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# Sustainable Adsorption of Congo Red Dye Using Organic Waste Materials as Green Adsorbents: A Mini-Review

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**ABSTRACT**

One of the most significant applications of green chemistry is the utilization of agricultural organic waste products as efficient and cost-effective adsorbents. This eventually leads to environmental sustainability and the safeguarding of natural resources. Previous studies have shown that many agricultural waste products may be used as source materials or with physical or chemical alterations in Congo red (CR) dye adsorption. Employing waste materials aligns with the concepts of sustainability and waste reduction, both of which are important aspects of green chemistry. Agricultural waste is often abundant and inexpensive, making it a viable alternative to conventional adsorbents. Transforming debris into usable commodities reduces the environmental effect of waste disposal and the demand for non-renewable resources. Many agricultural wastes have vast surface areas and functional groups, which can effectively adsorb pollutants from aqueous solutions. This mini-review looks at the use of organic waste materials such as agricultural leftovers, fruit peels, and biomass as sustainable adsorbents to remove the hazardous color Congo Red from water. It emphasizes the benefits of these materials over traditional adsorbents, looking at advances in their manufacture and modification to increase adsorption capacity. The review analyses the parameters that influence the adsorption process, compares green adsorbents to traditional ones, and considers their regeneration and reuse, highlighting their potential for environmental conservation and waste valorization.

## 1. Introduction

Population growing its presence, urbanization, and industry have all increased water usage. One notable impact is the release of pigments and dye pollution from the textile, paper, and leather industries, which harms flora, wildlife, and aquatic life [1]. The usage of dyes in many sectors is creating major environmental damage due to their poisonous and non-biodegradable nature [2]. The textile sector releases significant amounts of dyes, harmful metals, and chemicals into the water stream. The textile industry uses around 100,000 different dyes, according to estimates. The textile industry uses dyes to tint its products and consumes a lot of water. As a result, they produce large volumes of colored wastewater [3]. The textile industry " is responsible for an estimated 300,000 tons of pollutants in the stream each year [4]. Organic dyes are poisonous, stable, and difficult to decompose. Industrial wastewater from printing facilities and textile mills is often contaminated with dyes due to inadequate basic treatment [5]. The production of one ton of dyestuff requires a staggering amount of water, ranging from 200 to 270 tons. A significant portion of this water is then discarded as waste. Alarmingly, around 20% of the unused dyes find their way into nearby water bodies through untreated industrial effluents, posing a potential threat to the environment [6]. Colored effluents can

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contaminate potable water sources by mixing with surface and groundwater streams. Dyes may induce allergic dermatitis, skin irritation, cancer, and mutations [7]. These dyes harm the aquatic ecology by reducing photosynthesis and oxygen levels, as well as altering the color of water [8]. Removing dyes from wastewater is crucial for maintaining a sustainable ecosystem. Lately, there has been a growing focus on methods for eliminating anionic dye compounds from wastewater effluents [8]. The removal procedure should be straightforward, efficient, and cost-effective. Several techniques have been proposed to remove dyes from wastewater. These approaches include biological and physicochemical processes [7]. Several techniques have been developed for removing Congo Red dye from contaminated water samples, including ion exchange, coagulation-flocculation, ultrasonic irradiation, adsorption, mineralization, and photocatalysis [9]. Each Technique has advantages and disadvantages; hence, processes such as oxidation, precipitation-coagulation, and others are costly, difficult, and emit toxic secondary byproducts [10]. Despite the emergence of alternative approaches, adsorption continues to be a favored strategy for dye elimination owing to its comparative simplicity of operation and promising removal performance [11]. It is the preferred procedure because of its low cost, simplicity, and effectiveness. The main issue in this process is choosing a sustainable, low-cost, and effective adsorbent. The primary issue in the adsorption approach is to select a sustainable, low-cost, and effective adsorbent. Researchers want to identify inexpensive and ecologically friendly chemicals that may efficiently eliminate diverse organic pollutants [12]. Agricultural waste and carbon-based products obtained from waste crops are ideal for removing harmful compounds like dyes due to their availability, renewability, and low cost. Plant-based waste residues have been studied as potential adsorbents. Using low-cost adsorbents for hazardous material separation can benefit both waste management and water purification [13]. Agricultural waste and other bio-wastes are a cost-effective and sustainable way to remove pollutants from wastewater [12].

