1. Introduction

Lately, there has been an increasing emphasis on using lignocellulosic derived materials (LDMs) in an environmentally beneficial manner [1]. Researchers have tested adsorbents derived from agro-wastes such as orange peel, tea waste, watermelon rind, cactus leaves, rice husk, peanut, corn cob, almond shells, sugarcane bagasse, and other lignocellulose wastes for wastewater treatment with encouraging results. These agro-wastes are typically discarded and hence readily available at low cost.

LDMs active groups such as carboxyl (–COOH), hydroxyl (–OH), and amino (–NH₂) have adsorption capabilities for pollutants. However, the presence of a complex and dense fiber structure impedes adsorbate diffusion and lowers the number of active sites on the adsorbent. The presence of lignin will provide natural protective barrier and steric hindrance for biomass due to the strong relationship between lignin and cellulose microfibers. One of the most surprising findings is that lignin binds and inactivates cellulytic enzymes, necessitating the need for pretreatment/modification to alter or eliminate the lignin to allow enzymes access to the cellulose component [2]. Modification can reduce the amount of lignin and/or hemicellulose in biomass while also increasing surface area, porosity and exposing more active groups for pollutant adsorption [3]. Physical treatment, thermal treatments and chemical treatments have all been used to improve the ability of lignocellulosic material to remove contaminants [4]. These treatments could introduce new functions compatible with the contaminants being targeted [5]. Among these, chemical treatment is most extensively used. Chemical treatment basically includes the use of substances such as acids and bases. However, whereas base (alkaline) modification for LDMs take hours or days, acid modification of LDMs take much shorter time [6].

Water contamination has posed a significant danger to the environment and living beings as a result of the rapid rise of industry and the economy. Chemical pollution, such as heavy metals (cadmium (Cd), chromium (Cr), lead (Pb), Zinc (Zn), mercury (Hg), ...
copper (Cu), arsenic (As) etc.) and organic pollutants, account for the most pollutants in aqueous solutions (dyes, antibiotics etc.). For some decades, dyes and heavy metals removal from wastewater has been a subject of research. Heavy metals and dyes are thought to be among the most harmful contaminants in water bodies because they are immunogenic, carcinogenic, and mutagenic [7]. Without purifying wastewater before discharging into waterbodies can produce serious environmental and health issues for aquatic and wildlife, as well as human health [8]. Dyes can produce harmful substances, and ingestion, inhalation, or skin or eye contact with these compounds can result in a variety of symptoms, including skin irritation, burns, and even irreversible eye damage in animals and people [9]. Even at low quantities, long-term exposure causes bioaccumulation, which can result in mutations and carcinogenic effects, among other issues [10, 11]. Faced with severe water contamination, developing cost-effective methods based on low-cost materials is critical. Different researchers are seeking to find different solutions to this problem, among which we are among several who have focused on acid modification of LDMs for the decontamination of polluted water, which helps to process the LDMs into more valuable compounds. This is necessary to enable more accessibility of lignin, cellulose, and hemicellulose by enzymes and chemicals; by weakening their resistant structure, removing lignin efficiently, degrading hemicellulose, reducing cellulose crystallinity, and increasing surface porosity [12]. This review focuses on the state of the art of acid modification of LDMs and their use in removing organic contaminants-dyes and inorganic contaminants-heavy metals. This paper focuses on the discussion of three key sections: (i) the interaction mechanism of different types of acid modification for degradation of LDMs (ii) the techniques employed in characterizing the physical and chemical properties of LDMs (iii) the adsorption dynamics and mechanism in the way they affect the adsorption of dyes and heavy metals were reviewed.

2. Acid Modification Mechanism

Acid modification is a chemical modification where the hemicellulose section of a LDM is primarily solubilized [13]. In addition, the lignin is also solubilized by chemical hydrolyses, enabling the enzymes to act on the cellulose during the course of fermentation [14]. Modification with acid is a very effective chemical approach for cleaving glucosidic linkages and disrupting the lignocellulosic matrix. Acid modification has several advantages over other modification approaches with respect to lignocellulosic matrix disruption and cellulose conversion [15]. Also, it can be noted that modification with acid also helps in increasing both the physical and chemical properties of the LDMs. For instance, Jain et al. [16] noted that the surface area of Ficus racemosa increased from 21.177 to 41.796 m²/g after sulphuric acid (H₂SO₄) activation; likewise, the total pore volume rose from 0.066 to 0.109 cm³/g. Acid modification can be achieved either through inorganic or organic acid.

1. Inorganic Acid Modification

The most commonly used acids in acid hydrolysis are phosphoric acid (H₃PO₄), nitric acid (HNO₃), hydrochloric acid (HCl) and H₂SO₄ [17-19]. Modification with dilute acid is arguably the most extensively used of all the modification procedures evaluated. These acids and some inorganic acids have been investigated for the modification of LDMs, enabling the procedure to be ramped up to a commercial level [16]. According to previous studies, dilute H₂SO₄ is the most commonly utilized acid to modify LDMs [20]. The enzymatic hydrolysis in wild rice grass was evaluated using a dilute acid modification [20]. The results revealed that 10% of biomass modified with 0.4% H₂SO₄ produced 163 mg sugar. Sulphuric acid is favored over HNO₃ and H₃PO₄ because it is less expensive. Furthermore, despite the fact that H₂SO₄ is more harmful

