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Recent Studies on Orange Peel-Based Biochar: Minireview

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ABSTRACT

Biochar, a material made mostly of carbon, is made by heating types of waste biomass at high temperatures from 300 to 900 °C. Orange peels are a part of the food waste generated every year. They can be turned into biochar, which's rich in carbon and can be used to clean wastewater. In this study biochar made from orange peels was effective in removing types of pollutants. The temperature at which the biochar was made had an impact on how well it worked. When the temperature was higher, less biochar was made. The biochar had good properties like high carbon content, a big surface area and more fixed carbon. The results highlight the potential of orange peel-derived biochar as an adsorbent, for wastewater treatment. Adsorption capacities were strongly influenced by experiment conditions. It was noted that adsorption data was obeying Langmuir model and Freundlich isotherm. In conclusion, dye compounds, organic pollutants, heavy metal ions and could be effectively removed using orange peel-based biochar.

Introduction:

Biochar is a carbon-rich charcoal-like substance, made from organic materials, through a process called pyrolysis, where the material is heated in a low-oxygen or oxygen-limited environment, between 400°C and 700°C. The resulting product is highly carbon-rich (Nair et al., 2026), chemically stable, sterile immediately after production, and can support microbial life once introduced to soil or other environments. Orange peel biochar is a carbon-rich material derived from citrus peel waste, used for several purposes which includes pollutant adsorption, soil improvement, environmental remediation and carbon sequestration. Its effectiveness depends on pyrolysis temperature, contact time, functional group composition, and application rate. It remains a sustainable solution for managing citrus waste while improving environmental quality and soil.

Dye chemicals are colored organic molecules that give materials their color by absorbing and reflecting light wavelengths (Garg et al., 2025). They are categorized by their chemical structure or application technique and adhere to substrates at molecular levels via chemical bonding or physical force. Unlike most organic compounds, dyes possess color because they absorb light in the visible spectrum (400–700 nm), have at least one chromophore (color-bearing group), have a conjugated structure with alternating double and single bonds, and exhibit resonance of electrons, which is a stabilizing force in organic compounds. When any one of these features is lacking from the molecular structure the color is lost. In addition to chromophores, most dyes also contain groups known as auxochromes (Yagub et al., 2014), where their presence can shift the color of a colorant and they are most often used to influence dye solubility.

Dyes are broadly classified by their chemical structure and application methods. They are a commercially important family of azo compounds (Sushmita and Chattopadhyaya, 2013). They are synthetic and do not occur naturally. Azo dyes comprise 60–70% of all dyes used in textile and food industries. Many kinds of azo dyes are known, and several classification systems exist. Some classes include disperse dyes, metal-complex dyes, reactive dyes, and substantive dyes. These are employed for cellulose-based textiles, which include cotton. The dyes bind to the textile by non-electrostatic forces. Azo dyes can be classified according to the number of azo groups. Azo dyes derived from benzidine are carcinogens; exposure to them has classically been associated with bladder cancer.

Isotherm studies conducted using the well-known Langmuir and Freundlich isotherms at a range of temperatures, this revealed that when adsorption reaches equilibrium, the molecules are divided across the liquid and solid phases and at a range of temperatures, a study of adsorption isotherms was conducted using the well-known Langmuir and Freundlich isotherms (Gholam et al., 2026). Langmuir model operates under the presumption that adsorptions take place on the adsorbent at homogeneous spots. Freundlich model acknowledges the existence of heterogeneity on the surface and assumes that adsorption takes place at locations that have varying amounts of adsorption energy (Sethi et al., 2025).

Several methods have been used to remove diuron from water. Biological treatment usually includes biological wastewater treatment in which living organisms are used for control of the target materials. Filtration in water treatment is a physical or chemical process whereby water is passed through a porous material to filter out suspended solids, turbidity, and microorganisms from it. It serves as a last defense mechanism to clean up any residue before disinfection. Advanced oxidation processes in water treatment are chemical processes which oxidize persistent organic compounds and pathogens using hydroxyl radicals. These processes are meant to decompose difficult-to-treat pollutants such as pharmaceuticals, pesticides, and industrial chemicals into nonharmful products. Disadvantages of biological treatment, filtration and advanced oxidation processes techniques were low efficiency, high costs and secondary pollution, respectively. However, lack of comparative studies on the removal of diuron were reported. Here, adsorption capacities or removal efficiency will be reported based on different experimental conditions.

