Physical Education, Health and Social Sciences
https://journal-of-social-education.org
E-ISSN: 2958-5996
P-ISSN: 2958-5988


# Removal of Acid Orange Dye from Wastewater Using Quinoa Biochar and Its Nanocomposites: A Review

Sarib Shahid[1*], Momina Iftikhar[1], Ayesha Saddiqua[2], Hussnain Mushtaq[1] ,Maymoona Ishfaq[1]

[1] Department of Bioinformatics and Biotechnology, Government College University Faisalabad, Allama Iqbal Road, 38000, Faisalabad, Pakistan. Email: sarib.201905299@gcuf.edu.pk mominaiftikhar096@gmail.com hussnain4752@gmail.com moonaishfaq8@gmail.com
[2] Department of Food Science and Technology, Government College University Faisalabad, Allama Iqbal Road, 38000, Faisalabad, Pakistan. Email: ayeshasaddiqua634@gmail.com
***Corresponding Author's:** Sarib Shahid Email: sarib.201905299@gcuf.edu.pk

***DOI: https://doi.org/10.63163/jpehss.v4i1.1259***

## Abstract
Synthetic dyes in industrial effluents pose a significant environmental and health problem worldwide. Acid Orange dyes, which are azo dyes, are the most persistent, toxic, and non-biologically degradable among them. They are released into water bodies uncontrollably, which decreases light penetration, interferes with photosynthesis, and alters aquatic biodiversity. Moreover, the decomposition products of azo dyes are usually mutagenic and carcinogenic, which makes the long-term health risks to humans and the environment a concern. Although these conventional dye treatment technologies, such as coagulation-flocculation, advanced oxidation, and membrane-based processes, have proven to be effective under controlled conditions, they are characterized by high operational costs, secondary sludge formation, and low efficiency in the treatment of dilute dye effluents. Another alternative adsorbent that has proven to be economical, sustainable, and environmentally friendly is biochar, which is a carbon-rich substance formed through the pyrolysis of agricultural residues. Quinoa (Chenopodium quinoa) residues, including husks and stems, are a new feedstock for biochar production, with distinct physicochemical characteristics, and can be valorized as a waste in a circular economy context. In addition, nanocomposites of quinoa biochar with nanomaterials have been synthesized by modifying biochar with nanomaterials, which have increased adsorption capacity, surface reactivity, and reusability. The mini review illuminates the use of quinoa biochar and its nanocomposites in the removal of Acid Orange dye in wastewater, the mechanisms of adsorption, their performance comparison, challenges, and future outlook.

**Keywords:** Acid Orange dye, Quinoa biochar, Nanocomposites, Wastewater treatment, Adsorption

## Introduction
The problem of water pollution has become a serious environmental problem in the world because of the continuous release of industrial effluents into the water bodies. Synthetic dyes are one of the most dangerous groups of these pollutants due to their toxicity, stability, and degradation resistance (Tomar et al., 2023) . Synthetic dyes are widely used in textile, leather, paper, cosmetic, and food industries and finally end up in wastewater streams. The release of untreated effluents containing dye causes serious ecological disturbances, such as low light penetration, depletion of oxygen, and poisoning of aquatic organisms (Slama et al., 2021). In addition to this, most of the dyes and their decomposition products are carcinogenic and mutagenic to humans, which is of great health concern. Azo dyes, acid orange dyes, are commonly utilized in the textile and leather industries since they are bright and chemically stable. But it is these properties that also make them very persistent in the environment (Mehta et al., 2021). The most important physicochemical characteristics of Acid Orange dye that justify its permanence and environmental risks are presented in Table 1. These properties indicate why Acid Orange cannot be treated in a typical way and why new and sustainable

solutions like quinoa-based biochar and its nanocomposites are necessary.

Traditional solutions like coagulation, flocculation, and chemical oxidation are not effective to eliminate such dyes entirely, and alternative methods are expensive and energy-consuming, such as membrane filtration or advanced oxidation (Zaheer et al., 2019). Consequently, scientists are investigating green, low-cost, and sustainable methods of dye removal in wastewater. In this regard, biochar has received a lot of attention as a good adsorbent. Biochar is a carbon-based material that has been formed by the pyrolysis of biomass at low oxygen levels (Srivastava et al., 2022). It has a large surface area, porosity, and functional groups, which make it very applicable in the adsorption of pollutants, such as heavy metals and dyes. Quinoa (Chenopodium quinoa) is one of the potential feedstocks of biochar produced using a variety of biomass sources. The wastes produced by quinoa are agricultural wastes that can be utilized to obtain value-added products such as biochar, which would be a lasting solution to waste management and environmental remediation (Ardila-Leal et al., 2021). Moreover, in recent progress, it has been aimed at improving the adsorption capacity of biochar by transforming it into nanocomposites. The surface characteristics, functionality, and reusability of biochar are enhanced by the addition of nanoparticles, including metal oxides, magnetic particles, or graphene (Chowdhury et al., 2018). These changes render quinoa biochar nanocomposites extremely effective in the elimination of Acid Orange dye in wastewater. The purpose of this mini review is to give a general idea about Acid Orange dye pollution, the possibility of using quinoa biochar as a low-cost adsorbent, and the use of its nanocomposites to enhance the dye removal efficiency. It also addresses the adsorption mechanisms, compares it with other adsorbents, the current challenges, and prospects of using it on a large scale in wastewater treatment (Islam et al., 2022).

Table 1: Physicochemical Properties of Acid Orange Dye

| Property | Value / Description | Environmental Concern | References |
|---|---|---|---|
| **Molecular formula** | $C_{16}H_{11}N_2NaO_4S$ | Complex aromatic structure, resistant to degradation | (Sillanpää et al., 2023) |
| **Molecular weight** | ~350 g/mol | Stable in water, difficult to remove | (Oon et al., 2020) |
| **Dye class** | Azo dye | Releases toxic aromatic amines upon degradation | (Santhosh et al., 2020) |
| **Solubility in water** | High (anionic dye) | Easily spreads in aquatic environments | (Badeji et al., 2024) |
| **Color index (C.I.)** | Acid Orange 7 (C.I. 15510) | Causes coloration of water, aesthetic pollution | (Eleryan et al., 2024) |
| **Stability** | Stable under light and moderate temperatures | Persistent in wastewater treatment systems | (Stejskal & Prokeš, 2020) |
| **Toxicity** | Harmful to aquatic organisms, a potential mutagen | Serious ecological and health threats if untreated | (Hashemi & Kaykhaii, 2022) |