Table 1. Summary of Acid Modification of LDMs and Product

| Acid type | Acid Conc. (°C) | LDM source | Temp. (°C) | Time (min) | Recovery | Ref. |
|-----------|----------------|------------|------------|------------|----------|-----|
| Organic   |                |            |            |            |          |      |
| Peracetic | -              | Eucalyptus spp | 90         | 300        | 90% of delignification | [36] |
| Critic    | -              | Corn cob    | 160        | 60         | 93.4% enzymatic hydrolysis | [35] |
| Peracetic + maleic: 1.5 + 3 |  | Corn stover | 130        | 60         | 90% delignification | [28] |
| Acetic    | -              | Eucalyptus chips | 160       | 120        | 22.24% lignin | [107] |
| Formic    | 72             | Wheat straw | 130        | 15         | 75.4% delignification | [33] |
| Lactic acid | 4            | Rice straw | 140        | 72         | 42% glucose, 47.5% ethanol | [108] |
| Acetic    | 2              | Rice straw  | 80         | 1440       | 6.29 mg/kg biomethane yield | [90] |
| Acetic    | 8.24           | Oilplam shell | 107.3     | 30         | 40.408 mg/g reducing sugar | [109] |
| Inorganic |                |            |            |            |          |     |
| H₂SO₄     | 5-20           | Elephant grass | 121       | 30         | 89% glucose yield | [24] |
| H₃PO₄     | 4.49           | Pinewood sawdust | 106.7     | 269.4      | 90.95% xylose | [23] |
| H₃PO₄     | 70-80          | Achyranthes aspera | 86.2% cellulose to glucose | [25] |
| H₂SO₄     | 2              | Kenaf core fibre | 120       | 90         | 20% glucose yield | [26] |
| HNO₃      | 0.01           | Oilpalm frond Bagesse | 57        | 24         | 0.5 g/L xylan | [110] |
| H₂SO₄     | 2              | Date palm waste | 120       | 30         | 141.65 mL/g VS methane yield | [111] |
| H₂SO₄     | 1              | Cotton stalk | 120        | 20         | 93% of glucose recovered | [112] |
| H₂SO₄     | 1              | Rapeseed straw | 180       | 10         | 0.72 g/L Glucose recovered | [113] |
than the other dicarboxylic acids examined, such as oxalic acid. Critic acid, a tricarboxylic acid, performed better in modification study noted due to their increased pKa; dicarboxylic acid has superior catalytic performance than monocarboxylic acid [35]. As a result, critical acid, a tricarboxylic acid, performed better in modification than the other dicarboxylic acids examined, such as oxalic acid. Organic acids have recently been proposed as possible replacements for inorganic acids in order to prevent product degradation and acquire additional xylen sugars [35]. 93.4% of enzymatic hydrolysis was achieved when corn cob was treated with citric acid at 160°C for 60 mins. Organic acids have, over time, proven effective in achieving the delignification of the LDM. For instance, 90% of delignification was achieved when Eucalyptus spp was treated with peracetic acid at 90°C within 5 h [36]. Similarly, when Zhou et al. [33] treated wheat straw with formic at the temperature of 130°C for 15 min. 75.4% delignification was achieved (Table 1).

2.3. Impact of Concentration, Time, and Temperature on Acid Modification

The reaction time and temperature are important parameters to be considered in acid modification [37]. Longer reaction periods promote reagent movement within the wood structure, resulting in better yield. Reactant transport inside the cell wall of LDMs, where the majority of –OH are found, happens from the lumen to the cell wall and is controlled by diffusion and time. Vitas et al. [37] found that temperature is an important parameter in the interaction of citric acid with wood fiber, as it aids in the formation of citric acid cyclic anhydride. In the case of cellulose waste products, acid treatments can be carried out using both diluted and concentrated acids [38]. This can either be in the form of concentrated acids (30–70%) or dilute acids (0.1–10%) at low temperatures (100°C) and high temperatures (100–250°C), respectively [38]. Even though concentrated acid modification can greatly speed up the conversion of sugar (up to 90%), most concentrated acids are extremely hazardous and corrosive, necessitating substantial operational and maintenance expenditures. Furthermore, they cause cellulose breakdown, resulting in the release of repressive chemicals, for instance, furfural, 5-hydroxymethyl furfural, phenolic acids, and aldehydes [39]. Concentrated acids are dangerous because of their hazardous, poisonous, and highly corrosive characteristics and apparently, because of the corrosive nature and toxicity of the concentrated acids, they also harm the materials in the reactors [40, 41]. Concentrated acid and diluted acid methods are not with their individual pros and cons, while it has been observed that cellulose can be modified with concentrated H2SO4 at room temperature with a fast reaction speed, resulting in an apparent effect on sugar synthesis via enzymatic hydrolysiss [42]. Concentrated acid modification has a number of drawbacks, including high costs, difficulty recovering acid, significant equipment corrosion, and the creation of by-products that interfere with enzymatic hydrolysis and fermentation, all of which limit its use in practical production.

Whereas, during dilute H2SO4 modification, the hemicellulose in the lignocellulosic material can be broken down to monosaccharides (mainly xylose), and the lignin can be partially broken down, demonstrating the beneficial effects of enzymatic hydrolysis [43]. To break down the structure of lignocellulose, the use of low acid concentration in the modification process necessitates relatively harsh reaction conditions of pressure and temperature. Furthermore, cellulose, hemicellulose, and lignin can be degraded into by-products such as organic acids, phenols, aldehydes, furans, and aromatic components after dilute acid modification. As a result, this method has been thoroughly investigated. For a variety of
Modification is a process that reduces or eliminates impurities and having a simple operational process. Additionally, they add inorganic pollutants as other natural sorbents; they have the advantages of these modification procedures.

3. Lignocellulosic Materials for Removal of Organic and Inorganic Contaminants

3.1. Lignocellulosic Materials

Lignocellulose refers to the materials constituting three polymers, i.e., lignin (C₉H₁₀O₃(OCH₃)₀.₉), cellulose (C₆H₁₀O₅), and hemicellulose (C₅H₈O₄). They are as tiny amounts of proteins, pectin and ash [38]. Generally, the composition of LDM consists of 30-60%, 20-40%, and 15-25% of cellulose, hemicellulose, and lignin, respectively [45]. The most prevalent biopolymer and the fundamental structural component of natural fibers is cellulose. It is present in plants, stalks, grasses and woods. Hemicellulose is a polysaccharide consisting of xylose, sugar acids, glucose, galactose, arabinose, galactose, and mannose in a heterogeneous structure. Lignin is an aromatic biopolymer that is complex, crosslinked, and branching. It is a fundamental structural component of vascular plant cells' secondary cell walls [46]. The heterogeneity of lignin polyphenolic structure causes the plant cell walls to be recalcitrant to biological and biochemical degradation, which is the greatest stumbling block to the valorization of LDM. The structure is exceedingly complicated and resilient because celluloses and hemicelluloses are closely linked to lignin (aromatic polymer) via covalent and hydrogen bonds. Other components, including pectin, lipids, proteins and ashes can be found in these materials, although in smaller amounts. When lignin is removed, the lignin-carbohydrate matrix is disrupted, porosity is increased, and non-productive enzyme adsorption sites are reduced [47]. It is crucial to note that the chemical makeup of these components varies greatly depending on their sources, such as agro-wastes, hardwood, softwood, or grasses. Besides, the chemical makeup of a particular species of lignocellulosic material may fluctuate due to genetic heterogeneity across diverse sources, age, climate, and soil circumstances. Furthermore, due to genetic heterogeneity across different sources, age, climatic, and soil conditions, the chemical makeup of a single type of lignocellulosic material might change.