Citrus sinensis is a mix of pomelo and mandarin. Some popular types of oranges are created by crossing different varieties, for example Valencia oranges, blood oranges and navel oranges. Oranges are valuable and are used in ways (Ben et al., 2023). People eat them as fruit and use them to make essential oil. The flowers of the orange tree are useful for things just like the leaves and wood. Orange trees originally come from Southern China, Northeast India and Myanmar. Now you can find orange trees in parts of the world, especially in subtropical and tropical areas because they produce sweet fruit. People eat fresh oranges. Turn them into juice and they also peel oil from the skin of the oranges. The orange fruit and its products are enjoyed by people all over the world. Oranges are a popular fruit. Orange peel biochar is a carbon-rich material derived from citrus peel waste, used for several purposes which includes pollutant adsorption (Revathi et al., 2025), soil improvement, environmental remediation and carbon sequestration. Its effectiveness depends on pyrolysis temperature, contact time, functional group composition, and application rate. It remains a sustainable solution for managing citrus waste while improving environmental quality and soil (Aboagye et al., 2017).

In this work, preparation of orange peel-based biochar was reported. Properties of this sample were mentioned through literature survey. Removal of different types of pollutants was highlighted, and adsorption data was explained. Thermodynamic studies were described and nature of adsorption process will be determined.

Method:

A comprehensive search was carried out through several types of databases such as Scopus, Google Scholar, Web of Sciences and MEDLINE. Several related keywords such as biochar, orange peel, wastewater treatment, adsorption, surface area, removal capacity, dye compounds, heavy metal ions, organic pollutants, Langmuir model and Freundlich isotherm were searched. As a result, there are 400 papers published between 2013 and 2026 met with inclusion criteria.

Results:

There are 400 papers published in English version in the initial search stage. Following removal of 120 duplicates, 280 papers were subjected to title and abstract screening process. Finally, 80 papers were included in this work due to related to these research objectives. Inclusion criteria such as biochar, orange peel, wastewater treatment, adsorption, surface area, removal capacity, dye compounds, heavy metal ions, organic pollutants, Langmuir model and Freundlich isotherm were searched. While exclusion criteria such as production costs, charcoal prices, and recycled used charcoal.

Literature survey:

Citrus sinensis

Citrus sinensis is a cross between pomelo and mandarin. Hybrid sweet oranges include some well-known varieties, namely Valencia oranges, blood oranges, and navel oranges. The orange fruit is one of the most valuable agricultural crops that is used not only as a fruit but also as an ingredient for the preparation of essential oil. Orange flowers are used for various purposes as well as orange leaves and wood. Orange tree originates from Southern China, Northeast India, and Myanmar. Orange trees are grown all over the world in subtropical and tropical regions because of their sweet fruit. The fruit of the orange tree can be consumed fresh or processed into juice or peel oil. In 2024, the world produced 67.2 million tons of oranges, with Brazil supplying 23% of the total amount (Table 1), while China and Mexico follow next.

Oranges, with different taste – from sweet to sour, are eaten as desserts when peeled raw. Orange juice is pressed out using a special device and collected in a basin placed below. This process can be done either at home or, in large amounts, industrially. Orange flesh contains 87% of water, 12% carbohydrates, 1% of protein, and no fats. In reference to 100 g, orange flesh consists of 47 calories and is a great source of vitamin C, containing 59% of the Daily Value. There are no other micronutrients in orange flesh in any considerable quantities. Oranges are used for making jams in many countries, and in Britain, bitter Seville oranges are used for making marmalade. All of Spain's production of oranges is sent to Britain for this purpose. All parts of an orange are used in marmalade-making.

