from the water. A column of 12 inches in height and 2

inches in diameter of pretreated millet husk was used as a biosorbent. This column is sufficient to treat a 50 sm^3 solution (0.012 g/dm^3) of Cr(VI) ions and a 65 sm^3 solution (0.001g/dm^3) of Mn(VII) ions. The rate of flow of the solution was kept at 2 sm^3/min at room temperature and pH = 3-4 [56].

Millet husks and two other types of agricultural waste (rice and corn husks) were studied as sorption materials to remove Cr(VI), Mn(II), and Ni^{2+} ions from simulated solutions. The initial concentration of metal ions ranged from 0.2 to 1.0 mg/dm^3, the dosage of sorption materials – from 0.2 to 0.8 g/dm^3, the contact time – from 20 to 40 minutes, agitator revolutions – from 100 to 300 rpm. As shown by the experimental data, the highest degree of metal ion removal (90%) was provided at maximum values of the parameters [57].

Native and 1M HNO_3 solution-treated crushed millet husks with particle sizes 300 and 500 microns were used to remove Cd^{2+}, Ni^{2+}, and Pb^{2+} ions from simulated solutions with varying process parameters. The sorption process was relatively fast, and equilibrium was reached after about 40 min of contact at 100 rpm. Maximum removal efficiency for the three metal ions was observed at pH = 5.5. The highest percentage adsorption of Pb^{2+}, Cd^{2+}, and Ni^{2+} ions using millet husk was 98%, 94%, and 94%, and with acid-treated millet husk - 97%, 92%, and 94% for Pb^{2+}, Cd^{2+} and Ni^{2+} ions respectively [58].

Investigate the biosorption behaviors and the mechanisms of Cu^{2+}, Zn^{2+}, Cd^{2+}, and Cr(VI) ions onto foxtail millet (*Setaria italica* or *Panicum italicum* L.) shell in aqueous solution. The effects of pH = 2.0-6.0, contact time = 5–240 min, initial metal ions concentration - 25.0–300.0 mg/dm^3, particle size - 0.25–2.0 mm, and adsorbent dosage - 1.0–6.0 g/dm^3 on the adsorption efficiency of the target metal ions using millet shell were evaluated in batch experiments. The models of isotherms and kinetics were used to assess the removal behaviors of Cu^{2+}, Zn^{2+}, Cd^{2+}, and Cr(VI) ions from aqueous solution by foxtail millet shell. The results showed that the best-fitting equilibrium isotherm models for metal ions were Freundlich (Cu^{2+} and Zn^{2+}) and Langmuir (Cd^{2+} and Cr(VI)), respectively, under the proper adsorption conditions. The maximum biosorption capacities were 11.89, 10.59, 12.48, and 11.70 mg/g of Cu^{2+}, Zn^{2+}, Cd^{2+}, and Cr(VI) ions, respectively, in terms of the Langmuir model. The kinetics of adsorption of the target metal ions processes were best explained by a pseudo-second-order kinetic model. Furthermore, pseudo-second-order and intraparticle diffusion models were cooperative mechanisms during adsorption. Analysis of Fourier transform IR spectroscopy demonstrated that various functional groups, such as C—H, C=O, C=C, C—O, O—S—O, and Si—O groups, were engaged in the interaction between foxtail millet shell and metal ions [59].

Millet husks were also used to produce compound sorption materials and research to remove metal ions from aqueous media. In particular, a compound sorbent consisting of residual microalgae (*Chlorella sorokiniana*) biomass (5 g), chitosan (100 ml), and 5 g millet husk was used to remove Cd^{2+}, Pb^{2+}, and Zn^{2+} ions from simulated solutions. It can be seen that the sorption material has the highest sorption capacity; its specific surface is 2.720 m^2/g. The maximum sorption capacity for metal ions was as follows: Cd^{2+} - 22.4 mg/g, Pb^{2+} - 32.0 mg/g, and Zn^{2+} - 27.0 mg/g [60].

3. Use of Millet Processing By-Products to Remove Dyes from Aqueous Media

There are several works dedicated to the use of millet waste as a sorption material to remove dyes from aqueous media. So, foxtail millet (*Setaria italic* or *Panicum italicum* L.) shell as a raw efficient adsorbent was chosen to eliminate methylene blue (MB) based on the

eleven surfaces with many micropores, lots of negative charges, various functional groups, and some primary elements. The confirmed removal rates of MB by the adsorbents were reached at 92.04, 93.05, and 93.36%, respectively, from aqueous water, while the solution pH was at 3, 7, and 11, respectively. The behavior of adsorption for MB dye was well-described by Langmuir isotherm (R^2 = 0.9951), demonstrating favorable monolayer adsorption of MB on the adsorbent with the maximum capacity of 165.07 mg·L^{-1} in aqueous water. The data of MB dye removal was better assessed by a pseudo-second-order model ($R^2 \geq 0.9033$). The results showed that the foxtail millet shell could be applied to effectively remove MB dye from aqueous water with the combined effects of electrostatic attraction, ion exchange, functional group binding, and pore diffusion [61].