Different lignocellulosic materials have already been explored as potential metal ion adsorbents such as wood (sawdust and paper mill residues) and agricultural residues (such as almond shells, coconut shell, pineapple leaf, apricot shells, banana, apple peels etc.) [48-53]. These wastes have capacity to adsorb organic and inorganic pollutants as other natural sorbents; they have the advantages of being very low cost or free, having a wide availability, and having a simple operational process. Additionally, they add value to products that would otherwise be considered waste. Modification is a process that reduces or eliminates impurities or undesired chemicals in the raw material that will be used to make a product [54]. Modification is required to destroy the lignin-hemicellulose connection and damage the crystalline structure of cellulose [36]. Thus, improving the structure such as the porosity, surface area, etc. of LDM to be used as an adsorbent for removing pollutants. The adsorption rate of pollutants is influenced by pore size, and as the size of the micropores grows, the surface area increases on the adsorbent [55]. But, if the pores are too tiny, the number of accessible pores for adsorption is reduced. Therefore the passage of the adsorbed contaminant into the adsorbent's interior will be difficult [56].

3.2. Unmodified LDMs for Contaminants Removal

Various studies have been carried out on unmodified LDMs to eradicate pollutants such as dyes and heavy metals from solutions [57]. However, there are several substantial disadvantages to their use, including limited adsorption capacity in many circumstances and the discharge of soluble organic/matter lignin into the solution.

3.2.1. Dyes

Dyes are widely utilized in various industries, including food, textiles, coatings, cosmetics, printing, plastic, leather, and paper, because of their brightness, low cost of production, and excellent resistance to environmental conditions [58, 59]. Dyes are optically active and noticeable even at low concentrations; therefore, their effects on aquatic bodies are severe [60]. When they are inhaled, ingested, or come into contact with their human skin or eyes, they are capable of irritating and pose more health issues [61]. The color associated with textile dyes not only causes aesthetic damage to the water bodies but causes also low light penetration and oxygen consumption which have been documented to cause damage to aquatic ecosystems. Low light penetration impairs aquatic species' biological activity by affecting photosynthesis and respiration [62]. Dyes are referred to as recalcitrant molecules since their chemical structure is exceedingly stable and resistant to microorganism attack or breakdown mechanisms, either chemical or biological. This is because they contain auxochromes and chromophores, possessing complicated molecular structures that contribute to their stability. Textile dyes are also poisonous, mutagenic, and carcinogenic agents that persist as pollutants in the environment and span entire food chains, causing biomagnification, in which species at higher trophic levels show higher levels of contamination than their prey [63, 64]. Specifically, 15-50% azo dyes do not bind effective during fabric dyeing, which are eventually released into the water bodies [65]. These dyes have a negative effect to soil microbial communities and consequently affect the germination and growth of plants [65, 66].

3.2.1.1. Cationic dyes removal with unmodified LDMs

Cationic groups are very harmful due to their solubility and stability, carcinogenic effects, accumulation in the tissues of marine animals, and high solubility. Specifically, crystal violet (CV) are the most harmful and have piqued the interest of researchers [7]. A reported study showed that Tectona grandis sawdust (TGSD) is a good adsorbent for removing CV from wastewater [67]. Different investigative variables, including adsorbent dose, dye concentration, pH, contact time and temperature, were shown to influence the adsorption
of dyes using et al. [68] reported the influence of adsorbent dose on the uptake a certain initial dye concentration in an aqueous solution. Singh important part in establishing the uptake ability of an adsorbent at type of dye [68]. This indicates that adsorbent dose plays an im-
determines its adsorption ability for cationic dyes, likewise the capacity of 131.58 mg/g (Table 2). Also, the nature/type of LDM capability of TGSD for CV with maximal equilibrium adsorption

| LDM source                      | Acid treatment | Dye               | Adsorbent dose (g/L) | Adsorbate Conc. (mg/L) | Adsorption capacity (mg/g) | Opt. pH | Temp (°C) | Ref. |
|---------------------------------|----------------|-------------------|----------------------|------------------------|---------------------------|---------|-----------|------|
| Cationic                        |                |                   |                      |                        |                           |         |           |      |
| Abelmoschus esculentus          |                | Nile blue A       | 4.5                  | 50–750                 | 87.80                     | 8       | 30        | [9]  |
| Bamboo shoot skin               |                | Methylene blue    | 1                    | 20–200                 | 29.88                     | 3.0     | -         | [96] |
| Mango leaves                    |                | Methylene blue    | 1.25                 | 100–250               | 156                       | -       | 25        | [114]|
| Tectona grandis sawdust         |                | Crystal violet    | 2                    | 25–150                 | 131.58                    | 7.5     | 25        | [67] |
| Citrus Limetta Peel             |                | Congo red         | 5                    | 5–25                   | 6.361                     | 7       | -         | [68] |
| Zea mays cobs                   |                | Malachite green   | 5                    | 5–25                   | 8.733                     |         |           | [68] |
| Citrus lanatus (rind)           | H₂SO₄          | Methylen blue     | 15                   | 5–25                   | 4.440                     | 7       |           | [68] |
| Apricot stone                   | H₃PO₄          | Malachite green   | 15                   | 5–25                   | 4.440                     | 7       |           | [68] |
| Banana peels                    | H₂SO₄          | Methylen blue     | 0.8                  | 100–300                | 250                       | 11      | 30        | [80] |
| Anionic                         |                |                   |                      |                        |                           |         |           |      |
| Corn silk                       |                | Reactive red 218  | 5                    | 100                    | 63.3                      | 2       | 25        | [70] |
| Banana peel powder              |                | Reactive blue 19  | 1                    | 100                    | 71.6                      |         |           |      |
| Zea mays cobs                   |                | Congo Red         | 50–150               |                        | 49.2                      | 3       | 25        | [115]|
| Cucumber peel                   |                | Congo red         | 12.5                 | 5–25                   | 8.417                     | 7       | -         | [68] |
| Potato peel                     |                | Orange G          | 1                    | 100–300                | 40.5                      | 2       | -         | [10] |
| Ficus racemose                  | H₂SO₄          | Acid violet 17    | 5                    |                        | 61.35                     | 2       | 30        | [16] |
| Celery residue                  | H₂SO₄          | Congo red dye     | 1.5                  | 100                    | 238.0                     | 6.5     | 30        | [116]|

capability of TGSD for CV with maximal equilibrium adsorption
capacity of 131.58 mg/g (Table 2). Also, the nature/type of LDM
determines its adsorption ability for cationic dyes, likewise the
type of dye [68]. This indicates that adsorbent dose plays an im-
portant part in establishing the uptake ability of an adsorbent at
certain initial dye concentration in an aqueous solution. Singh
et al. [68] reported the influence of adsorbent dose on the uptake
dye using Zea mays cob (ZMC) and Citrus limetta peel (CLP)
with dosages between 2.5–25 g/L of each adsorbent, and the optimum
dose was found to be 1.25 and 0.5 g/L for ZMC and CLP, respectively
for three dyes (methyl blue – MB, malachite green – MG and Congo
red – CR). It was reported that 94 and 99.6% of MB dye was removed
at 15 g/L of ZMC and CLP, respectively and nearly 96% MG
dye was removed with a dose of 2.5 and 5 g/L of ZMC and CLP,
respectively. However, using the optimum doses (1.25 g/L of ZMC
and 5 g/L of CLP) of both adsorbents could not remove more than
90% CR, indicating that adsorbents had more affinity for cationic
dyes than anionic dye. Also, it was recorded that the most suitable
adsorbent for adsorption of MB, MG, and CR dyes with the maximum
dye adsorption capacity was found to be ZMC, indicating that
source LDMs play a significant part in its adsorption capacity for
pollutants.