## Biochar as an Adsorbent

Biochar has gained a lot of interest over the past few years as a cheap and sustainable substance in the treatment of wastewater. It is normally obtained through pyrolysis of agricultural residues, forestry wastes, or animal manures in conditions of limited oxygen. The process not only transforms the waste biomass into a solid carbon-rich material but also minimizes greenhouse gas emissions by trapping carbon in solid form (Ahmadian et al., 2023). Due to the special physicochemical characteristics, biochar has been widely investigated as an adsorbent to eliminate organic pollutants, dyes, and heavy metals in aqueous solutions. High surface area and porosity of biochar are one of the key factors that have contributed to its popularity as an adsorbent. In the pyrolysis process, there is the release of volatile matter, and what remains after the process is a network of pores in the biochar structure (Cheng et al., 2021). These are pores that can be used as active sites where the dye molecules can be trapped and stored. The pyrolysis conditions and the feedstock can give rise to a wide range of surface area of biochar that affects adsorption capacity (Kumkum & Kumar, 2024). An example of this is that, with an increase in temperature, the biochar tends to have more surface area and pore volume, which directly increases the capacity of the biochar to remove dye. The other important consideration that makes biochar effective in adsorption is the availability of surface functional groups like hydroxyl, carboxyl, and carbonyl groups (Shi et al., 2022). These groups offer binding sites of pollutants by hydrogen bonding, electrostatic interactions, and π–π interactions. These functional groups may be important in adsorption in the case of Acid Orange dye, which is an anionic dye, where strong electrostatic forces are formed between the negatively charged dye molecules and the positively charged surface sites of the biochar. Biochar has a number of economic and environmental advantages besides adsorption (El-Nemr et al., 2020). The feedstock used in the manufacture of biochar is usually cheap and in large quantities, such as agricultural waste. The process of its preparation is comparatively easy and does not involve the use of costly equipment, as opposed to sophisticated wastewater treatment procedures. In addition, biochar use in wastewater treatment helps in waste management by turning agricultural residues into useful products, hence encouraging a circular economy (M. Zhang et al., 2022). Another factor that has increased the use of biochar is its versatility. Various biomasses like rice husk, wheat straw, sugarcane bagasse, and corn stover have been utilized effectively to produce biochar with effective adsorption properties. The feedstock gives each biochar a different structural and chemical property, and therefore, researchers can choose the right biomass based on the desired pollutant (Huang et al., 2020). Summing up, biochar is a cost-effective, efficient, and sustainable solution to the elimination of wastewater pollutants. It has tunable surface characteristics, functional groups, and porous structure, which make it a good candidate to tackle the increasing dye pollution problem (Patra et al., 2017). Its adsorption efficiency can be greatly increased with additional changes, including its transformation into nanocomposites, which would allow its application as an even more efficient means of treating recalcitrant dyes, such as Acid Orange.

**Quinoa Biochar**

Quinoa is a very nutritious crop that is grown predominantly in South America, but is slowly gaining popularity in other regions of the world because it can withstand extreme weather conditions (Vilcacundo & Hernández-Ledesma, 2017). In the process of growing and processing, a lot of agricultural waste, including stalks, husks, and bran, is produced. These wastes usually remain unused or are disposed of as waste, which contaminates the environment (Akram et al., 2024). The use of these by-products to produce biochar is a sustainable measure to eliminate waste materials, and at the same time, it can be used as a cheap adsorbent in wastewater treatment (Nowak et al., 2016). The residues of quinoa are specifically good materials to prepare biochar due to their high lignocellulosic content. These residues produce a biochar that is rich in carbon and well-developed pore structure when they are pyrolyzed in limited oxygen conditions (Yang et al., 2020). The quinoa biochar that results tends to have a high surface area, stable structure, and a high number of functional groups, which are critical properties of the adsorption of organic contaminants like dyes. The performance of quinoa biochar is dependent on its structural properties (Ren et al., 2023). The porous structure that is formed during the pyrolysis process offers many active sites on which the dye molecules bond. Acid Orange dye is a large and stable molecule and needs an adsorbent with accessible pores and surface heterogeneity, which can be found in quinoa-derived biochar (Naeem et al., 2020). Moreover, quinoa biochar tends to include mineral constituents such as potassium, calcium and magnesium, which may be used to improve adsorption by ion-exchange. The other benefit of quinoa biochar is its surface chemistry (Jaikishun et al., 2019). The availability of oxygen-containing groups like -OH, -COOH and -C=O increases its capacity to interact with dye molecules by hydrogen bonding and electrostatic interactions. This causes quinoa biochar to be particularly useful in the removal of anionic dyes such as Acid Orange in aqueous solutions (Deng et al., 2023). Figure 1 shows the general workflow of the production of biochar using quinoa residues.

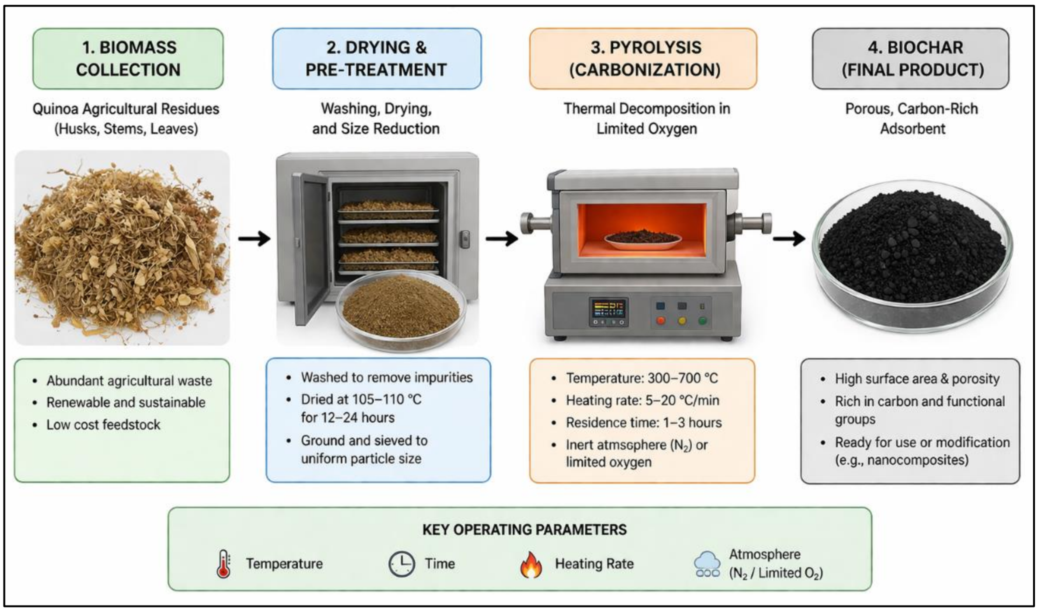



**Figure 1:** Biochar production from quinoa residues

Furthermore, the biochar surface can be chemically or physically modified to enhance its adsorption capacity, and it is therefore applicable in a wide range of treatment applications. Quinoa biochar has a very bright future in terms of environmental and economic aspects. The production of quinoa also produces high amounts of agricultural waste which in most cases have low economic value (Abril et al., 2022). By transforming these residues into biochar, waste management problems are minimized and a useful product to clean the environment is obtained. As quinoa is commonly cultivated in both developing and developed nations, the availability of feedstock is not particularly troublesome which makes quinoa biochar production sustainable (Angeli et al., 2020). To conclude, quinoa biochar is a low-cost, eco-friendly, and efficient adsorbent that is obtained using agricultural wastes. Its favorable structural characteristics, numerous functional groups and its ability to be subjected to modifications render it very appropriate in the removal of Acid Orange dye in wastewater (Hernández-Ledesma, 2019). Recent developments indicate that the performance of quinoa biochar can be considerably improved by the addition of nanoparticles, and thus quinoa biochar nanocomposites with enhanced adsorption performances were obtained (Afzal et al., 2022).