Also, the adsorption of Crystal violet dye from aqueous solution using pearl millet powder was investigated in a batch mode. The effect of initial concentration for crystal violet dye, sorption time, dose of adsorbent, pH, and temperature on dye removal were studied. The equilibrium sorption isotherms have been analyzed using the Freundlich, Langmuir, and Temkin models. Sorption kinetic is quick, and the data agree well with the pseudo-first-order kinetic model. However, the kinetics studies were provided in pseudo-second order. The adsorption capacity (Qo) of pearl millet powder was found to be 48.535 mg/g. Thermodynamic parameters such as the free energy change (ΔG^o = -5.6031 kJ/mol at 313K), enthalpy change (ΔH^o = 51.582 kJ/mol), and entropy change (ΔS^o = 0.1827 kJ/molK) reported show the adsorption process is endothermic [62].

Poly-amidoxime ligands have been synthesized from millet husk and used as an adsorbent to investigate the removal of Congo red dye from an aqueous solution. The effects of initial concentration, adsorbent dosage, and contact time have been studied. The optimum condition was found to be at an initial concentration of 60 mg/dm^3, the adsorbent dosage of 0.3 g/dm^3, and a contact time of 45 min with percentage removal of 95.9 % predictably and 94.89 % experimentally, respectively [63].

The straw of Indian Pearl millet (*Pennisetum glaucum*) was studied and characterized for the first time. The feedstock was separated into peripheral leaves, sheath, and core, and their chemical composition was determined. The long fibers obtained from pearl millet straw were used as a biosorbent for a cationic dye, methylene blue, and two anionic dyes, reactive blue 171 and acid red 57. Kinetic and thermodynamic studies were conducted to determine the adsorption mechanism of these dyes on *Pennisetum glaucum* straw. The saturation adsorption of methylene blue was 50 mg/g, while that for anionic dyes was 35 mg/g-38 mg/g. The adsorption process was endothermic. Results indicate that a combination of physical and chemical sorption mechanisms are responsible for the adsorption of dyes on pearl millet straw [64].

Pennisetum glaucum-based novel composites with functionalized carbon nanotubes (CNT) were developed to effectively and efficiently remove methylene blue and safranine O dyes from the single and binary systems. In batch studies, both dyes were effectively removed at neutral pH with 1 g/dm^3 of adsorbent dosage and 10 min of contact time at 30°C. The adsorption isotherm and kinetic data were well-fitted by the Langmuir isotherm and pseudo-second-order model, respectively. The maximum adsorption capacity of the composite containing 0.5% of carbon nanotubes was 181.81 mg/g for methylene blue and 386.1 mg/g for Safranine O dyes, respectively, which were 267.29% and 94.61% greater than raw *P. glaucum* adsorbent. The adsorption was spontaneous, exothermic, and physisorption in nature, involving electrostatic, π-π, and H-bonding interactions [65].

Also, a *Pennisetum glaucum* raw material (RM) based green bio-composite adsorbent containing 0.5% functionalized carbon nanotube was synthesized. The adsorption efficiency of prepared biocomposite adsorbents was investigated for the efficient and effective removal of three cationic dyes such as methylene blue (MB), safranine O (SO), and crystal violet (CV) from single and multi-component systems. In a single component, the process kinetics and adsorption behavior of the adsorbent were well explained by the pseudo-second-order kinetic model and Langmuir isotherm, giving a higher monolayer adsorption capacity of value, i.e., 510.96, 169.70, and 98.77 mg/g for CV, SO, and MB dyes, respectively, at neutral pH. The modified Langmuir isotherm model was employed to investigate the inhibiting effects of dyes in binary systems (MB+CV; CV+SO; SO+MB) and ternary systems (MB+CV+SO), which revealed the competitive behavior of dyes. The regeneration studies of bio-composites showed excellent recovery capability, retaining their good adsorption efficiency after 10 regeneration cycles [66].

An efficient, cost-effective, and environmentally friendly cetyltrimethylammonium bromide (CTAB) surfactant-modified *Pennisetum glaucum* (RM) based composite containing 0.5% functionalized carbon nanotube (CNT) has been developed. The main aim of this study was to assess and optimize the synthesized adsorbent used for the removal of Reactive Red 35 (RR), Coomassie Brilliant Blue R-250 (BB), and Eriochrome Black-T (EBT) dyes in their single, binary, and ternary solutions by employing the Box Behnken Design (BBD) under Response Surface Methodology (RSM). The equilibrium experimental data was best fitted to the monolayer Langmuir adsorption isotherm model, giving a maximum adsorption capacity of 210.97, 259.07, and 289.85 mg/g for RR, BB, and EBT dyes, respectively, in individual component systems, at neutral pH conditions, and a pseudo-2nd-order kinetic model best followed the kinetic data. The modified Langmuir model was used to study the interactions among the dye molecules in multi-component systems, and the observed results indicate the synergistic and competitive behavior of dyes [67].