The goal of this mini-review is to assess the feasibility and efficacy of employing organic waste materials as sustainable adsorbents to remove Congo Red dye from aqueous solutions. It seeks to combine recent research findings, describe improvements in material production and modification, and emphasize the advantages and disadvantages of these green adsorbents in comparison to conventional ones, with the ultimate goal of supporting environmental conservation and waste valuing.

## 2. Classification of Dyes

Over 100,000 distinct dyes are used in modern industrial processes, together with other chemicals for synthesis and stabilization. According to reports, dyes are being dumped into the environment in unsafe and unregulated ways, particularly into water sources, potentially leading to long-term environmental degradation [4]. As human civilization and population rise, so does the need for dyes and pigments, driven by a desire for bright colors at reasonable rates. Natural dyes and pigments were commonly used until the mid-1800s, when William Henry Perkin invented the first synthetic dye, mauve or aniline purple, in 1856. Synthetic dyes are widely used and manufactured due to their longevity, broad color range, simplicity of application, and low cost [14]. Whereas some pigments come from plants or animals, the most often used food dyes are manmade chemical compounds. Natural dyes have limitations, such as decreased coloring intensity, degradation during food preparation, and the possibility of disagreeable smells [15]. Dyes are classified by their origin (plant, animal, mineral, microbe, and waste), chemical structure (e.g., indigoid, flavonoid, and tannin dyes), color, and application (mordant dyes and direct dyes) [16]. Also, Dyes are categorized into two types based on their ionic nature: ionic and nonionic as shown in Figure 1 [8]. In animals, azo dyes are broken down by bacterial azoreductase enzymes in the anaerobic lower gastrointestinal tract. Mammalian enzymes found in organs such as the liver and kidneys may help to degrade azo dyes, although their role is uncertain [15].

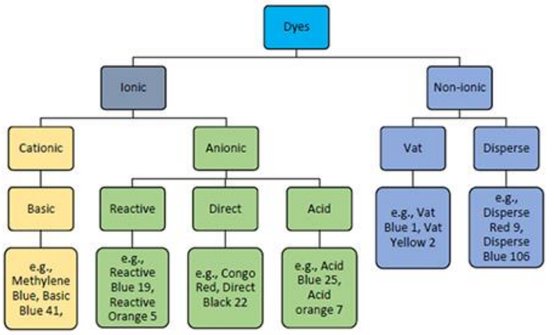


**Figure 1.** Ion-based-dye classification with examples [17]

## *2.1 Anionic Azo Dyes*

Anionic dyes depend on negative ions. Anionic dyes are molecules from many dye families that have unique structural differences (e.g., azoic, anthraquinone, triphenylmethan, and nitro dyes) yet are water-soluble with ionic substituents. Anionic dyes also include direct dyes, and chemically, anionic azo dyes make up a large portion of the reactive dyes [18]. Azo dyes have $R^1$-N=N-$R^2$ bonds, which may be reduced enzymatically to provide aromatic amines. Amphoteric properties can be linked to the presence of functional groups such as carboxyl, hydroxy, amino, or sulfonyl. Azo dyes are among the most widely used synthetic and adaptable colorants. Azo dyes can damage both humans and plants [4]. Around 65% of azo dyes are used as food additives in products such as soft drinks, jams, confectionery, and pickles. European Regulation (EC) No. 1333/2008 restricts the use of azo dyes as food additives. Despite laws, regulations, and consumer information (such as food labeling), safety concerns persist. Imported foods have complex monitoring and testing methods to verify compliance with allowed levels of use, making safety assessments questionable [15]. Dietary azo dyes may cause health hazards. Artificial colors may be safe to ingest in quantities below the Allowable Daily Intake (ADI). Larger doses may have health implications, particularly in children. Allergies, attention deficit hyperactivity disorder (ADHD), asthma, anxiety, cytotoxicity, and genotoxicity/cancer are among the potential dangers mentioned. Azo dyes are stable under aerobic conditions [19]. The presence of azo dyes in freshwater can be unpleasant, and dye compound breakdown (colorless aromatic amines) has been associated with cancer, toxicity, and mutation [20]. A 70 kg adult (5 L of blood) with an oral absorption rate of 2-5% may have a peak concentration of 2-5 mg/mL in their blood [21].