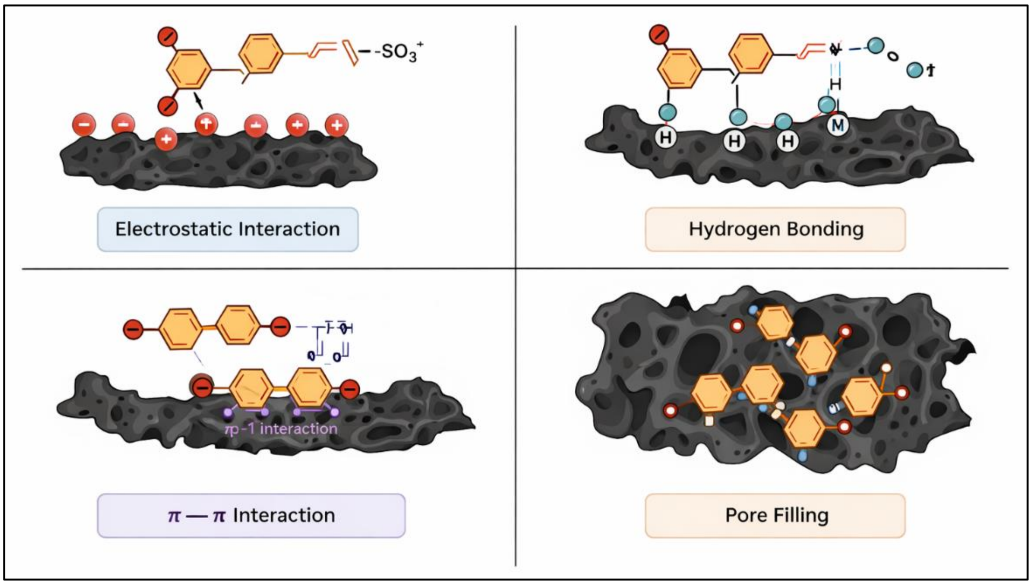
## Nanocomposites of Quinoa Biochar

Despite the good potential of quinoa biochar as a single adsorber in dye removal, researchers have investigated the possibility of increasing its adsorption capacity. The formation of nanocomposites, where the nanoparticles are incorporated on the biochar surface, is one of the promising methods. Nanomaterials greatly enhance the surface chemistry, porosity, and reactivity of biochar, which is much more useful in the treatment of wastewater (Majeed et al., 2023a). Biochar is used to create nanocomposites with various nanoparticles, including metal oxides ($Fe_3O_4$, $TiO_2$, ZnO), carbon-based (graphene, carbon nanotubes) or silica-based particles. Such nanoparticles offer extra active sites and functional groups, which enhance the adsorption of complex and persistent molecules such as Acid Orange dye (Alsamadany et al., 2022). With quinoa biochar, nanocomposites in addition to increasing adsorption capacity, increase reusability, stability and selectivity to specific pollutants. Among the modifications that have been examined the most is the magnetization of biochar with iron oxide nanoparticles. Magnetic quinoa biochar nanocomposites have the benefit of being highly adsorptive and able to be recovered readily following treatment. After the dye has been adsorbed, the magnetic nanocomposite may be detached in water with the help of a simple external magnet, which lowers the operational expenses and makes the process more realistic in a practical application (Mousa et al., 2022). The other method that is significant is metal oxide functionalization. Nanoparticles such as $TiO_2$ or ZnO added to quinoa biochar not only enhance adsorption, but also could have photocatalytic abilities. It enables the integrated adsorption and photocatalysis process in which the Acid Orange dye molecules are initially adsorbed to the biochar surface and then broken down in the presence of light. This dual mechanism greatly enhances the removal efficiency and reduces the secondary pollution. There has also been the development of carbon-based nanocomposites with quinoa biochar (Salama et al., 2021). Graphene oxide or carbon nanotubes increase the surface area, electron conductivity and availability of π–π interaction sites, which is especially valuable in binding aromatic dye molecules such as Acid Orange. These nanocomposites have better dye affinity and binding stability than the biochar that is not modified. Besides the efficiency of adsorption, quinoa biochar nanocomposites also exhibit enhanced mechanical and chemical stability (Tourajzadeh et al., 2024). The nanoparticles enhance the biochar structure making it difficult to degrade with repeated usage. The system is more sustainable due to this reusability and affordable when treating large volumes of wastewater. In general, quinoa biochar nanocomposites are a major improvement compared to the raw biochar. Their multi-functional character as a combination of adsorption, magnetic separation, photocatalysis, and structural stability offers a multi-functional platform to effectively remove Acid Orange dye. Ongoing studies on optimization of these nanocomposites would be instrumental in coming up with practical, environmentally-friendly, and scalable solutions to dye-polluted wastewater (Ahmad et al., 2023).

**Mechanism of Removal of Acid Orange Dye**

The process of removing Acid Orange dye in wastewater with quinoa biochar and its nanocomposites is mainly founded on adsorption processes. The process whereby dye molecules are bound to the surface of the biochar by a number of physical and chemical forces is referred to as adsorption (Xia et al., 2020). The importance of understanding these mechanisms is that it not only helps us comprehend how biochar functions, but also helps us to make future alterations to enhance its efficiency. Electrostatic interaction is one of the most important mechanisms. Acid Orange is an anionic dye, i.e., it is negatively charged in water. Based on the surface charge and pH of the solution, quinoa biochar can acquire positively charged sites. The negatively charged dye molecules are attracted to these sites leading to a strong electrostatic binding (Mcyotto et al., 2021). Nanocomposites, such as iron oxide or zinc oxide, are added and, in addition to increasing the quantity of charged sites, improve dye removal. The other prominent process is hydrogen bonding. Quinoa biochar surface has functional groups including hydroxyl (-OH) and carboxyl (-COOH). These groups are able to hydrogen bond with the nitrogen or oxygen atoms on the Acid Orange dye molecules (Abdul Mubarak et al., 2021). This kind of interaction aids in the stabilization of the dye molecules on the biochar surface, which allows effective removal of the dye molecules on the wastewater. π-π interactions are also significant, particularly since Acid Orange consists of aromatic rings (Qurrat-ul-Ain et al., 2020). Quinoa biochar contains carbon-rich structure that has graphitic areas where delocalized p-electrons are found. These areas are able to π-π stack with the aromatic rings of dye molecules resulting in greater adsorption. This form of interaction is also increased by the addition of carbon-based nanomaterials such as graphene (Kan et al., 2020). Moreover, pore-filling mechanism is also involved in the removal of dye. In the process of pyrolysis, quinoa biochar acquires a porous structure with micro and mesopores. The molecules of Acid Orange are able to enter these pores and be physically trapped by their size and shape. This process enhances the total adsorption capacity of biochar (Dutta et al., 2022). The modification of nanocomposites may increase the size of pore and surface area which facilitates the entry of dye molecules and occupancy with more adsorption sites. In the case of nanocomposites that have photocatalytic properties (e.g., $TiO_2$-modified biochar), there is an extra mechanism of dye removal. The first one is to adsorb dye molecules onto the surface and then photocatalytic degradation takes place under light irradiation (B. Zhang et al., 2020). Reactive radicals (hydroxyl radical, OH) or superoxide radicals ($O^{2-}$) are formed, which decompose Acid Orange into smaller, less toxic products. This adsorption-degradation hybrid increases the effectiveness of nanocomposites over unmodified biochar. Lastly, with magnetic quinoa biochar nanocomposites, easy separation and recovery are also a part of the mechanism (Zhao et al., 2021). Once the adsorption is done, the nanocomposite can be harvested in the treated water by means of a magnetic field. This is to ensure that the adsorbent is not left in the water and can be reused several times without becoming ineffective (Budnyak et al., 2020). The principle of Acid

Orange dye removal with quinoa biochar and its nanocomposites is founded on a mixture of electrostatic attraction, hydrogen bonding, π-π interactions, pore filling, and, in certain instances, photocatalytic degradation. All these routes justify the high efficiency of quinoa biochar-based adsorbents and indicate their prospects of large-scale wastewater treatment (Ariaeenejad et al., 2022). Figure 2 shows the




adsorption processes that occur during the removal, which include electrostatic interactions, hydrogen bonding, π- π interactions, and pore filling.