Table 1: Global production of oranges in 2024

Country	Millions of tonnes
Brazil	15.7
China	7.6
Mexico	4.8
Egypt	4.2
India	3.9
Spain	2.9
Total	67.2

Properties and the removal capacity of an adsorbent

The samples' microstructures were examined by scanning electron microscopy (SEM). It is found that the microstructure of orange peel-based sample carbonized at 400 °C has a smoother surface without any pores apart from the tubular channels of orange peel itself, thus, its pores are larger in size and therefore unsuitable for adsorption of pollutants in water. Carbonizing at 800 °C results in more pores on the sample surface depending on the concentration of KOH. The surface of the orange peel-based sample carbonized in 9M KOH has the highest number of pores as highlighted in figure 1 (Weichao et al., 2022). Orange peel-based biochar that was dissolved by 9 mol/L KOH solution showed the best adsorption performance towards the three pollutants. Its adsorption rate in the methylene blue solution is 99.17%. In the tetracycline and fluorescein sodium solutions, it reaches 73.50% and 94.24%, respectively. Large specific surface area (1046.5 m^2/g) allows enhancing the contact area between adsorbent and pollutant. Moreover, numerous oxygen-containing functional groups play an important role in contaminant adsorption. Pseudo first order and, pseudo second order kinetics have been employed for the fitting of adsorption kinetic data and comparison between them to understand the mechanism of adsorption. In general, the initial stage of the reaction process, particularly the initial stage of fast adsorption, is well compatible with pseudo first order kinetics. Pseudo second order kinetics is well compatible with long term adsorption where chemical adsorption is rate controlling. The obtained results revealed a good fit of the real adsorption data with the linear form of first order kinetics.

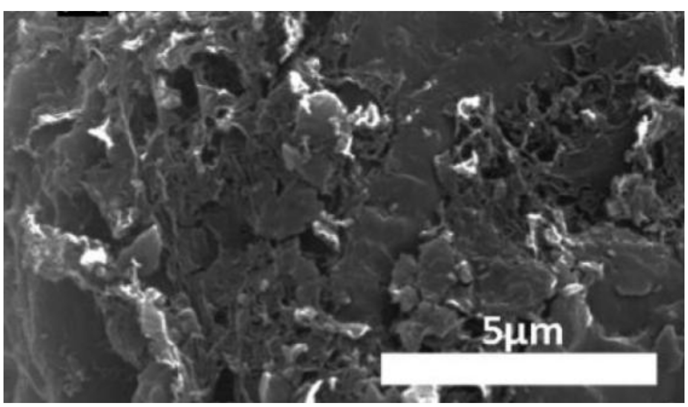

Figure 1. SEM images of orange peel-based samples

Phosphorus not only plays an essential role in making up the human dental and skeleton system, but it is also a key element influencing plant growth and development. Nevertheless, too much phosphorus, which always appears in the form of phosphate, affects aquatic environment through many negative ways, such as decreased growth of plants and oxygen solubility. Decreased oxygen solubility kills off aquatic life forms and damages significantly the quality of groundwater. Rate of eutrophication has increased enormously because of the excessive application of chemical fertilizers in agriculture, aquaculture practices, and phosphorus-containing detergents used to produce urban domestic sewage. Complex structure of functional groups and porous structure make biochar extremely efficient in removing hazardous substances from water. Orange peel biochar was obtained by slow pyrolysis at 300°C, 400°C, and 500°C for 6 hours in this study (Yue et al., 2023). The results indicated that orange peel biochar (81.2%) could be produced at the maximum yield of 300°C. The results obtained by using BET analysis suggested that the specific surface area, average pore size, and volume were 2.4 m2/g, 7.16 nm and 0.0054 cm3/g respectively. It was observed that 5 g of orange peel biochar could absorb around 5.79 mg/g of phosphate in 26 h and the efficiency of absorption was 81.1 %. Adsorption process of phosphate using orange peel biochar was consistent with second order kinetic model and was governed by chemical adsorption.