## *2.2 Congo Red Dye (CR)*

Congo red (CR), with its full chemical name 1-Naphthalene sulfonic acid, 3,3'-(4,4' biphenylene bis(azo)) bis (4-amino) disodium salt, is a benzidine-based dye. It possesses the potential to metabolize into benzidine, which is a known human carcinogen. Moreover, Congo red can potentially induce skin irritation and allergic dermatitis. This dye belongs to the class of benzidine-based dyes (Figure 2) [22]. The physical properties of the CR dye are listed in Table 1. Congo red (CR) is a negatively charged dye that exhibits insolubility in both acidic and alkaline environments, making it challenging to eliminate once released into the environment. It hinders the growth of animals and plants, affecting human digestive and circulatory systems to varying extents [23]. The anionic Congo red dye exhibits high solubility in water, resulting in detrimental color alterations that can adversely affect aquatic ecosystems. CR is an azo dye that transforms into benzidine, posing serious health risks to humans, including skin, eye, and gastrointestinal irritation [24]. Congo Red dye (diazo) is a known carcinogen due to its aromatic amine composition. Dyes can have long-term harmful consequences on wildlife and the environment [13].

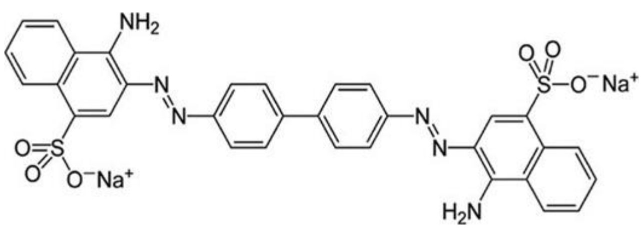

**Figure 2.** Molecular structure of CR dye [25].

**Table 1.** The physical properties of CR [12].

| Chemical formula | Molecular weight | Color index/type | $\lambda_{max}$ |
|---|---|---|---|
| $C_{32}H_{22}N_6Na_2O_6S_2$ | 696.665 | 22,120/Azo dye | 498 nm |

## 3. Decolorization Techniques

Textile and related sectors account for 10-25% of dye spills, with around 2% spilled into industrial waterways. As a result, the effluent has a substantial amount of color. This wastewater is normally treated with physical and chemical methods. Due to expensive expenses and disposal concerns, businesses routinely dump untreated sewage. The discharge of colored wastewater is a leading cause of environmental problems [26]. Azo dye decolorization and degradation are major global concerns. There are two primary methods for eliminating colorants from wastewater: physiochemical and biological. However, small businesses cannot employ these costly techniques to handle a wide range of dye wastes [27]. To remove azo dyes from water, a variety of methods have been employed, including reverse osmosis, biological degradation, flocculation, coagulation, ultrasonic techniques, electrochemical processes, flotation, photodegradation, and adsorption. Adsorption is a promising approach due to its simplicity, effectiveness in pipeline systems, cost-effectiveness, environmental friendliness, sludge-free cleaning, non-destructiveness, biocompatibility, and ease of application [28].
There are four sorts of therapeutic approaches: physical, chemical, nanoparticle-based, and biological. Several physical/chemical methods, such as adsorption, chemical precipitation, photolysis, chemical oxidation, reduction, and electrochemical treatment, have been used to remove dyes from wastewater. Much research has employed physicochemical methods to remove color from dye-containing effluents [29]. As shown in Figure 3, the classification of dye-based wastewater treatment strategies. Physical approaches provide several advantages, including simplicity, ease of operation, low cost, less chemical needs, and no inhibitory influence from dangerous substances [30].