Figure 2: Adsorption Mechanisms of Acid Orange Dye on Biochar

Comparison with Other Adsorbents

The ability of quinoa biochar and its nanocomposites to remove Acid Orange dye can be more comprehensively interpreted in comparison to other widely used adsorbents. Researchers have, over the years, experimented with a broad range of adsorbent materials to remove dyes such as activated carbon, clay minerals, zeolites, agricultural residues, and synthetic polymers (Bhatt et al., 2023). There are benefits and drawbacks to each adsorbent, but quinoa biochar shows a balance of cost-effectiveness, sustainability, and efficiency that is unique (Qi et al., 2021). Activated carbon is regarded as the most popular adsorbent to use in the process of dye removal because it has a large surface area, porosity, and adsorption capacity. Table 2 provides a comparative review of quinoa biochar and its nanocomposites, as well as other popular adsorbents commonly used to remove Acid Orange dye. This table shows the variations in the surface area, adsorption capacity, price, benefits, and drawbacks of each adsorbent.

Table 2: Comparison of Quinoa Biochar and Its Nanocomposites with Other Adsorbents for Acid Orange Dye Removal

| Adsorbent | Surface Area ($m^2/g$) | Adsorption Capacity (mg/g) | Cost | Advantages | Disadvantages | References |
|---|---|---|---|---|---|---|
| **Quinoa Biochar** | 250–400 | 80–120 | Low | Sustainable, eco-friendly, porous structure | Variable properties depending on pyrolysis | (Daraei et al., 2024) |
| **Quinoa Biochar Nanocomposite ($Fe_3O_4$)** | 300–450 | 150–200 | Moderate | Magnetic separation, reusable, high efficiency | Slightly higher cost, nanoparticle loss possible | (Majeed et al., 2023b) |
| **Activated Carbon** | 800–1200 | 180–250 | High | High adsorption | Expensive, energy | (Raninga et al., 2023) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | capacity, well-studied | intensive, non-renewable | |
| **Clay Minerals (e.g., Bentonite)** | 50–150 | 30–60 | Low | Abundant, cheap | Low adsorption for large dye molecules | (Xie et al., 2024) |
| **Zeolites** | 400–500 | 40–70 | Low | Porous, ion-exchange capability | Limited pore accessibility for large dyes | (Irannajad & Kamran Haghighi, 2021) |
| **Agricultural Residues (Rice husk, Wheat straw)** | 100–200 | 20–50 | Very Low | Eco-friendly, cheap | Less stable, low reusability | (Amen et al., 2020) |
| **Synthetic Polymers/Resins** | 300–500 | 100–150 | High | Customizable functional groups, selective | Complex synthesis, costly, disposal issues | (Urbano et al., 2020) |

Nonetheless, it is costly to prepare and is energy-intensive, and thus not viable in large-scale applications in developing countries. Comparatively, biochar of quinoa is made of agricultural waste through comparatively basic and inexpensive pyrolysis procedures. Although in certain instances activated carbon can demonstrate a little higher adsorption, quinoa biochar is a more sustainable and cost-effective option, particularly as a nanocomposite. Dye removal has also been used with clay minerals and natural zeolites. They are cheap and have a large supply, but can tend to have poor adsorption capacity with large dye molecules, such as Acid Orange (George et al., 2024). Their accessibility to adsorption sites is limited by their limited surface area and the size of the pore. The porous nature and tunable surface chemistry of quinoa biochar are superior to both clays and zeolites in adsorption capacity and response to various wastewater conditions (Largo et al., 2020). Other low-cost adsorbents that are usually used include agricultural residues, including rice husk, wheat straw, and corn cob. They are cheap and eco-friendly, but these raw materials are not always stable and durable during the treatment of wastewater (Sahoo et al., 2023). Conversely, quinoa biochar has a higher binding capacity due to its richness in carbon and its structural stability, which is more stable, thus can be used again and again without much loss in its efficiency. In addition, its nanocomposites also improve structural integrity and adsorption, which is more effective than untreated agricultural residues (Nour et al., 2024). Removal of dyes with synthetic polymers and resins is occasionally used because of their functional groups and selectivity, which are customizable. Their manufacture, however, is characterized by complicated chemical reactions, high cost, and possible environmental risks following the disposal (Agarwala & Mulky, 2023). Quinoa biochar and nanocomposites, on the other hand, are eco-friendly, biodegradable, and safer to be used in practice. They are similar in their performance without the disadvantages of synthetic materials. In sum, quinoa biochar and its nanocomposites are a mixture of the strengths of high adsorption efficiency, low production cost, and environmental sustainability (Aragaw & Bogale, 2021). Although the activated carbon is still used as the gold standard of adsorption research, quinoa biochar offers an eco-friendlier alternative with the added advantage of using agricultural waste and the possibility of nanotechnology-based improvement. Thus, relative to other adsorbents, quinoa biochar qualifies as a promising candidate for the effective and environmentally sustainable removal of Acid Orange dye in wastewater (El maguana et al., 2020).

**Challenges and Limitations**

Despite the promising outcomes of quinoa biochar and its nanocomposites in the removal of Acid Orange dye in wastewater, it has a number of challenges and limitations that cannot be ignored before proceeding to large-scale applications (Bal & Thakur, 2022). These are technical and practical problems, and it is important to solve them to make this approach more effective and commercially viable. Among the biggest challenges is the variation in biochar properties. Quinoa biochar properties are highly dependent on the pyrolysis temperature, heating rate and feedstock composition (Mojiri et al., 2023). Although minor variations in these parameters may cause large variations in surface area, porosity, and functional group distribution, which directly influence the adsorption efficiency. This inconsistency renders quinoa biochar production hard to standardize to be consistent in wastewater treatment (Cai et al., 2017). The second weakness is the problem of scalability and cost of nanocomposites preparation. Raw quinoa biochar is comparatively cheap to manufacture, whereas in order to create nanocomposites, this may necessitate extra materials and methods, including metal oxides or carbon-based nanomaterials. Such changes may raise the total cost and large-scale application may be difficult to achieve, particularly in resource-constrained areas where wastewater pollution is the worst (Al-Sakkaf et al., 2023). Adsorbent regeneration and disposal is also an issue. Quinoa biochar can also lose its activity after repeated adsorption cycles, either by pore clogging or by deactivation of functional groups. The recovery process, in case of nanocomposites, can be associated with the loss of nanoparticles, which results in secondary water contamination. In addition, the dye-loaded biochar should be safely disposed to prevent environmental risks (Kusumlata et al., 2024). Otherwise, the used adsorbent itself may be polluted. The other serious constraint is the co-existing pollutants competition in actual wastewater. Quinoa biochar is frequently tested against one dye in laboratory experiments. Nevertheless, industrial wastewater typically consists of a complicated combination of dyes, heavy metals, salts, and organic substances (Satyam & Patra, 2024). The competing pollutants can disrupt the adsorption process and not achieve the same level of efficiency of quinoa biochar in real world applications as in laboratory settings. Lastly, it has regulatory and acceptance obstacles. To become a viable and applicable biochar-based adsorbent in actual wastewater treatment facilities, quinoa biochar-based adsorbents should meet high environmental standards and be accepted by industries (Sharma et al., 2022). The barriers to biochar technology adoption currently are lack of awareness, inadequate large-scale pilot studies, and inadequate commercialization strategies. Overall, although quinoa biochar and its nanocomposites are very promising materials to use in the removal of Acid Orange dye, issues of standardization, cost, regeneration, competition with other pollutants, and regulatory acceptance must be considered (Alsukaibi, 2022). To address these constraints, more research, technological progress, and policy promotion will be needed to make this solution more feasible and scalable.