When we looked at the biochar after it was heated, we saw that the surface area of the biochar got a lot bigger. But when we raised the temperature from 500 °C to 700 °C we got biochar. It went down from 28 percent to 13.5 percent. This happened because the carbonization process got stronger and the lignin and cellulose in the biochar turned into ash and fixed carbon. Heating the biochar at temperatures makes the organic compounds turn into gas, which makes the biochar more porous and gives it a bigger surface area. This is what we want for things that absorb substances. Both the microbiochar and the nanobiochar had a lot of surface area and space inside when we heated them at higher temperatures. The nanobiochar always had a surface area and more space inside than the microbiochar no matter what temperature we used. The best one was the nanobiochar that we made at 700 °C. It had a surface area of 296 meters per gram and a lot of space inside (Aairah et al., 2025). This means it has a lot of places where it can absorb things, which makes the 700 °C nanobiochar good at absorbing substances. The EDX spectra showed peaks for carbon, oxygen, potassium, magnesium and calcium before and after the material was heated. This means that these minerals were still present and spread out on the surface of both the small biochar after it was heated. The peaks got stronger after heating, which's a good sign. The results from the EDS test also showed that the biochar has a lot of carbon and keeps the minerals that help it work well. These results suggest that biochar, the small kind, could be useful for cleaning up the environment. When the biochar is heated to temperatures the minerals inside it start to rearrange and form more ordered structures. The XRD test showed that the big and small biochar have patterns but there are some big differences in the peaks. This means that the minerals are getting more crystalline and changing shape. The peaks get sharper. Move to different positions when the temperature gets higher, which shows that the original minerals are breaking down and new ones are forming. To see if this biochar can be used for applications, the small biochar that was heated to 700 °C was tested to see how well it can absorb things. It was able to remove a lot of lithium, methylene blue and Eriochrome Black T. 58.5 mg/g, 45.3 mg/g and 46.1 mg/g respectively. This is a sign that it could be used to clean up pollutants.

Element such as lead is a bad thing for people. It can hurt the brain and the nervous system. If kids eat or breathe in lead it can cause problems with how they grow and learn. It can also cause heart problems in adults. Copper is a story. We need a bit of copper to be healthy. It helps our bodies make energy. It helps our brains grow. If we eat or breathe in too much copper it can be very bad for us. It can cause stomach problems, hurt our organs and even cause problems with our brains. Someone made a kind of material called oil-based drilling cutting pyrolysis doped orange biochar composite. They made it by heating up oil-based drilling cuttings and orange peels. They wanted to see if this material could help get rid of lead and copper from water. The results were good. This material is very good at picking up lead and copper. It is better than materials that are made from just oil-based drilling cuttings or just orange peels. When they studied how this material worked, they found out that it was very good at picking up lead and copper. They also found out that it could hold a lot of lead and copper. The material could pick up 95.11 milligrams of copper per gram and 164.08 milligrams of lead per gram (Gao et al., 2023). This is good news because it means that this material could be used to help get rid of lead and copper from water and make people healthier.