3.2.1.2. Anionic dyes removal with unmodified LDMs
The adsorption potential of LDMs for anionic dyes is also dependent
on the type of feedstock from which the adsorbent was produced.
LDMs such as raw coconut shells (CS), cauliflower cores (CC),
and broccoli stalks (BS) were chosen to adsorb a set of anionic
dyes including, Reactive Blue-4 (RB-4), Acid Blue-29 (AB-29), and
Acid Blue 113 (AB-113) [69]. The performance of LDMs for the
uptake of the anionic dyes was CC > BS > CS. The major charac-
teristic used to explain this adsorption pattern was the biopolymer
content of these adsorbents. As the cellulose content of the LDMs
increased, dye adsorption also increased. The best adsorbent was
CC, which had the highest cellulose content, the lowest point of
zero charge (pHpzc), lowest cellulose content, and smaller surface
area than CS, comparable porosity but the highest pHpzc. It was
inferred that the exterior cellulose layer of LDM played a vital
part in the uptake of these dyes and that hemicellulose and lignin
had a minor role to play. It was concluded that it is reasonable
to assume that LDM with a high cellulose content will be favorable
for anionic just like other contaminants is determimned by a number
of factors, and this includes the type of dye, pH of the adsorbate
and low-cost adsorbents for removing these anionic dyes in water
purification and treatment. The adsorption ability of a LDM for
anionic just like other contaminants is determined by a number
of factors, and this includes the type of dye, pH of the adsorbate
solution; however, these vary. For example, cornsilk was found
to have nearly 99% adsorption efficiency for reactive blue 19
and reactive red 218 dye at pH 2 [70]. Similarly, where cucumber
peel and potato were used to remove orange-G (OG), cucumber
peel had a greater adsorption capacity of 40.5 mg/g than potato
peel with 23.6 mg/g [10].
3.2.2. Heavy metals

Heavy metals are well-known inorganic pollutants with a high density and atomic weight. Even at low doses, it is poisonous [71], and unlike organic substances, they are non-biodegradable, meaning they do not degrade naturally and can accumulate in living creatures’ tissues [72]. Heavy metals can be ingested through the air, surface water, or food. Human activities, including mining, automotive emissions, and the usage of heavy metals containing compounds in manufacturing, are often responsible for the occurrence of heavy metals in water sources across various locations. Industry-generated effluent is released into the environment, primarily in watercourses. Common heavy metals found in wastewater include Pb, Cd, Cu, Cr, Hg, and As have been proved to be highly harmful [73]. Heavy metals like Pb, has been reported as a ubiquitous environmental pollutant, capable to causing physiological, morphological, and biochemical damages in plant tissue; This may perhaps be as a result of the strong binding affinity of these heavy metals with biomolecules [74]. Research has shown that Cu can be as toxic as Pb [75]. It is capable of causing mucosal irritation, necrotic changes in the kidney and liver in animals and human being [76]. All these heavy metals have shown to be genotoxic. A research revealed that water from rivers contaminated with Cd, Zn and Cu were mutagenic in nature [74]. These metals are deposited into water resources without being properly treated poses a significant concern [77]. The development of efficient adsorbents for heavy metals has been a major undertaking. Various modern materials, such as biopolymer nanofiber membranes, graphene oxide nano-composites, and carbon nanotubes, have enticing adsorption properties for heavy metals, but their cost and preparation procedure severely limit their use [78]. Removing heavy metals by LDMs has recently been the subject of attention. The adsorption capabilities of various LDMs for heavy metals vary significantly. The origin of LDM, its nature and the surface shape, metal variation, absorption method, and kind of binding forces are all contributing factors. For instance, agave bagasse (AB) gave maximal uptake capacity of 93.14 mg/g for Pb(II) (Table 3) but lower capacities of 28.50 and 24.66 mg/g for Cd(II), and Zn(II), accordingly [79].

3.3. Modified LDMs for Contaminants Removal

The disadvantages of unmodified lignocellulosic materials are eliminated when raw LDMs are modified. Modifying LDMs to improve their binding capacities and reduce the leaching of soluble organic compounds and colored pigments is becoming more popular.

3.3.1. Dye removal with unmodified LDMs

3.3.1.1. Cationic dyes removal with Modified LDMs
Banana peels were modified with H2SO4 for the uptake of MB [80]. The physical characteristics indicated that the high concentration of modifying agent H2SO4 led to a low surface area (1.73 m2/g) adsorbent. This was reported to be responsible for the increase in the oxygen content (37.95%) on the surface of the adsorbent, thereby producing hydrophilic adsorbents and adversely dropping the surface area and pore volume. In addition, the presence of sulfur was noticed as a result of H2SO4 activation, owning for

| LDM source | Acid treatment | Heavy metal Adsorbate dose (g/L) | Metal Conc. (mg/L) | Opt. pH | Temp (°C) | Adsorption capacity (mg/g) | Ref. |
|------------|----------------|---------------------------------|-------------------|--------|----------|---------------------------|-----|
| Taro       | -              | Pb(II)                          | 0.9               | 10–500 | 6        | 25                        | 291.56 | [93] |
| Phytolacca americana L | -              | Pb(II)                          | 20                | 5–300  | 6        | 25                        | 10.83  | [86] |
| pomelo peels | -              | Pb(II)                          |                   | 25     |          |                           | 91.18  | [96] |
| rape straw | -              | Cu (II)                         | 3                 | 25–500 | 5        | 20                        | 52.48  | [117] |
| agave bagasse | -              | Cd(II)                         | 0.4               | 10–1,000 | 5.5       | 15                        | 28.50  | [79] |
| Orange peel | -              | Cd(II)                          | 0.04              | 240    | 5        | 45                        | 128.23 | [118] |
| foxtail millet shell | -              | Cu, Zn, Cd, Cr                 | 4                 | 25–300 | 5        | 25                        | 11.89  | |
| Persimmon leaves | -              | Pb                              | 3                 | 0.5–20 | 6        | 20–40                     | 22.59  | [105] |
| Date pits  | -              | Hg(II)                          |                   | 5      | 20       |                           | 38.5   | [120] |
| Phytolacca americana L | HNO₃           | Pb(II)                          | 20                | 5–400  | 6/25     | 120                       | 12.66  | [86] |
| pomelo peels | Conc. H₂SO₄    | Pb(II)                          |                   | 150    | 5        | 25                        | 145.13 | [96] |
| Date palm coir (DPC) | -              | Cr(VI)                          | 3                 | 100    | 2        | 30                        | 138.89 | [103] |
| Watermelon rind | -              | As(III), As (V)                | 1                 | 4      | 8.2/4.6  | 3.42, 3.25              | [89] |
| Watermelon rind | Citric acid    | As(III), As (V)                | 1                 | 4      | 7.2      | 2.42, 3.10              | [89] |
| Sago Bark  | HNO₃           | Pb (II)                         | 0.1               | 600    | 5        | 25                        | 314375 | [121] |
the creation of the sulfonic acid groups (−SO₃⁻) on the adsorbent’s surface. This probably facilitated its adsorption capacity reaching 250 mg/g. This trend has been reported by other studies [5, 11, 17, 42]. Watermelon peels were also modified with H₂SO₄ (CWMR) [81], which enhanced the uptake capacity of the adsorbent, recording 200 mg/g for MB removal from the solution. The low surface area of CWMR (0.357 m²/g) was attributed to the high concentration of H₂SO₄ reducing the surface area and pore volume.