**Future Perspectives**

Further studies of quinoa biochar and its nanocomposites in the removal of Acid Orange dye can be done in a number of areas. To start with, there exists a necessity to increase the laboratory scale to industrial scale production with appropriate economic feasibility studies to define the cost-effectiveness against traditional adsorbents. It is also crucial to design sustainable surface modification methods, which will be able to increase the adsorption efficiency without the creation of harmful by-products (Firmansyah et al., 2025). The other important point is the regeneration and reuse of quinoa biochar, as to treat wastewater practically, the material should be able to be used repeatedly. Integration of biochar into hybrid treatment systems (e.g., photocatalysis, membrane technology, or electrochemical processes) that may be used to deliver synergistic effects through the combination of adsorption and degradation should be explored in the future as well (Kumari et al., 2023). Moreover, the majority of the available research is confined to synthetic dye solutions; hence, to determine the actual applicability of quinoa biochar, it is necessary to test quinoa biochar in actual industrial wastewater. Meanwhile, there is a need to conduct an extensive environmental and toxicological analysis to make sure that the use of biochar does not cause secondary ecological issues (Javed et al., 2025). Lastly, policy support, commercialization strategies, and circular economy models need to be put in place to be able to translate laboratory findings into practical solutions, in which quinoa agricultural residues are turned into biochar to treat wastewater later and reuse them as soil amendments or renewable energy sources. Such an integrative strategy can be used to make quinoa biochar a sustainable, scalable and environmentally friendly solution to dye-polluted wastewater treatment.

## Conclusion

Quinoa biochar and quinoa nanocomposites have also been seen as promising solutions to the removal of Acid Orange dye in wastewater because of their low cost, environmental friendliness, and high adsorption capacity. Controlled pyrolysis can be used to convert quinoa residues that are usually treated as agricultural waste to useful biochar, providing a way of environmental remediation. Quinoa biochar has physicochemical characteristics, such as high surface area, porous structure, and functional groups, which are significant in dye adsorption and nanocomposites, increasing its adsorption and catalytic efficiency. It has been pointed out by different studies that quinoa biochar is a good option to be used instead of synthetic dyes in aqueous solutions, as it is able to remove the dye effectively. Although this has potential, there are still a number of challenges. Production at large scale, cost optimization, and regeneration approaches are yet to be explored, and additional studies are needed to verify the efficacy of quinoa biochar in actual industrial wastewater, which is usually a complex combination of contaminants. The use of modified biochar also requires environmental safety tests to determine that there are no secondary risks associated with the application of modified biochar. However, with the introduction of quinoa biochar into enhanced hybrid systems and encouragement of its application in the context of the circular economy, it is possible to turn this material into a commercially viable and sustainable adsorbent, which is agricultural residue. To conclude, quinoa biochar and its nanocomposites offer an efficient and green route to eliminating Acid Orange dye in wastewater. As further studies are conducted on large-scale applications, environmental safety, and policy support, the technology has enormous potential to answer one of the most significant problems in the area of industrial wastewater management.

## Acknowledgement

The authors are grateful to Government College University Faisalabad which facilitated the preparation of this review through encouraging academic environment and access to resources. This piece of work was done free of any external funding and all it needed was the efforts of the authors and their teamwork.

Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this review article.

## References

Abdul Mubarak, N. S., Chuan, T. W., Khor, H. P., Jawad, A. H., Wilson, L. D., & Sabar, S. (2021). Immobilized Fe-Loaded Chitosan Film for Methyl Orange Dye Removal: Competitive Ions, Reusability, and Mechanism. Journal of Polymers and the Environment, 29(4), 1050–1062. https://doi.org/10.1007/s10924-020-01949-8

Abril, D., Ferrer, V., Mirabal-Gallardo, Y., Cabrera-Barjas, G., Segura, C., Marican, A., Pereira, A., Durán-Lara, E. F., & Valdés, O. (2022). Comparative Study of Three Dyes' Adsorption onto Activated Carbon from Chenopodium quinoa Willd and Quillaja saponaria. Materials, 15(14), 4898. https://doi.org/10.3390/ma15144898

Afzal, I., Basra, S. M. A., Rehman, H. U., Iqbal, S., & Bazile, D. (2022). Trends and Limits for Quinoa Production and Promotion in Pakistan. Plants, 11(12), 1603. https://doi.org/10.3390/plants11121603

Agarwala, R., & Mulky, L. (2023). Adsorption of Dyes from Wastewater: A Comprehensive Review. ChemBioEng Reviews, 10(3), 326–335. https://doi.org/10.1002/cben.202200011

Ahmad, S., Imran, M., Natasha, Amin, M., Al-Kahtani, A. A., Arshad, M., Nawaz, R., Shah, N. S., & Schotting, R. J. (2023). Potential of magnetic quinoa biosorbent composite and HNO3 treated biosorbent for effective sequestration of chromium (VI) from contaminated water. International Journal of Phytoremediation, 25(7), 929–939. https://doi.org/10.1080/15226514.2022.2122926

Ahmadian, A., Goharrizi, B. A., Shahriari, T., & Ahmadi, S. (2023). Adsorption of chromium (VI) and Acid Orange 7 on lemon peel biochar: A response surface methodology approach. International Journal of Environmental Science and Technology, 20(3), 2939–2958. https://doi.org/10.1007/s13762-022-04726-3

Akram, M. Z., Libutti, A., & Rivelli, A. R. (2024). Drought Stress in Quinoa: Effects, Responsive Mechanisms, and Management through Biochar Amended Soil: A Review. Agriculture, 14(8), 1418. https://doi.org/10.3390/agriculture14081418

Al-Sakkaf, M. K., Basfer, I., Iddrisu, M., Bahadi, S. A., Nasser, M. S., Abussaud, B., Drmosh, Q. A., & Onaizi, S. A. (n.d.). An Up-to-Date Review on the Remediation of Dyes and Phenolic Compounds from Wastewaters Using Enzymes Immobilized on Emerging and Nanostructured Materials: Promises and Challenges.

Alsamadany, H., Alharby, H. F., Al-Zahrani, H. S., Alzahrani, Y. M., Almaghamsi, A. A., Abbas, G., & Farooq, M. A. (2022). Silicon-nanoparticles doped biochar is more effective than biochar for mitigation of arsenic and salinity stress in Quinoa: Insight to human health risk assessment. Frontiers in Plant Science, 13. https://doi.org/10.3389/fpls.2022.989504

Alsukaibi, A. K. D. (2022). Various Approaches for the Detoxification of Toxic Dyes in Wastewater. Processes, 10(10), 1968. https://doi.org/10.3390/pr10101968

Amen, R., Yaseen, M., Mukhtar, A., Klemeš, J. J., Saqib, S., Ullah, S., Al-Sehemi, A. G., Rafiq, S., Babar, M., Fatt, C. L., Ibrahim, M., Asif, S., Qureshi, K. S., Akbar, M. M., & Bokhari, A. (2020). Lead and cadmium removal from wastewater using eco-friendly biochar adsorbent derived from rice husk, wheat straw, and corncob. Cleaner Engineering and Technology, 1, 100006. https://doi.org/10.1016/j.clet.2020.100006

Angeli, V., Miguel Silva, P., Crispim Massuela, D., Khan, M. W., Hamar, A., Khajehei, F., Graeff-Hönninger, S., & Piatti, C. (2020). Quinoa (Chenopodium quinoa Willd.): An Overview of the Potentials of the "Golden Grain" and Socio-Economic and Environmental Aspects of Its Cultivation and Marketization. Foods, 9(2), 216. https://doi.org/10.3390/foods9020216

Aragaw, T. A., & Bogale, F. M. (2021). Biomass-Based Adsorbents for Removal of Dyes From Wastewater: A Review. Frontiers in Environmental Science, 9. https://doi.org/10.3389/fenvs.2021.764958