Overwhelming amounts of release of toxic heavy metals like cadmium into the environment is a big worry across the globe because of their hazardous effects on all forms of life. Sectors like mining, refining, electroplating, electronics, alloys, batteries, and pesticides are among the most dangerous to human lives since they discharge various amounts of wastewater containing toxic heavy metals into the environment. One of these toxic heavy metals is cadmium, which causes various problems ranging from emphysema, renal damage, high blood pressure, and testicular atrophy. Exposure to cadmium even in low levels can have long-term impacts on man health hence; it is a substance in the priority list of pollutants. Removal of toxic heavy metals is environmentally crucial and hence, scientifically of much value for investigations into simpler and efficient ways of doing the same. The common methods of removal of toxic heavy metals from water include chemical precipitation, solvent extraction, flotation, lime coagulation, ion exchange, reverse osmosis, and adsorption. The abundant utilization of various adsorbents and chars is attributed to the complexing agents present in them that enhance their capacity to remove toxic metals. The biochar samples obtained from orange peels were characterized by poor porosities and roughness. Hence, their poor textural properties can lead to the conclusion that adsorption of Cd might occur predominantly due to high surface functionality. Thus, points at which adsorption is maximal for orange peel biochar were found to be equal to 100 mg/L of initial cadmium concentration and pH=5. The poor adsorption of $Cd2+$ in low pH environment could be due to competition between hydrogen ions and metal cations for available adsorption sites, while increased pH level promotes metal adsorption primarily due to negatively charged sites (Hossien et al., 2017). Concerning orange peel biochar, 55.6% of cadmium was adsorbed within the first 30 minutes; after that period, adsorption gradually increased up to 86.2%. Beyond 60 minutes, there was no further increase in removal percent of cadmium, showing equilibrium condition. Removal rate of metal was initially rapid due to availability of large surface area of the adsorbent to cadmium ions. With increasing time, more quantity of cadmium was settled on adsorbent surface, leading to reducing availability of surface area for cadmium ions. As has been widely discussed in literature, it normally leads to a two-step sorption process, where the first step occurs rapidly and predominantly whereas the second step occurs slowly and insignificantly. Energetic analysis of the process is very important for determining the feasibility and spontaneity of the adsorption process as well as its practical implementation. Equilibrium results give the correct basis for evaluating the equilibrium constant which can be used in van Hoff equation for calculation of thermodynamic parameters. As seen from the obtained values for ΔH, the adsorption of cadmium ions on the surface of adsorbents is endothermic in nature. The negative ΔG value indicates the feasibility and spontaneity of cadmium ions adsorption. The kinetic results indicate that the pseudo-second order model describes the kinetics of adsorption more successfully than others.

From the findings, the pH value of the point of zero charge of biochar was 9.5. Equilibrium can be achieved very quickly (within 1 minute) during kinetic studies and 80.6–96.9% removal rate can be obtained (Hai et al., 2015). The findings were found to fit the pseudo-second-order model well. The Langmuir model was used to estimate the adsorption capacity. The adsorption capacity of Cd on biochar was not influenced by the pyrolysis temperature and heating time. The maximum adsorption capacity of Cd was 114.69 mg/g. The adsorption of Cd on biochar was chemisorption. The dominant mechanisms of adsorption were $C\pi$ – cation interaction and surface precipitation. Cadmium could react with calcite to precipitate (Ca, Cd) $CO3$ on biochar. Comparing cadmium removal efficiency of a magnetized biochar based on orange peel with those of conventional orange peel and unmodified biochar.

The orange peel biochar was pretreated with sulfuric acid solution and was found to have a high amount of carbon and oxygen with 48.8% and 46.56%, respectively (Dhafir et al., 2019). This biochar was characterized with the help of bulk density, ash content, and moisture content, which were found to be 0.6 g/mL, 4% and 1.6%, respectively. The weak peak appearing around 2900 cm^{-1} is associated with aliphatic C–H stretching (methine, methyl and methylene groups of side chains). The peak occurring at 1700 cm^{-1} corresponds to the C=O stretching of ketones, aldehydes, lactones or carboxyl groups, while the peak at 1600-1580 cm^{-1} is related to C=C vibrations in aromatic rings. The IR peaks within 1300 and 1000 cm^{-1} belong to the oxidized carbon materials and can be associated with C–O and/or C–O–C stretching in acids, alcohols, phenols, ethers and/or esters groups and sulphonic acid groups. Thus, FT-IR spectrum of the sample before the adsorption process indicates that the external surface of the sample has many functional groups, including carboxylic and carbonyl species oxygen. When the methylene blue is adsorbed on the surface of the sample, the band intensity is decreased in the presence of methylene blue molecules. Spectral changes observed above signify that the presence of these functional groups is possible on the surface of the sample in the adsorption process. XRD spectra reveal a broad hump revealing that the carbon sample is amorphous in nature. However, second hump observed near 40º reveals the existence of short-range crystallographic ordering in the sample. Point of zero charge of the sample was 4.80 which reveals the acidic nature of the surface of the sample. In general, adsorption of anions is favorable at pH below point of zero as the surface of the sample is positive in nature due to protonation. Conversely, adsorption of cations takes place above the point of zero pH as the surface of the sample becomes negative in nature. Dye removal was performed using 0.08 g sample and further increase in dosage did not affect much in the methylene blue removal. Increase in the adsorption with respect to dosage was because of the increase in surface area of the adsorbent as the adsorption sites become more in number. No increase in dye removal was observed beyond 0.08 g/ 100 mL sample dose because of conglomeration of adsorbent particles.