3.3.1.2. Anionic dyes removal with Modified LDMs
Contrary to other researches that have reported a reduction in the surface area as a result of H₂SO₄ modification of LDM, when *Ficus racemosa* was modified with H₂SO₄ to remove Acid Violet 17 (AV 17) dye from wastewater, the BET surface area was increased from 21.177 to 41.796 m²/g after H₂SO₄ treatment with increased porosity of the adsorbent [16]. These were beneficial properties for adsorption of dye, given 61.35 mg/g adsorption capacity for AV 17 dye. Few studies are available on the acid modification of LDM for anionic dyes removal.

3.3.2. Heavy metals
Unmodified LDMs have been utilized in several studies to adsorb heavy metals from aqueous solutions [82-84]. Such limitations are eliminated by modifying raw lignocellulosic materials. To serve as an adsorbent for the removal of Cu²⁺ from water, sugar cane bagasse was modified with 0.1M oxalic acid at pH 2 and 100 min of contact time. At optimum conditions, the modified adsorbent gave a higher maximum uptake capacity than the untreated (1.854 mg/g vs. 0.556 mg/g) [82]. This research discovered that removing potassium and calcium ions (K⁺ and Ca²⁺) from orange peels with 0.1 M HNO₃ made Cd(II) uptake more appealing [83]. According to Rehman et al. [84], modification with 0.1 M HCl greatly boosted the Cr(VI) uptake effectiveness by LDM (87.33%) as opposed to raw biomass (47.38%). Sometimes, modification makes a lot of difference in the adsorption capability of the LDM, whereas, in some, insignificant differences are observed. For example, pomelo peels gave an adsorption capacity of 91.18 mg/g when used to adsorb Pb(II), however, modifying the pomelo peels with H₂SO₄ gave a huge increase in adsorption capacity of 145.13 mg/g [85]. Whereas, the variation in the adsorption capability of *Phytolacca americana*-L for Pb(II) before and after modifying with HNO₃ was 10.83 and 12.66 mg/g, showing just a little increase in the adsorption [86]. Modification of LDMs with acid usually makes the existing functional groups on the surface of the adsorbents more abundant and introduces more functional groups. For instance, functional groups such as –OH, –COOH and carbonyl (C=O) on the surface of CWMR were substantially responsible for the uptake of MB from solution, as evidenced by FT-IR spectrum findings. Furthermore, the production of surface SO₃⁻ groups through the sulfonation process with conc. H₂SO₄ played an essential role in the uptake process (as evidenced by EDX analysis) [70]. This has been confirmed by other studies, which further emphasize that the formation of SO₃⁻ was dependent on the modification of the adsorbents with H₂SO₄ [87]. Also, another study confirmed that acid modification led to the high concentration of H₂O⁺ in the solution providing the carboxylate and acetates groups protonation when water hyacinth was treated with HNO₃ [88]. This led to the capacity of the adsorbent to remove 71.8 mg/g of Pb(II) against the unmodified given 40.7 mg/g. The uptake efficiency of watermelon rind (WMR) for removing As(III) and As(V) in solution was somewhat increased by chemical modification approaches. Results demonstrated that citric acid watermelon rind (citric acid-WMR) possessed up to 49% higher sorption than WMR both for As(III) and As(V). The highest removal of As(III) was attained at pH 7.2 by citric acid-WMR, while the maximum removal of As(V) was recorded at pH 4.5 [89]. The data revealed that the initial concentration of 4 mg/L for As(III)/(V), 1 g/L of adsorbent dose at 2 h were optimal for maximal uptake of As(III)/(V) from aqueous solution.

4. Characterization Techniques

Instrumental analysis is critical in determining the characteristics of adsorbents both before and after interactions. This is a useful tool for determining which characteristics, such as structural, morphological, optical, and/or physicochemical, regulate adsorption capabilities, as well as for elucidating the associated mechanisms during pollutant-adsorbent interactions. There are several techniques used in characterizing adsorbents, of which there are three most common ones scanning electron microscopy (SEM), the Brunauer-Emmett-Teller (BET), Fourier transform infrared spectroscopy (FT-IR).

4.1. Scanning Electron Microscopy
SEM is a technique used to get an insight into the morphological features of the surface of an adsorbent. It is one of the common and first technique used. It provides information about the structure of adsorbent before adsorption and morphological changes that occur after the uptake of pollutants (in this case dye and heavy metals). Sometimes, SEM is used to identify the existence of channels and cavities and evaluate the size of the adsorbent’s particles. For instance, the SEM analysis of the microstructures of rice straw before and after modification with 2% acetic acid for 24 h. Unmodified rice straw fibers were smooth and well-ordered whereas, before modification, rice straw fibers were coarse and disordered with visible cusps on the surface, indicating partial lignin breakdown during pretreatment [90].

4.2. Brunauer-Emmett-Teller Analysis
The BET theory explains the physical adsorption of gas molecules on a solid surface. It serves as the foundation for a critical analysis technique for calculating the specific surface area of materials, total pore, and diameter. Garlic peel was chemically modified with three different agents, namely: HNO₃, citric acid, and sodium hydroxide (NaOH) for the adsorption of Rhodamine B. The result revealed that HNO₃ (1.264 m²/g) had the most remarkable effect on the BET surface area of the adsorbent, which might have contributed to its best adsorption capacity of Rhodamine B in comparison with other three modifiers: citric acid having 0.824 m²/g while, NaOH had the least 0.701 m²/g [91]. BET surface area for the fallen leaves of *Ficus racemosa* was 21.177 m²/g, which was increased to 41.796 m²/g after H₂SO₄ modification of *Ficus racemosa* [16].
The total pore also increased from 0.066 to 0.109 cm²/g after H₂SO₄ modification. These led to the increase in the adsorbent’s porosity and hence favoured the adsorption of acid violent 17.