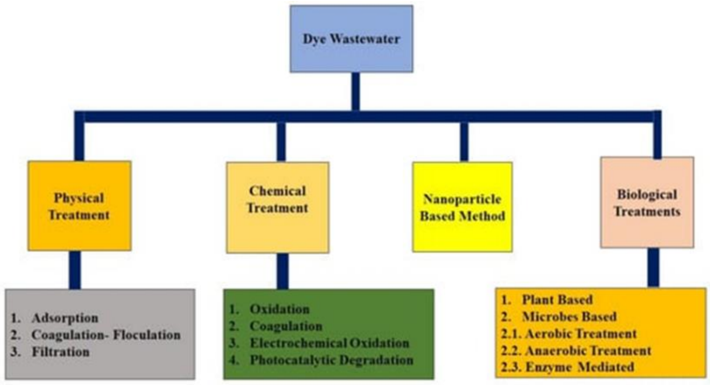


**Figure 3.** The classification of dye-based wastewater treatment strategies [26].

### *3.1 Adsorption*

Various techniques have been used to remove CR dye from wastewater, including as ion exchange, membrane separation, reverse osmosis, adsorption, and coagulation [24]. Adsorption is a very promising technology due to its effectiveness, ease of application, nontoxicity, simplicity, and moderate reaction conditions. Adsorption is used to remove and recover harmful compounds from liquids and gases by decolorizing, separating, detoxifying, deodorizing, purifying, and preconcentrating them [31]. Adsorbents are the primary key for adsorption, and a variety of materials were utilized for this purpose [32]. Due to its exceptional efficiency and ability to adsorb pollutants, commercial activated carbon is widely employed as an adsorbent. Nevertheless, the high initial cost, rapid saturation, and challenges associated with the regeneration of activated carbon make it a less favourable choice as an adsorbent material. For these reasons, several investigations have been conducted to find inexpensive, environmentally safe, and effective alternative adsorbent materials [31]. Adsorption processes are characterized as physical or chemical according to how the adsorbate adheres to the adsorbent surface as illustrated in Figure 4. [5]. Adsorbate is bound to adsorbents by weak physical forces such van der Waals, polarity, hydrogen bonding, hydrophobicity, dipole interactions, static interactions, and π-π interactions. Chemical adsorption occurs when an adsorbate and an adsorbent surface exchange electron [33].