Hexadecyl trimethyl ammonium bromide, also known as CTAB, is a useful and cheap substance that helps with cleaning. It makes the spaces between layers of a material and the surface area larger. This is good for getting rid of things like the dye Congo red. CTAB works with the material to make it better at picking up dye because of the way they attract each other. It was noted that using CTAB with biochar which is a type of charcoal made from living things is a way to make it better at cleaning up the dye. The CTAB was put onto the surface of the orange peel biochar, which's a type of biochar made from orange peels. This made a material that can pick up bad things in many ways. The surface area of the material got a little smaller, going from 697.05 to 618.44 meters per gram (Hua et al., 2023). The average size of the holes in the material got bigger, going from 4.26 to 7.28 nanometers. The CTAB-modified orange peel biochar was much better at picking up the Congo dye than the regular orange peel charcoal. It could pick up a lot more of the dye going from 200 milligrams per gram to 609.8 milligrams per gram. The pH value of the dye solution which's a measure of how acidic or basic it is, had a big effect on how well the biochar worked before and after it was modified with CTAB. The biochar did not work well when the pH value was higher. The CTAB-modified orange peel biochar was used five times to clean up the dye. It still worked well. It was able to remove than 70% of the Congo red dye each time. This shows that the CTAB-modified orange peel biochar is a good material for cleaning up bad dyes, like Congo red. The material is good for staying stable. It can be recycled easily. It is much better than charcoal that is made from orange peels. When we used the orange peel biochar that was modified with CTAB to clean a dye solution that had Congo Red in it the results were like what the Langmuir model says. The biochar was able to absorb a lot of the dye. About 609.8 milligrams for every gram of biochar. The way the biochar absorbed the dye was also like what the quasi-secondary kinetic model says. The main ways the biochar absorbed the dye were through attraction and surface adsorption. The orange peel biochar is good at absorbing the Congo Red dye because of these things.

Eriochrome Black T (EBT) is an azo dye and is also categorized into anionic dye that is used for dyeing silk, wool, and nylon textiles. It is not degradable by the conventional aerobic treatment and biological oxidation process. Dyes are artificial substances that have color and are resistant to fading when exposed to light, chemicals and water. Furthermore, they are organic, non-degradable and have complex aromatic structures. The contamination of water bodies with the presence of dyes results in causing adverse impacts on aquatic life because dyes block sunlight, inhibit photosynthesis activities and disturb re-oxygenation ability. Moreover, surface water and groundwater contamination will result in making water bodies unfit for any other usage purpose and cause cancerous and mutagenic impacts. Amongst synthetic dyes, azo dyes account for 70% of the total market around the globe. Reactive azo dye consists of one or more azo linkage that acts as chromophore in its molecular structure. Moreover, it belongs to the largest group of organic dyes that are difficult to degrade even at low concentrations because of high resistance to light, heat, water, chemicals and microbial attack.