4.3. Fourier Transform Infrared Spectroscopy

Fourier transform infrared spectroscopy (FT-IR) is a vibrational spectroscopic technique commonly used to identify functional groups present in adsorbents that could be involved in the uptake of pollutants such as dyes and heavy metals. The modification of LDMs with acid creates changes in the functional groups observed in the LDM, such as increase or reduction, in the functional group and sometimes the introduction of a new functional group into the matrix of the adsorbent or removal of functional. For example, after 24 h of modification of rice straw fibers with 2% acetic acid, FT-IR spectra of the unmodified and modified rice straw were compared [90]. It was noted that the intensities of the peaks were affected after modification with acetic. There was an increase and shift in the binding energy of the peak near 1,640 cm⁻¹ assigned to –OH group, which is characteristic of cellulose in the samples. The observed shift was attributed to a decrease in cellulose concentration following pretreatment, as well as the likely production of intermolecular hydrogen bonds after acetic acid molecules infiltrated the adsorbent, causing an increase in intramolecular spacing and swelling of the adsorbent. The stretching vibration of the C=O bond, which is characteristic of the para-substituted aryl skeleton, is the absorption peak of about 1,640 cm⁻¹. The acetylation of cellulose by acetic acid is confirmed by the increased intensity of this peak after acid modification. Stretch vibration of C-O-C in alkyl, aryl, and ether bonds caused the weakening of the peak at 1,240 cm⁻¹. This demonstrates the ether chain within lignin molecules changed the structure of the lignin molecules. In conclusion, the change in functional groups of rice straw following modification represent efficient acetic acid breakdown of the straw.

5. Properties and Dynamic of Adsorption

Mechanism of Dye and Heavy Metals

5.1. Adsorption Properties and Dynamics

The adsorption kinetics, isotherm, and thermodynamics are important in determining the mechanism of an LDM for removing both dyes and heavy metals. Several models are used to fit each parameter, and the best fit model gave the understanding of the nature of the adsorption process that rose between the adsorbent and adsorbate. However, sometimes, data fit excellently well into more than one model. For instance, Pathania et al. [92] reported that equilibrium data fitted well for the Langmuir, Freundlich, and Tempkin isotherm models. This phenomenon describes that the adsorption was heterogeneous and occurred through physicochemical interactions. Also, a similar trend occurred in the report of Saha et al. [93], where Taro was used to remove Pb(II). A high correlation coefficient (R² = 0.9963) was accounted for by the Langmuir model, but the Freundlich model gave a higher value (R² = 0.9982), indicating that Taro’s surface could be heterogeneous and that the adsorption process involved multilayer adsorption, indicating a complex process.

For thermodynamic of adsorption, the negative ΔG° values indicate that the sorption of dye onto biosorbent is feasible and spontaneous. The change in the enthalpy (ΔH°) value implies that the state of adsorption, if positive, expresses endothermic, while negative an exothermic reaction. The positive entropy change (ΔS°) value signifies that the solid-solution interface has greater randomness [86, 94, 95], while negative ΔS° values indicate the reduction in the randomness at the interface of LDM and adsorbate, respectively [96]. Several studies have observed different trends in the uptake of both heavy metals and dyes by LDMs [67, 86, 94, 95]. For instance, in the uptake of CV by Tectona grandis Sawdust (TGSD), throughout the whole temperature range, the adsorption process was reported to be followed by a drop in Gibbs’ free energy. This shows that CV adsorption by TGSD is possible [67], while the pseudo-second order model was followed for adsorption kinetic.

5.2. Adsorption Mechanism

The interactions between the functional groups of LDMs and contaminants are generally complex. The physics and chemistry of the carbon-containing material surface, the characteristics of the aqueous solution, and the type of the adsorbate all influence adsorption performance. The mechanisms influencing the removal of aqueous contaminants by LDMs are summarized in Tables 4 and 5. In general, physisorption and chemisorption are usually involved in the uptake of heavy metals and dyes unto LDMs; however, chemisorption has a greater impact on removing contaminants from solution than physisorption. Surface functional groups are effective in several mechanisms, including ion exchange, electrostatic attraction/interaction, and surface complexation, under certain conditions. A schematic figure of these mechanisms is represented in Fig. 1.

Due to the adsorbent surface charge, the ionization degree, the conformation of the adsorbate unto the adsorbent can be greatly modified by the solution pH. Solution pH is the most critical factor determining dye and heavy metal sorption [97]. One of the essential parameters to explore in the uptake of heavy metals is the influence of...
of hydrogen ion concentration. The solubility of metal ions and the functional groups on the adsorbent surface are both affected by pH [98]. The metal ion speciation is significantly changed with change in pH which has a direct impact on the removal capacity [99]. Usually, at pH < 2, the metal ions removal is minimal. At lower pH values, functional groups on the adsorbent, such as carboxylate, are protonated. The surface becomes positively charged, causing H+ ions to compete with metal ions, resulting in little metal ion biosorption. But as the pH increases, adsorption is usually progressive. This is by electrostatic interaction/attraction. Electrostatic interaction is one of the essential processes for the adsorption of ionizable species [100]. The adsorption of heavy metals as influenced by pH differs from one metal to another. For example, as the pH value was increased from 2.0 to 5.0, the adsorption of metal ions increased, and the maximum removal of Pb, Cu, and Cd was achieved at pH 5.0 and for Zn at pH of 3.0 when adsorbed with H3PO4 modified olive branches [98]. Electrostatic attraction does not only occur between the negatively charged surface of adsorbents and positively charged adsorbates such as heavy metals but also for ions such as cationic dyes. When pH < pHeZC (low pH) surface sites of adsorbent are protonated as demonstrated in (Eq. (1)), however at higher pH, pH > pHeZC, the adsorbent surface charges become negative (Eq. (2)), while the ions of metals/cationic dyes in the solutions are attracted to its surface.

\[ \text{M–OH} + \text{H}^+ = \text{M–OH}^2+ \]  
\[ \text{M–OH}–\text{H}^+ = \text{M–O}^- \]  

A possible π–π stacking interaction for the adsorption of MB using LDMs is depicted in Fig. 2. Ion exchange is a common separation process that is frequently recognized as a mechanism in various adsorption techniques. Because exchangeable ions like alkali and alkaline earth metals (Na+, K+, Ca2+, and Mg2+) may be placed into adsorbent materials, these ions can be switched for the target adsorbate during the adsorption process. Zn(II) and Cd(II) were shown to be adsorbed mostly through ionic exchange between metal ions and calcium ions on the surface of an AB [101]. The report of Saha et al. [102] also showed a similar trend during the uptake of Pb(II), Ca2+, and K+ were predominantly released from the Taro, indicating the involvement of an ionic exchange process.