Ardila-Leal, L. D., Poutou-Piñales, R. A., Pedroza-Rodríguez, A. M., & Quevedo-Hidalgo, B. E. (2021). A Brief History of Colour, the Environmental Impact of Synthetic Dyes and Removal by Using Laccases. Molecules, 26(13), 3813. https://doi.org/10.3390/molecules26133813

Ariaeenejad, S., Motamedi, E., & Salekdeh, G. H. (2022a). Highly efficient removal of dyes from wastewater using nanocellulose from quinoa husk as a carrier for immobilization of laccase. Bioresource Technology, 349, 126833. https://doi.org/10.1016/j.biortech.2022.126833

Ariaeenejad, S., Motamedi, E., & Salekdeh, G. H. (2022b). Highly efficient removal of dyes from wastewater using nanocellulose from quinoa husk as a carrier for immobilization of laccase. Bioresource Technology, 349, 126833. https://doi.org/10.1016/j.biortech.2022.126833

Badeji, A. A., Omoniyi, M. T., Ogunbayo, T. B., Oladipo, S. D., & Akinbulu, I. A. (2024). Quantum chemical investigation of the degradation of acid orange 7 by different oxidants. Discover Chemistry, 1(1), 55. https://doi.org/10.1007/s44371-024-00059-x

Bal, G., & Thakur, A. (2022). Distinct approaches of removal of dyes from wastewater: A review. Materials Today: Proceedings, 50, 1575–1579. https://doi.org/10.1016/j.matpr.2021.09.119

Bhatt, P., Joshi, S., Urper Bayram, G. M., Khati, P., & Simsek, H. (2023). Developments and application of chitosan-based adsorbents for wastewater treatments. Environmental Research, 226, 115530. https://doi.org/10.1016/j.envres.2023.115530

Budnyak, T. M., Błachnio, M., Slabon, A., Jaworski, A., Tertykh, V. A., Deryło-Marczewska, A., & Marczewski, A. W. (2020). Chitosan Deposited onto Fumed Silica Surface as Sustainable Hybrid Biosorbent for Acid Orange 8 Dye Capture: Effect of Temperature in Adsorption Equilibrium and Kinetics. The Journal of Physical Chemistry C, 124(28), 15312–15323. https://doi.org/10.1021/acs.jpcc.0c04205

Cai, Z., Sun, Y., Liu, W., Pan, F., Sun, P., & Fu, J. (2017). An overview of nanomaterials applied for removing dyes from wastewater. Environmental Science and Pollution Research, 24(19), 15882–15904. https://doi.org/10.1007/s11356-017-9003-8

Cheng, H., Liu, Y., & Li, X. (2021). Adsorption performance and mechanism of iron-loaded biochar to methyl orange in the presence of Cr6+ from dye wastewater. Journal of Hazardous Materials, 415, 125749. https://doi.org/10.1016/j.jhazmat.2021.125749

Chowdhury, I. H., Kundu, S., & Naskar, M. K. (2018). Effect of organic acids on the physicochemical properties of titania and its photodegradation efficiency of methyl orange. Journal of Physics and Chemistry of Solids, 121, 367–374. https://doi.org/10.1016/j.jpcs.2018.05.032

Daraei, E., Bayat, H., & Gregory, A. S. (2024). Impact of natural biochar on soil water retention capacity and quinoa plant growth in different soil textures. Soil and Tillage Research, 244, 106281. https://doi.org/10.1016/j.still.2024.106281

Deng, X., Duan, F., Zhu, Y., Wang, A., & Zheng, Y. (2023). Fabrication of porous adsorbent by quinoa husk stabilized foam templates for dye adsorption and carbonization for soil remediation. Bioresource Technology, 388, 129754. https://doi.org/10.1016/j.biortech.2023.129754

Dutta, S. K., Amin, M. K., Ahmed, J., Elias, Md., & Mahiuddin, Md. (2022). Removal of toxic methyl orange by a cost-free and eco-friendly adsorbent: Mechanism, phytotoxicity, thermodynamics, and kinetics. South African Journal of Chemical Engineering, 40, 195–208. https://doi.org/10.1016/j.sajce.2022.03.006

El maguana, Y., Elhadiri, N., Benchanaa, M., & Chikri, R. (2020). Activated Carbon for Dyes Removal: Modeling and Understanding the Adsorption Process. Journal of Chemistry, 2020(1), 2096834. https://doi.org/10.1155/2020/2096834

Eleryan, A., Hassaan, M. A., Aigbe, U. O., Ukhurebor, K. E., Onyancha, R. B., El-Nemr, M. A., Ragab, S., Hossain, I., & El Nemr, A. (2024). Kinetic and isotherm studies of Acid Orange 7 dye absorption using sulphonated mandarin biochar treated with TETA. Biomass Conversion and Biorefinery, 14(9), 10599–10610. https://doi.org/10.1007/s13399-023-04089-w

El-Nemr, M. A., Abdelmonem, N. M., Ismail, I. M. A., Ragab, S., & El Nemr, A. (2020). The efficient removal of the hazardous azo dye Acid Orange 7 from water using modified biochar from Pea-peels. Desalination and Water Treatment, 203, 327–355. https://doi.org/10.5004/dwt.2020.26190

Fdez-Sanromán, A., Pazos, M., Rosales, E., & Sanromán, M. A. (2020). Unravelling the Environmental Application of Biochar as Low-Cost Biosorbent: A Review. Applied Sciences, 10(21), 7810. https://doi.org/10.3390/app10217810

Firmansyah, M. L., Ashraf, M., & Ullah, N. (2025). A critical review on the removal of anionic dyes by cross-linked resin: Recent progress, challenges and future perspective. Separation and Purification Technology, 360, 131111. https://doi.org/10.1016/j.seppur.2024.131111

George, G., Ealias, A. M., & Saravanakumar, M. P. (2024). Advancements in textile dye removal: A critical review of layered double hydroxides and clay minerals as efficient adsorbents. Environmental Science and Pollution Research, 31(9), 12748–12779. https://doi.org/10.1007/s11356-024-32021-w

Guevara Soto, V. I., García Bustos, K. A., Colina Andrade, G., Pacheco Tanaka, A., dos Santos, J. C., & Terán Hilares, R. (2025). Strategies for valorization of quinoa stalks in an integrated biorefinery approach: Citric acid-assisted hydrothermal pretreatment, membrane separation, production, and use of activated charcoal. Environmental Technology & Innovation, 38, 104206. https://doi.org/10.1016/j.eti.2025.104206

Hashemi, S. H., & Kaykhaii, M. (2022). Chapter 15 - Azo dyes: Sources, occurrence, toxicity, sampling, analysis, and their removal methods. In T. Dalu & N. T. Tavengwa (Eds.), Emerging Freshwater Pollutants (pp. 267–287). Elsevier. https://doi.org/10.1016/B978-0-12-822850-0.00013-2

Heredia Salgado, M. A., Coba S, J. A., Cianferoni, A., Säumel, I., & Tarelho, L. A. C. (2022). Conversion of quinoa and lupin agro-residues into biochar in the Andes: An experimental study in a pilot-scale auger-type reactor. Frontiers in Bioengineering and Biotechnology, 10. https://doi.org/10.3389/fbioe.2022.1087933

Hernández-Ledesma, B. (2019). Quinoa (Chenopodium quinoa Willd.) as source of bioactive compounds: A review. Bioactive Compounds in Health and Disease, 2(3), 27. https://doi.org/10.31989/bchd.v2i3.556