SEM image of orange peel exhibited relatively clear, grid-like pattern with irregular spots before modification. It consisted of large pores whose size was about 50 µm. However, after alteration, the surface morphology of orange peel was changed to give rise to rough surface exhibiting distinct patterns. This is due to the composition of the orange peel being broken down during modification such that the surface becomes irregular thus increasing its contact surface area and structural features due to the presence of pores, which serve as adsorption sites. Pore size was reduced to 30 µm after modification. XRD analysis gives information on the structure, phase, crystal orientation, lattice parameters, crystallite size, strain and crystal defects. From the results of the orange peel biochar and modified orange peel biochar, there was a slight change in peaks (Kanwal et al., 2025). The XRD peak pattern (figure 2) of orange peel biochar at 2θ° was 19.19, 22, 26.6, 33.4, 46.2 and 61.5, while that of modified orange peel biochar had peaks at 2θ° of 16.8, 22.9, 25, 25.5, 44.63, 52.5, 58.8 and 76.96. Three clear peaks of nickel are observable (44.63°, 52.5°, 76.96°). Presence of Ni increases surface sites. The metal Ni exhibits a face-centered cubic crystal structure where atoms are arranged in a certain manner in the crystal lattice. This assists in the adsorption process. The sharpness of the peak is used to estimate the size of the crystallite; the sharper the peak, the larger the crystallite size, while the broadness of the peak represents the small size of the crystallite. It was observed that there was a stronger and sharper XRD peak in modified carbon. Because of highly ordered structural arrangement of graphene layers and increased graphitization. On the other hand, it was found that the adsorbate concentration is among the significant factors that play an essential role in an effective adsorption process. Orange peel biochar exhibited the highest adsorption capacity of EBT at a concentration of 25 ppm (60%), while it had the lowest adsorption capacity of 29% at 100 ppm. On the other hand, in case of modified orange peel biochar, 98% was the maximum adsorption capacity at 25 ppm, while the minimum adsorption capacity of 88% was achieved at a concentration of 100 ppm. As dye concentration increases, the percent dye removed decreases because all active binding sites become saturated at a certain concentration such that no dye molecule interacts with the adsorbent's binding site. Modified orange peel biochar (MOPB) was seen to have a significant improvement in the adsorption capacity than unmodified biochar. Langmuir isotherm model with R2 = 0.99 best fits the adsorption of the EBT dye, meaning that the adsorption of EBT dye onto the MOPB is monolayer adsorption. Pseudo second order kinetics model was established to best fit the reaction (R2 = 0.99), hence being the rate limiting step for the reaction.