![Fig. 2](image.png)

Fig. 2. A possible π–π stacking interaction for the adsorption of MB using LDM.

Other mechanisms such as bonding π–π stacking interactions, hydrogen, have also been reported [81]. The functional groups that are accessible on the watermelon rind surface interacted with nitrogen atoms of MB to form hydrogen bonds which facilitated the removal of this dye [81]. Likewise, the π–π stacking interactions occurred between the aromatic rings of MB and WWR graphene structure [81].

5.3. Multiple Mechanisms

Generally, in heavy metals removal by LDMs, electrostatic attraction, ion exchange, and surface complexation routes are used in general [101]. The mechanism of electrostatic attraction and hydrogen bonding seems to be the common phenomena in the adsorption of dye unto LDMs. For instance, in the adsorption of Nile Blue-A (NBA) by Okro Abelmoschus esculentus seed (OAES), it was observed that the adsorbents functional groups such as -COOH and -OH contained in the OAES adsorbent played a vital role in the uptake of NBA from the aqueous solution [9]. Functional groups deprotonation was reported to have caused the OAES surface to become negatively charged at pH above 6.06. As a result, OAES appears to possess the ability to adsorb positively charged NBA dye from aquatic environments.

As the pH of the solution exceeds the pHeZC of the OAES (6.06), the -OH on the surface of OAES deprotonates, and the electrostatic interaction between NBA dye (being a cationic dye) in the solution and negatively charged places on the surface of OAES occurred. The -COOH undergoes a similar deprotonation event to create the -COO−, which then forms an ion pair with NBA, which has the positively charged.

The combination of electrostatic interaction and hydrogen bonding has also been described by Mashkoor et al. [67] in the adsorption of crystal violet (CV) by TGSD (Table 4). The electrostatic interaction between -OH and -COOH of negatively charged adsorbent and the cationic dye resulted in the attachment of CV to TGSD. In addition to the interaction between the opposite site of CV and the -OH–COOH of TGSD, the mechanistic representation of CV molecule adsorption on TGSD adsorbent also depended on hydrogen bonding between the -OH of the adsorbent and the -NH2 of the CV dye were also assumed to be involved. Fig. S2 shows the combination of three mechanisms (electrostatic interaction and hydrogen bonding) in the involvement of TGSD for the removal of CV.

However, in some instances, ion exchange and complexation also play a great role in the uptake mechanism of heavy metals onto adsorbents. Likewise, the combination of different mechanisms occurs in the adsorption processes. Notably, in a binary and multi-component system where more than one metals ions are in solution, different mechanisms of adsorption are usually at play. The mechanism responsible for the uptake particular metal ion but not necessarily affect every other metal ion in the solution. For instance, Zn(II) and Cd(II) were mostly adsorbed onto AB through an ion-exchange mechanism with the calcium ion on the adsorbent’s surface [79], but, Pb(II), in addition to the cationic exchange mechanism, complexion with the -COOH and -OH groups of cellulose is also linked to the adsorption mechanism. However, other parameters influencing adsorption in multi-metal solutions include electrostatic repulsion, initial metal ion concentration and affinity for...
Fig. 3. Possible adsorption mechanism of Cr(VI) ions by LDM.

particular functional groups, and so on [102]. Fig. 3 reveals the possible involvement of the multi-mechanism approach, namely: electrostatic attraction and surface complexation in the adsorption of Cr by Date palm coir (DPC) [103]. The characteristic functional groups (C–O–C, C=C, –OH, C–H, and C=O) available on the DPC surface were reported to play a key part in the adsorption mechanism. Firstly, when the pH is acidic, the surface of DPC protonates from sufficient H+, which attracts the negative Cr(IV) through electrostatic interactions. Secondly, at the low pH, there was bioreduction of Cr(VI) to Cr(III), which was trapped into the matrix of DPC with possible ligand exchange reactions via surface complexation reactions.

5.4. Critical Evaluation of Adsorption Mechanism

Electrostatic attraction between the adsorbent surface and adsorbents is quite common because most of the adsorbents possess functional groups at lower pH. However, in some instances, electrostatic is excluded in the mechanism of adsorption of these contaminants by LDMs. At high pH solution, the adsorbent’s surface is charged negatively; this is when high adsorptive removal of basic dyes or cationic metals is often realized, whereas the opposite is true for anionic metal forms such as acidic dyes [104]. Functional groups protonation increases the binding ability of these surfaces to anionic...
In some cases, a cation can form a negative complex by interacting with negatively charged ligands. For example, persimmon leaf was used to remove Pb, Cd, and Cu [105]. It was noted that the pH_{PZC} of the persimmon leaf was 5.6, however the maximum adsorption for heavy metals was observed at pH of 4, 3 and 3–4 for Cu, Cd and Pb, respectively. As a result, the involvement of electrostatic attraction mechanism in the adsorption process of these heavy metals by the persimmon leaf was ruled out. However, the ion-exchange mechanism appears to be linked to the abrupt rise in adsorption with increasing pH. Also, Stavrinou et al. [10] noted that the uptake efficiency of MB was 64.6, 81.1, and 96.8% for cucumber peel, potato peel, and banana peel, respectively, indicating the uptake of MB on the surface of all samples was found to be acceptable.

### Table 5. Summary of Adsorption Mechanism for Unmodified and Modified Treatment of Adsorbent for the Removal of Heavy Metals