Huang, K., Li, W., Wang, Y., Liu, B., Xu, R., Dai, J., Zheng, X., Yang, N., Qiu, M., & Han, L. (2020). Adsorption of Acid Orange 7 in Aqueous Solution by Biochar from Peanut Shell Supported with Clay Mineral Kaolinite. Nature Environment and Pollution Technology, 19(4), 1657–1662. https://doi.org/10.46488/NEPT.2020.v19i04.033

Irannajad, M., & Kamran Haghighi, H. (2021). Removal of Heavy Metals from Polluted Solutions by Zeolitic Adsorbents: A Review. Environmental Processes, 8(1), 7–35. https://doi.org/10.1007/s40710-020-00476-x

Islam, M. T., Islam, T., Islam, T., & Repon, M. R. (2022). Synthetic dyes for textile colouration: Process, factors and environmental impact. Textile and Leather Review., 5, 327–373. https://doi.org/10.31881/TLR.2022.27

Jaikishun, S., Li, W., Yang, Z., & Song, S. (2019). Quinoa: In Perspective of Global Challenges. Agronomy, 9(4), 176. https://doi.org/10.3390/agronomy9040176

Javed, T., Ghzal, Q., Zghair, A. N., Haider, M. N., Abed, M. J., Jasim, L. S., & Iftikhar, R. (2025). Sustainable Dye Wastewater Treatment: A Review of Effective Strategies and Future Directions. Physical Chemistry Research, Online First. https://doi.org/10.22036/pcr.2025.501339.2633

Kan, H., Soklun, H., Yang, Z., Wu, R., Shen, J., Qu, G., & Wang, T. (2020). Purification of dye wastewater using bicarbonate activated hydrogen peroxide: Reaction process and mechanisms. Separation and Purification Technology, 232, 115974. https://doi.org/10.1016/j.seppur.2019.115974

Kumari, R., Mohanta, J., Sambasivaiah, B., Qaiyum, M. A., Dey, B., Samal, P. P., Dutta, S., & Dey, S. (2023). Dye sequestration from aqueous phase using natural and synthetic adsorbents in batch mode: Present status and future perspectives. International Journal of Environmental Science and Technology, 20(12), 14033–14052. https://doi.org/10.1007/s13762-023-04782-3

Kumkum, P., & Kumar, S. (2024). A Review on Biochar as an Adsorbent for Pb(II) Removal from Water. Biomass, 4(2), 243–272. https://doi.org/10.3390/biomass4020012

Kusumlata, Ambade, B., Kumar, A., & Gautam, S. (2024). Sustainable Solutions: Reviewing the Future of Textile Dye Contaminant Removal with Emerging Biological Treatments. Limnological Review, 24(2), 126–149. https://doi.org/10.3390/limnolrev24020007

Largo, F., Haounati, R., Akhouairi, S., Ouachtak, H., El Haouti, R., El Guerdaoui, A., Hafid, N., Santos, D. M. F., Akbal, F., Kuleyin, A., Jada, A., & Addi, A. A. (2020). Adsorptive removal of both cationic and anionic dyes by using sepiolite clay mineral as adsorbent: Experimental and molecular dynamic simulation studies. Journal of Molecular Liquids, 318, 114247. https://doi.org/10.1016/j.molliq.2020.114247

Majeed, A., Amjad, M., Imran, M., Murtaza, B., Naeem, M. A., Jawad, H., Qaisrani, S. A., & Akhtar, S. S. (2023a). Iron enriched quinoa biochar enhances Nickel phytoremediation potential of Helianthus annuus L. by its immobilization and attenuation of oxidative stress: Implications for human health. International Journal of Phytoremediation, 25(13), 1830–1843. https://doi.org/10.1080/15226514.2023.2200834

Majeed, A., Amjad, M., Imran, M., Murtaza, B., Naeem, M. A., Jawad, H., Qaisrani, S. A., & Akhtar, S. S. (2023b). Iron enriched quinoa biochar enhances Nickel phytoremediation potential of Helianthus annuus L. by its immobilization and attenuation of oxidative stress: Implications for human health. International Journal of Phytoremediation, 25(13), 1830–1843. https://doi.org/10.1080/15226514.2023.2200834

Mcyotto, F., Wei, Q., Macharia, D. K., Huang, M., Shen, C., & Chow, C. W. K. (2021). Effect of dye structure on color removal efficiency by coagulation. Chemical Engineering Journal, 405, 126674. https://doi.org/10.1016/j.cej.2020.126674

Mehta, M., Sharma, M., Pathania, K., Jena, P. K., & Bhushan, I. (2021). Degradation of synthetic dyes using nanoparticles: A mini-review. Environmental Science and Pollution Research, 28(36), 49434–49446. https://doi.org/10.1007/s11356-021-15470-5

Mojiri, A., Zhou, J. L., KarimiDermani, B., Razmi, E., & Kasmuri, N. (2023). Anaerobic Membrane Bioreactor (AnMBR) for the Removal of Dyes from Water and Wastewater: Progress, Challenges, and Future Perspectives. Processes, 11(3), 855. https://doi.org/10.3390/pr11030855

Mousa, M. A. A., Abo-Elyousr, K. A. M., Ibrahim, O. H. M., Alshareef, N. O., & Eissa, M. A. (2022). Shrimp-Waste-Derived Biochar Induces Metal Toxicity Tolerance of Wastewater-Irrigated Quinoa (Chenopodium quinoa). Agriculture, 12(11), 1748. https://doi.org/10.3390/agriculture12111748

Naeem, M. A., Shabbir, A., Amjad, M., Abbas, G., Imran, M., Murtaza, B., Tahir, M., & Ahmad, A. (2020). Acid treated biochar enhances cadmium tolerance by restricting its uptake and improving physio-chemical attributes in quinoa (Chenopodium quinoa Willd.). Ecotoxicology and Environmental Safety, 191, 110218. https://doi.org/10.1016/j.ecoenv.2020.110218

Nour, H. M., Khater, H. A., Salem, A. A., & Abdelkader, N. H. (2024). The comparison effects of quinoa stalks activated carbon on adsorption of cadmium and lead polluted soils. Egyptian Journal of Chemistry. https://doi.org/10.21608/ejchem.2024.275802.9433

Nowak, V., Du, J., & Charrondière, U. R. (2016). Assessment of the nutritional composition of quinoa (Chenopodium quinoa Willd.). Food Chemistry, 193, 47–54. https://doi.org/10.1016/j.foodchem.2015.02.111

Oon, Y.-L., Ong, S.-A., Ho, L.-N., Wong, Y.-S., Dahalan, F. A., Oon, Y.-S., Teoh, T.-P., Lehl, H. K., & Thung, W.-E. (2020). Constructed wetland–microbial fuel cell for azo dyes degradation and energy recovery: Influence of molecular structure, kinetics, mechanisms and degradation pathways. Science of The Total Environment, 720, 137370. https://doi.org/10.1016/j.scitotenv.2020.137370

Patra, J. M., Panda, S. S., & Dhal, N. K. (2017). Biochar as a low-cost adsorbent for heavy metal removal: A review.