4. The Use of Millet Biomass for Activated Carbons and Carbonizates Production and the use of the Latter to Remove Various Pollutants from Aqueous Media

One of millet biomass applications is activated carbons and carbonates production [68]. The latter are used as sorbents to remove various pollutants from aquatic environments. Active carbons were produced by pyrolysis at 400-800°C from millet bran (MBBC). Biochars were modified by potassium permanganate (MBBC-PP), potassium ferrate (MBBC-PF), and citric acid (MBBC-CA). The results showed that the adsorption capacities of these adsorbents were in the order: MBBC-PP (36.5 mg/g) > MBBC-PF (32.5 mg/g) > MBBC-CA (18.5 mg/g) > MBBC (5.2 mg/g). Obviously, better fits were obtained using the Langmuir model than were obtained from the Freundlich model, suggesting that the mechanism of Cd^{2+} ions adsorption onto these biochars is more consistent with the Langmuir model. The sorption kinetics of Cd^{2+} ions on adsorbents follows pseudo-second-order [69].

To remove Hg2 + ions from model media biochar–bentonite composite (CB) was prepared from local millet straw and bentonite using the solution intercalation-composite heating method. The prepared CB and MB (modified biochar) had a maximum adsorption capacity for Hg^{2+} ions of 11.722 and 9.152 mg/g, respectively, far exceeding the corresponding adsorption value of biochar and bentonite (6.541 and 2.013 mg/g, respectively). The adsorption of Hg^{2+} on the CB was characterized using a kinetic model and an isothermal adsorption line, which revealed that the pseudo-second-order kinetic model and Langmuir isothermal model

well represented the adsorption of Hg^{2+} on the CB, indicating that the adsorption was mainly chemical adsorption of the monolayer. Thermodynamic experiments confirmed that the adsorption process of Hg^{2+} ions by the CB was spontaneous and endothermic. It was shown that after Hg^{2+} ions were adsorbed by CB, functional groups, such as the –OH group (or C=O, COO–, C=C) on the CB, induced complexation between Hg and –O–, and part of Hg^{2+} ions was reduced Hg^{+}, resulting in the formation of single or double tooth complexes of Hg–O– (or Hg–O–Hg) [70].

To remove Zn^{2+} ions, a combined chitosan-based sorbent was synthesized, and heat-treated threshing millet (HTMT) with different content (10%, 20%, 30%, and 40% of the total weight) was obtained. The mechanical properties (abrasion and grind ability) of the obtained composite sorption materials were determined, and it was shown that the best sorption characteristics of composite material with the addition of the filler were 30%. Comparing the sorption capacity of modified materials with different content of heat-treated threshed millet showed that the maximum sorption capacity (50 g/g) is for CMCM with HTMT40 and 20%. With HTMT additive 40% granules, mechanical strength is much lower than with additive 20% [71]. A technological scheme for the production of heat-treated millet threshing and chitosan composite materials for wastewater treatment was developed. The microstructural study of the obtained materials showed that heat-treated additive threshing of millet increases [72].

Also, it treats cleaning wastewater originating from industrial buildings using sorption materials. As sorption materials for the recovery of heavy metal ions, industry wastes were used: threshing millet, cotton fiber, and chitosan. The thermal treatment mode for the carbonized millet waste (CMW) was a temperature of 300°C for 20 min, and the weaving cotton fabrics waste, a 450°C temperature for 8 minutes (TCF). The basic sorption characteristics, such as purification efficiency, sorption capacity, specific surface, and sorption capacity on water, were considered. For a CMW, the specific surface area is S= 188 m^2/g, and the total pore volume in water is V = 0.3 cm^3/g. The main characteristics for cotton fiber: the specific surface area is - Ssp = 50.8 m^2/g, the total pore volume in water is V pore = 0.8 cm^3 /g, for TCF: the specific surface is - Ssp = 1700 m^2/g, the total pore volume by water Vpor = 1.4 cm^3/g. It was found that the maximum sorption capacity of CMW for metal ions was as follows: Cd^{2+} - 16 mg/g, Cu^{2+} - 14 mg/g, Pb^{2+} – 15 mg/g and Zn^{2+} - 18 mg/g, for TCF: Cd^{2+} - 14.4 mg/g, Cu^{2+} - 15.1 mg/g, Pb^{2+} – 6.9 mg/g and Zn^{2+} - 13.2 mg/g. A combined use of materials in the form of a layer-by-layer filter and granules is proposed. The efficiency of cleaning materials is 93 to 99.9%, and the sorption capacity is from 6.9 to 50 mg/g [73].