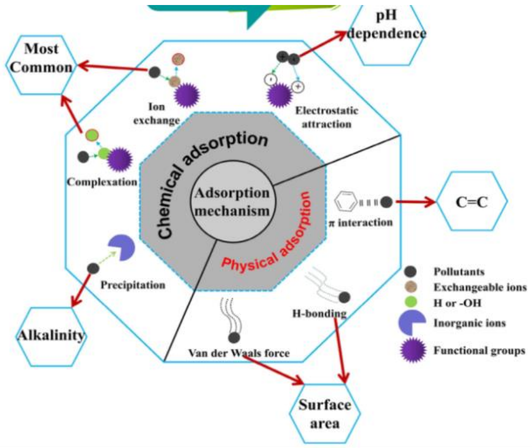


**Figure 4**. Physical and chemical adsorption mechanism [5]

## 4. Organic waste adsorbents

Adsorption efficiency in wastewater treatment relies on selecting an appropriate adsorbent. Developing efficient and cost-effective adsorbent materials is crucial for practical implementation [23]. The production of innovative, inexpensive, efficient, and environmentally friendly adsorbents has become a significant requirement for wastewater treatment [34]. Agricultural waste has low economic value and is often difficult to dispose of. Effective exploitation of agricultural waste is crucial [35]. Sustainable adsorbents derived from natural plant and agricultural wastes are becoming increasingly popular due to their low cost. Lignocellulose is a low-cost material to collect. Lignocellulose biomasses, including bagasse, cotton gin waste, oat straw, wheat straw, and rice straw, which mostly contain lignin (10-25%), hemicellulose (20-30%), and cellulose (40-50%) [8]. Table 2 lists some of the agricultural wastes that were used as adsorbents for CR dye adsorption and the optimum values of some environmental and conditional parameters. Biomass-based adsorbents are gaining popularity due to their environmental friendliness, low cost, and superior surface characteristics. Figure 5 illustrates a recent increase in the number of publications. The paper matches the search criteria "biosorbents for dye removal" [36].

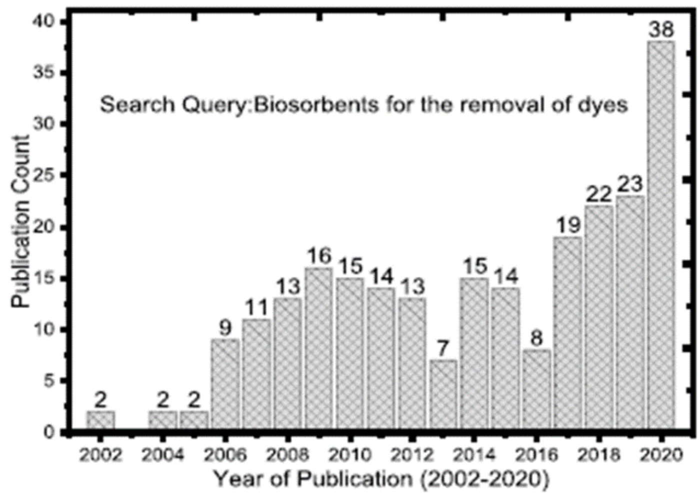


**Figure 5.** Publication trends in biosorbents for dye removal from 2002-2020 [36].

**Table 2.** Some CR dye adsorbents are generated from organic waste sources.

| Waste-Material | Reference |
|---|---|
| Activated carbon prepared from coir pith | [37] |
| Azadirachta indica leaf powder (neem leaf) (NLP) | [38] |
| activated rice husk carbon (RHCAS) | [39] |
| coconut shell, and bael fruit | [40] |
| cattail root | [41] |
| Cashew nut shell | [42] |
| Aloe Vera leaf shells-based activated carbon (AV-AC) | [43] |
| Banana peel | [44] |
| Modified banana leaves | [10] |
| Jojoba seeds | [12] |
| Activated carbon derived from waste black cardamom peels | [24] |
| Silica extracted from sand and biochar derived from coffee husks | [6] |

## 5. Applying modification for enhancing CR adsorption

The adsorption performance of agricultural organic waste materials can be enhanced through various modification techniques, despite their inherent limitations such as low selectivity, weak affinity, and inefficient regeneration due to their complex polymeric nature. Chemical, mechanical, and physical modification methods can be employed to improve their adsorption properties [45]. Classification of modification strategies for agricultural waste are illustrated in Figure 6. Agricultural waste may be used as a biosorbent in two ways: naturally and by modification. Agricultural waste is a low-cost, environmentally friendly, and plentiful alternative to traditional adsorbent materials. Agricultural wastes outperform other adsorbents because they require minimum processing (e.g., washing, drying, grinding), which reduces production costs and eliminates the need for heat processing [18]. Virgin biosorbents can benefit from modifications such as physical and chemical activation, nanoparticle insertion, and polymer integration [46]. As a result, the act of activation has less influence on a material's porosity than chemical activation, which can introduce a wide range of functional groups. Chemical activation is the process of activating the adsorbent with a chemical agent before heating it, such as pyrolysis [47].