Qi, X., Tong, X., Pan, W., Zeng, Q., You, S., & Shen, J. (2021). Recent advances in polysaccharide-based adsorbents for wastewater treatment. Journal of Cleaner Production, 315, 128221. https://doi.org/10.1016/j.jclepro.2021.128221

Qurrat-ul-Ain, Khurshid, S., Gul, Z., Khatoon, J., Raza Shah, M., Hamid, I., Tawab Khan, I. A., & Aslam, F. (2020). Anionic azo dyes removal from water using amine-functionalized cobalt–iron oxide nanoparticles: A comparative time-dependent study and structural optimization towards the removal mechanism. RSC Advances, 10(2), 1021–1041. https://doi.org/10.1039/C9RA07686G

Raninga, M., Mudgal, A., Patel, V. K., Patel, J., & Kumar Sinha, M. (2023). Modification of activated carbon-based adsorbent for removal of industrial dyes and heavy metals: A review. Materials Today: Proceedings, 77, 286–294. https://doi.org/10.1016/j.matpr.2022.11.358

Ren, G., Teng, C., Fan, X., Guo, S., Zhao, G., Zhang, L., Liang, Z., & Qin, P. (2023). Nutrient composition, functional activity and industrial applications of quinoa (Chenopodium quinoa Willd.). Food Chemistry, 410, 135290. https://doi.org/10.1016/j.foodchem.2022.135290

Sahoo, J. K., Hota, A., Singh, C., Barik, S., Sahu, N., Sahoo, S. K., Sahu, M. K., & Sahoo, H. (2023). Rice husk and rice straw based materials for toxic metals and dyes removal: A comprehensive and critical review. International Journal of Environmental Analytical Chemistry, 103(20), 9131–9153. https://doi.org/10.1080/03067319.2021.2003349

Salama, D. M., Abd el-aziz, M. E., El-naggar, M. E., Shaaban, E. A., & Abd el-wahed, M. S. (2021). Synthesis of an eco-friendly nanocomposite fertilizer for common bean based on carbon nanoparticles from agricultural waste biochar. Pedosphere, 31(6), 923–933. https://doi.org/10.1016/S1002-0160(21)60024-3

Santhosh, C., Daneshvar, E., Tripathi, K. M., Baltrėnas, P., Kim, T., Baltrėnaitė, E., & Bhatnagar, A. (2020). Synthesis and characterization of magnetic biochar adsorbents for the removal of

Cr(VI) and Acid orange 7 dye from aqueous solution. Environmental Science and Pollution Research, 27(26), 32874–32887. https://doi.org/10.1007/s11356-020-09275-1

Satyam, S., & Patra, S. (2024). Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review. Heliyon, 10(9), e29573. https://doi.org/10.1016/j.heliyon.2024.e29573

Sharma, B., Kumari, N., Mathur, S., & Sharma, V. (2022). A systematic review on iron-based nanoparticle-mediated clean-up of textile dyes: Challenges and prospects of scale-up technologies. Environmental Science and Pollution Research, 29(1), 312–331. https://doi.org/10.1007/s11356-021-16846-3

Shi, C., Wang, Y., Zhang, K., Lichtfouse, E., Li, C., & Zhang, Y. (2022). Fe-biochar as a safe and efficient catalyst to activate peracetic acid for the removal of the acid orange dye from water. Chemosphere, 307, 135686. https://doi.org/10.1016/j.chemosphere.2022.135686

Sillanpää, M., Mahvi, A. H., Balarak, D., & Khatibi, A. D. (2023). Adsorption of Acid orange 7 dyes from aqueous solution using Polypyrrole/nanosilica composite: Experimental and modelling. International Journal of Environmental Analytical Chemistry, 103(1), 212–229. https://doi.org/10.1080/03067319.2020.1855338

Slama, H. B., Chenari Bouket, A., Pourhassan, Z., Alenezi, F. N., Silini, A., Cherif-Silini, H., Oszako, T., Luptakova, L., Golińska, P., & Belbahri, L. (2021). Diversity of Synthetic Dyes from Textile Industries, Discharge Impacts and Treatment Methods. Applied Sciences, 11(14), 6255. https://doi.org/10.3390/app11146255

Srivastava, A., Rani, R. M., Patle, D. S., & Kumar, S. (2022). Emerging bioremediation technologies for the treatment of textile wastewater containing synthetic dyes: A comprehensive review. Journal of Chemical Technology & Biotechnology, 97(1), 26–41. https://doi.org/10.1002/jctb.6891

Stejskal, J., & Prokeš, J. (2020). Conductivity and morphology of polyaniline and polypyrrole prepared in the presence of organic dyes. Synthetic Metals, 264, 116373. https://doi.org/10.1016/j.synthmet.2020.116373

Tomar, T., Kahandawala, N., Kaur, J., Thounaojam, L., Choudhary, I., & Bera, S. (2023). Bioremediation of synthetic dyes from wastewater by using microbial nanocomposites: An emerging field for water pollution management. Biocatalysis and Agricultural Biotechnology, 51, 102767. https://doi.org/10.1016/j.bcab.2023.102767

Tourajzadeh, O., Piri, H., Naserin, A., & Cahri, M. mahdi. (2024). Effect of Nano Biochar addition and deficit irrigation on growth, physiology and water productivity of quinoa plants under salinity conditions. Environmental and Experimental Botany, 217, 105564. https://doi.org/10.1016/j.envexpbot.2023.105564

Urbano, B. F., Bustamante, S., Palacio, D. A., Vera, M., & Rivas, B. L. (2020). Polymer supports for the removal and degradation of hazardous organic pollutants: An overview. Polymer International, 69(4), 333–345. https://doi.org/10.1002/pi.5961

Vilcacundo, R., & Hernández-Ledesma, B. (2017). Nutritional and biological value of quinoa (Chenopodium quinoa Willd.). Current Opinion in Food Science, 14, 1–6. https://doi.org/10.1016/j.cofs.2016.11.007

Xia, Y., Wang, G., Guo, L., Dai, Q., & Ma, X. (2020). Electrochemical oxidation of Acid Orange 7 azo dye using a PbO2 electrode: Parameter optimization, reaction mechanism and toxicity evaluation. Chemosphere, 241, 125010. https://doi.org/10.1016/j.chemosphere.2019.125010

Xie, S., Huang, L., Su, C., Yan, J., Chen, Z., Li, M., Du, M., & Zhang, H. (2024). Application of clay minerals as adsorbents for removing heavy metals from the environment. Green and Smart Mining Engineering, 1(3), 249–261. https://doi.org/10.1016/j.gsme.2024.07.002

Yang, A., Akhtar, S. S., Li, L., Fu, Q., Li, Q., Naeem, M. A., He, X., Zhang, Z., & Jacobsen, S.-E. (2020). Biochar Mitigates Combined Effects of Drought and Salinity Stress in Quinoa. Agronomy, 10(6), 912. https://doi.org/10.3390/agronomy10060912

Zaheer, Z., AbuBaker Bawazir, W., Al-Bukhari, S. M., & Basaleh, A. S. (2019). Adsorption, equilibrium isotherm, and thermodynamic studies to the removal of acid orange 7. Materials Chemistry and Physics, 232, 109–120. https://doi.org/10.1016/j.matchemphys.2019.04.064

Zhang, B., Wu, Y., & Cha, L. (2020). Removal of methyl orange dye using activated biochar derived from pomelo peel wastes: Performance, isotherm, and kinetic studies. Journal of Dispersion Science and Technology, 41(1), 125–136. https://doi.org/10.1080/01932691.2018.1561298

Zhang, M., Lin, K., Zhong, Y., Zhang, D., Ahmad, M., Yu, J., Fu, H., Xu, L., Wu, S., & Huang, L. (2022). Functionalizing biochar by Co-pyrolysis shaddock peel with red mud for removing acid orange 7 from water. Environmental Pollution, 299, 118893. https://doi.org/10.1016/j.envpol.2022.118893

Zhao, D., & Cai, C. (2021). Cerium-based UiO-66 metal-organic framework for synergistic dye adsorption and photodegradation: A discussion of the mechanism. Dyes and Pigments, 185, 108957. https://doi.org/10.1016/j.dyepig.2020.108957