Also, millet biomass-based ACs have been studied as sorbents of dyes from colored waters. In particular, there was a study of the removal of the Methylene blue dye by AC produced by pyrolysis of millet straw and activated by H_3PO_4 at 450°C for 45 minutes. It was found that the maximum sorption capacity of the dye was 390 mg/g [74].

The Methylene blue maximum sorption capacity of the carbonizate with a total surface area of 52.91 m^2/g produced from millet husk was 82.37 mg/g at pH = 6 and a temperature of 32°C. It was found that the Freundlich model more accurately describes the adsorption isotherm and the main mechanism of the process is intraparticle diffusion [75].

Millet husks were carbonized at 600°C to produce AC with a surface area of 1342 m^2/g. It was found that the maximum sorption capacity for this dye was 16.75 mg/g. The adsorption isotherm is most accurately described by the Langmuir model, and the process kinetics by the pseudo-second-order model [90].

Besides, AC was also made from Kodo millet (*Paspalum scrobiculatum*) husk by thermal treatment at 450°C for 1 hour and activation with orthophosphoric acid. It was determined that the total area of the AC was 393 m^2/g with a pore volume of 0.671 cm^3/g. The maximum sorption capacity for this dye was found to be 16.75 mg/g. It was also revealed that the adsorption isotherms at different temperatures were more accurately described by the Langmuir model, and the process kinetics followed the pseudo-second-order model. The thermodynamic parameters (ΔG^o = -28.23 - -31.47 kJ/mol at 305-325 K, ΔH^o = 26.36 kJ/mol, ΔS^o = 179 kJ/mol·K) are indicative of the endothermic controlled physical adsorption [77, 78].

There was a study of the ability of AC from millet husk treated by thermal exposure at 500°C for 3 hours and activated by iron oxide and hydrogen peroxide to remove the Congo red dye. It was found that the most kinetic model applied to it is a pseudo-second-order model. At an initial dye concentration of 55 mg/dm^3, the degree of removal by native husk and AC based on it amounted to 27% and 85%, respectively [79].

Millet straw ACs were also studied to remove the color from real textile production wastewater. The initial wastewater color was 25570 pt/co. It was found that at a sorbent dosage of 10 g/dm^3 after 7 hours of contact, the color decreased to 1410 pt/co. At an AC dosage of 35 g/dm^3, the wastewater color was 1059 pt/co. From the experiments with varying dosages, the maximum color removal was 95.9% at 35g/dm^3 dosage. Experiments with varying times indicate that maximum color removal is 95.5% at 7 hrs contact time [80].

Millet biomass ACs were also tested as sorbents to remove various hydrocarbons from aqueous media. Thus, AC was produced from bagasse, millet, and sorghum straws by chemical activation with H_3PO_4. Carbon precursors with a particle size of 1180 μm were used. The active carbons were highest at 450°C with an optimum impregnation ratio of 13.6. The potential of the AC as an efficient and economical means of removing a mixture of aromatic hydrocarbon contaminants from the water was indicated by the complete removal of objectionable odor from contaminated water samples containing 35.1348 mg/cm^3 benzene and 34.8534 mg/cm^3 toluene [81].

Millet straw-derived AC exhibited superior properties in S_{BET}, S_{mic}, and adsorption capacities of both toluene and ethyl acetate. The optimal preparation conditions include a carbonization temperature of 572°C, carbonization time of 1.56 h, and impregnation ratio ($ZnCl_2$/PM, w/w) of 1.60, which was verified experimentally, resulting in millet straw AC with a toluene adsorption capacity of 321.9 mg/g and ethyl acetate adsorption capacity of 240.4 mg/g. The descriptive ability of the isothermals via the Redlich–Peterson equation suggests a heterogeneous surface on AC. Recyclability testing has shown that millet straw AC maintained a stable adsorption capacity throughout the second to fifth cycles [82].

5. Conclusions

The paper provides literature data on the use of millet biomass components (straw, husk, and bran) as sorption materials to remove metal ions and dyes from aqueous media. The analysis showed that the adsorption isotherms, in most cases, were more accurately described by the Langmuir and Freundlich models, and the process's kinetics most often correspond to the pseudo-second-order model. It has also been shown that millet biomass components can be used as precursors to produce activated carbons and carbonizates, which are also powerful sorbents to remove various pollutants from model and real wastewater. Some literature sources describe millet biomass components and activated carbons as promising materials for studying the sorption processes of pollutant removal from aquatic environments.

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Conflicts of Interest

The authors declare no conflict of interest.

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