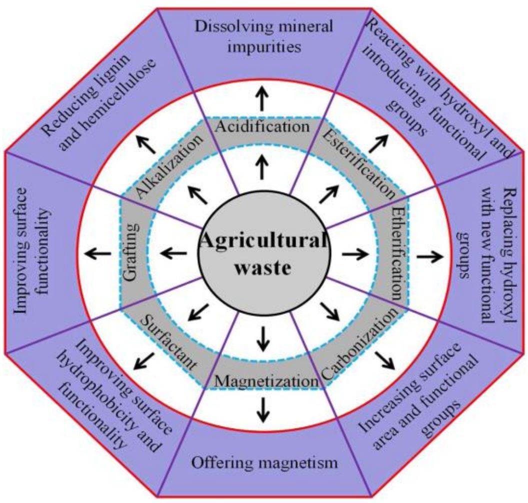


**Figure 6.** Classification of modification strategies for agricultural waste [5]

## 6. Optimization of some of the environmental and conditional adsorption parameters

The adsorbent, cashew nut shell, is capable of entirely removing CR dye from aqueous solutions. For the effective removal of CR dye through the adsorption process, several key factors have a crucial role. These operating parameters of the conditions analysed include the: pH of the solution, the dosage of the adsorbent material, dye concentration before removing it, time of the process, and temperature at which the process occurs. In this case, for the removal of Congo red dye to be complete during the adsorption process, the conditions that offer optimal results include; a pH of 3.2, dosage of 24.76 g/L, initial dye concentration of 20 mg/L, the period of the process as 67 min, and a temperature of 30 °C. The experimental results were consistent with the presented values [48]. At room temperature, batch adsorption experiments were carried out to remove CR dye from an aqueous solution using *bougainvillea glabra* (BG) leaf powder as the adsorbent. The study investigated the effect of contact time on the removal of dye CR from an aqueous solution and the ability of fruit extracts (banana peel) to absorb CR dye from an aqueous solution inducing shaking speed was 120 rpm, adsorbate concentration of 25 mg/L, and adsorbent quantity of 0.1 g at room temperature, under these conditions the experiments were carried out [2]. Adsorption studies examined several responsive parameters such as adsorbent concentration, initial CR concentration, pH, temperature, and contact time. Freundlich and Langmuir's isotherm models were used to investigate the dye adsorption equilibrium. Correspondingly, the kinetics of CR adsorption were assessed using pseudo-first-order and pseudo-second-order kinetic models. The dye adsorption isotherm and kinetics were consistent with both pseudo-second-order kinetics and Langmuir isotherm. The capacity of dye adsorption was reported at 1.727 mg/g.

## 7. Conclusions

The mini-review on the sustainable adsorption of Congo Red dye utilizing organic waste materials as green adsorbents emphasizes the materials' enormous potential in combating environmental pollution. Organic waste materials, such as agricultural byproducts, industrial leftovers, and natural biomass, have shown excellent adsorption capabilities for Congo Red dye. Their abundance, low cost, and environmentally benign nature make them appealing alternatives to traditional synthetic adsorbents. One of the most important applications of green chemistry is the utilization of agricultural organic waste products as both effective and inexpensive adsorbents. This eventually leads to attaining environmental sustainability and conserving natural resources. Previous studies have shown that some agricultural waste products can be used as raw materials or after physical or chemical modification in CR dye adsorption.

The use of organic waste materials not only provides an effective solution for dye removal but also helps with waste management and resource recycling, which aligns with the ideals of sustainability and circular economy. However, future studies should address problems such as adsorbent regeneration and reuse, adsorption process scalability, and a full knowledge of adsorption processes. Finally, the mini-review stresses that organic waste materials show potential as sustainable and effective adsorbents for Congo Red dye, offering a realistic method for reducing water pollution and promoting environmental sustainability. Further research and development in this subject may lead to novel solutions that combine waste valorization with water filtration technology.

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