| LDM source                  | Treatment | Temp (°C) | Heavy metal | Isotherm/Kinetic | Thermodynamic | Surface functional group | Adsorption mechanism                      | Ref.  |
|-----------------------------|-----------|-----------|-------------|------------------|---------------|--------------------------|-------------------------------------------|-------|
| Agave bagasse               | Pb(II)    | 25-75     |             | Langmuir/Pseudo-second-order | ΔG = -3.07~ -4.37  | -OH, -COOH                | Ion exchange, complexation                 |       |
| Taro                        | Pb(II)    | 30-60     | Cd(II)      | Freundlich/Pseudo-second-order | ΔG = -2.165~ -2.77 | O-H, C=O and C=O          | Ion exchange, electrostatic interaction    | [105] |
| Phytolacca americana L      | Pb(II)    | 30-50     | Cd(II)      | Langmuir/Pseudo-first-order | ΔG = -2.02~ -0.09  | -OH, -COOH                 | Ion exchange, surface complexation, ion-exchange | [103] |
| Orange peel                 | Pb(II)    | 30-50     | Cu          | Freundlich/Pseudo-second-order | ΔG = -7.24~ -9.29  | -OH, -COOH                 | Electrostatic attraction, complexation, surface complexation, ion-exchange | [117] |
| Persimmon leaves            | Pb(II)    | 30-50     | Cd(II)      | Langmuir/Pseudo-second-order | ΔG = -2.02~ -0.09  | -OH, -COOH                 | Ion exchange, surface complexation          | [120] |
| Date palm coir (DPC)        | Cr(VI)    | 30-60     |             | Langmuir/Pseudo-second-order | ΔG = 2.02~ -0.09  | -OH, -COOH                 | Electrostatic attraction, ion-exchange     | [96]  |
| Rape straw                  | Cu(II)    | 20-40     | Hg(II)      | Langmuir/Pseudo-second-order | ΔG = -7.44~ -8.73  | -OH, -COOH                 | Ion exchange                               | [119] |
| Date pits                   | Zn(II)    | 20-40     |             | Langmuir/Pseudo-second-order | ΔG = -5.80~ -5.34  | -OH, -COOH                 | Ion-exchange, surface complexation          | [79]  |
| Phytolacca americana L      | HNO₃      | 25        | Pb(II)      | Freundlich/Pseudo-second-order | ΔG = -3.50~ -5.34  | -OH, -COOH                 | -OH, -COOH, NH²⁻, C=O, C-O, C-O, C=O       | [103] |
| Pomelo peels                | Conc. H₂SO₄| 25        | Pb(II)      | Langmuir/Pseudo-second-order | ΔG = -7.44~ -8.73  | -OH, -COOH                 | Ion exchange                               | [119] |
| Watermelon rind             | Citric acid| 25        | Cd(II)      | Langmuir/Pseudo-second-order | ΔG = -7.44~ -8.73  | -OH, -COOH                 | Ion exchange                               | [119] |
| Foxtail millet shell         | Cu, Zn, Cd, Cr | 25-45     |             | Langmuir/Pseudo-second-order | ΔG = -14,320.72~1,1446.86 | -OH, -COOH                 | Ion-exchange, surface complexation, ion-exchange | [120] |
| Sago Bark                   | HNO₃      | 25        | Pb(II)      | Langmuir/Pseudo-second-order | ΔG = -3.50~ -5.34  | -OH, -COOH                 | Ion exchange, complexation                  | [121] |

Metals at lower pH values (acidic). On the other hand, these impacts can only be prominent if electrostatic attraction constitutes the main adsorption mechanism. The pH_{PZC} has a minor effect when additional sorption interactions are present.

In some cases, a cation can form a negative complex by interacting with negatively charged ligands. For example, persimmon leaf was used to remove Pb, Cd, and Cu [105]. It was noted that the pH_{PZC} of the persimmon leaf was 5.6, however the maximum adsorption for heavy metals was observed at pH of 4, 3 and 3–4 for Cu, Cd and Pb, respectively. As a result, the involvement of electrostatic attraction mechanism in the adsorption process of these heavy metals by the persimmon leaf was ruled out. However, the ion-exchange mechanism appears to be linked to the abrupt rise in adsorption with increasing pH. Also, Stavrinou et al. [10] noted that the uptake efficiency of MB was 64.6, 81.1, and 96.8% for cucumber peel, potato peel, and banana peel, respectively, indicating the uptake of MB on the surface of all samples was found to be acceptable.
was 2.8 %, 4.5 % and 5.7% for banana peel, cucumber peel, and potato peel, respectively, there was no significant adsorption of OG on the surface of the adsorbents. The adsorbents exhibited high adsorption capacity for MB, but the low capacity for OG was assumed to be due to the electrostatic attraction between the dye ions and the charged sites of the adsorbent surfaces, instead of the physical sorption of dye molecules into the pores of adsorbents. The negatively charged functional groups on surface sites (–COOH and –OH) were found to attract cationic dye but repel anionic dye. The solute transfer in a solid-liquid sorption process using CLP and ZMC adsorbs MB, MG, and CR was defined by three major steps: i) exterior mass transfer, ii) pore diffusion, and iii) equilibrium reaction [68]. Thus, it was inferred that the uptake of these dyes using ZMC and CLP was controlled by pore diffusion and film diffusion mechanism. The sorption of MG on oat husks was found to be practicable, spontaneous, and endothermic based on thermodynamic characteristics and activation energy values [106]. Furthermore, physical interaction between dye and adsorbent molecules was expected.

6. Conclusions, Challenges, and Futures Outlook

6.1. Conclusions
Owing to its availability and low cost, the use of LDMs as adsorbents for water treatment has received a lot of attention recently. The advantage of modification of LDMs far outweighs the unmodified for removing heavy metals and dyes. Both organic and inorganic acids have been used effectively in the modification of LDMs to remove dyes and heavy metals, as discussed in this review. Inorganic acids have been found to be very effective in the modification of LDMs especially for the removal of heavy metals from solution; however, reports have shown the alternative use of organic acid is also promising. The mechanism of adsorption of these contaminants by lignocellulosic material also gives a better understanding of how the pollutants are adhered to and removed by the adsorbents. Where functional groups such as C–C, C=O, –COOH of the LDMs play a very crucial role in enhancing their ability for the above-mentioned pollutants. The modification of these LDMs gives additional functional groups such as SO₃⁻, NH₂ which further enhances the adsorption ability of LDMs for the pollutants. The use of organic acid to be investigated further for properly understanding and also incorporating in modification of LDMs for the removal of dyes which has limited studies on it.

6.2. Future Outlook and Challenges
Modification technology has a number of drawbacks, including the synthesis of inhibitory chemicals and the generation of wastewater with significant acidification potential, aquatic and human toxicity potential for consumption, and exposure. To boost the yield of particular substrates in LDM, advances in modification procedures are constantly created and improved. Given the recent focus on green chemistry, there will be plenty of room for organic acid advances in the modification of lignocellulosic biomass.

Despite the fact that organic acid modification has shown to be a viable substitute for inorganic acid, there are few studies that gives in-depth understanding as how it can be used for modification of LDM for heavy metals removal from the wastewater. With respect to this, more research work can be tailored toward their utilization for lignocellulose modification.

The adsorptive performance of LDMs for removing dyes and heavy metals has been considered over the years in order to understand its feasibility as an adsorbent. Hitherto, the importance of modification has been proven to be far more effective for the removal of these contaminants. However, the commercialization of modified LDMs has not been well established. Further research in this field could help with the future commercialization and optimization of this adsorbent as a dye metal adsorbent, which would benefit a variety of industries.

Acknowledgments
This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2021R111A305924311).

Conflict-of-Interest
No potential conflict of interest was reported by the authors.

Author Contributions
M.S.A. (Ph.D.): Conceptualization, Data Collection, Writing - original draft, Visualization, Software, Validation, Writing review & editing.
H.J.C. (Prof. Ph.D.): Conceptualization, Methodology, Visualization, Writing-review & editing.

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