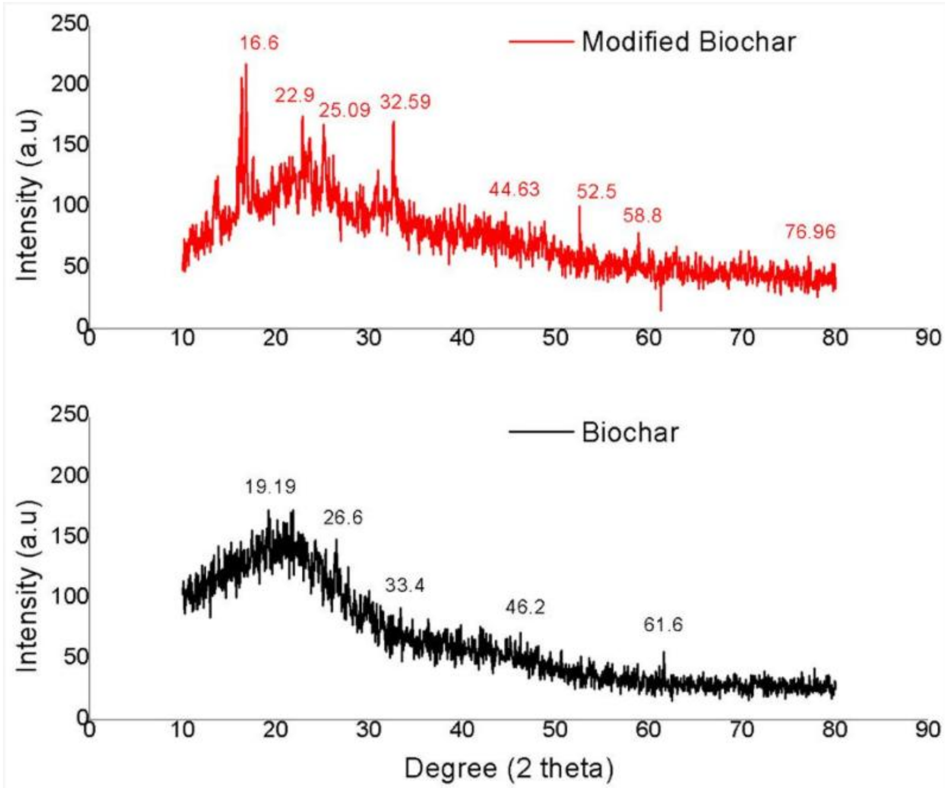

Figure 2: XRD studies of biochar and modified biochar samples

Quinoline is a type of nitrogen-containing compound that comes from coal tar or is made for use. It is a liquid that turns dark when exposed to light. Quinoline is bad for humans due to it can hurt the liver. It is also thought to cause cancer in humans. Some researchers made a kind of charcoal from orange peels. They changed the charcoal with a chemical called NaOH to make it better at grabbing onto things. They used this charcoal to try to remove quinoline from water. The charcoal worked well and could grab onto 197.53 milligrams of quinoline per gram of charcoal. The researchers found out that quinoline sticks to charcoal in a way. It follows a rule called the pseudo-order kinetic model. Charcoal and quinoline also follow another rule called the Freundlich isotherm model. The researchers used a tool to see how quinoline sticks to charcoal. They found out that quinoline likes to stick to parts of the charcoal that have oxygen. These parts are called hydroxyl groups. The researchers think that quinoline sticks to charcoal in a few ways such as hydrogen bonding, acid-base interaction, π–π interactions and n–π interactions. These are all ways that quinoline and charcoal can stick together.

A new kind of activated biochar has been made using orange peel. This activated biochar is good at removing Cr (VI) from water. It has a surface area of 1998 m2/g and a lot of tiny holes that help it work well (Sun et al., 2023). The activated biochar also has groups that contain oxygen and lots of sites that are active. The surface area of the activated biochar is large because it has tiny holes. This means it has sites that can help remove Cr (VI) from water. The size of the holes in the activated biochar is just right for Cr (VI) ions to fit into which helps get rid of them. The activated biochar was tested using a tool to see how much of it was made up of graphitic material. The results showed two bands at 1350 cm^{-1} and 1580 cm^{-1}. These bands are typical of materials that're not perfect graphitic materials. The ratio of these two bands is 1.03 for the activated biochar. This ratio shows how defects the activated biochar has and how disordered its atoms are. The activated biochar is good at removing Cr (VI) from water because of its properties. All these characteristics make KC biochar have active sites. This helps to speed up the adsorption of Cr (VI). The activated biochar has a high absorption capacity for Cr (VI). It can absorb 285.5 milligrams of Cr (VI) per gram for 2400 minutes at a pH of 2. The effects of pH, contact time, concentration and temperature on remediation are studied. The adsorption behavior follows the Elovich model. This shows that the adsorption process happens through chemical reactions. The Langmuir model works better than the Freundlich model for simulating the adsorption isotherm. This means that Cr (VI) adsorption happens in a layer through chemical reactions. Studies on the mechanism show that chemical adsorption, reduction, ion exchange and complexation are involved. These processes are assisted by oxygen-containing groups and porosity.

Glyphosate the ingredient in Roundup is considered the most widely used weed killer in the world. It can pollute soil, groundwaters, surface waters and the bottom of these waters after use. Glyphosate was found in crops, food that has been processed drinking water and medicine products. When it breaks down in soil it turns into acid, a toxic substance that affects many living things. This includes animals, humans and tiny living things in soil and water. Glyphosate and aminomethyl phosphonic acid are usually found together in the environment. Diuron does not break down easily in water or sunlight. This means it stays in the environment for a time. Diuron does not stick well to soil. It can move through the soil. It can also be carried away by water flowing on the surface. This can cause it to get into groundwater. How easily Diuron moves through soil depends on how much organic matter's, in the soil. Diuron can seep into the ground. Contaminate both ground and surface water.

Several techniques have been used to remove diuron as reported (Table 2). Diuron is a synthetic urea herbicide and algaecide that inhibits the process of photosynthesis in plants. Diuron is extensively used both in agricultural and non-agricultural settings for controlling broad leaf weeds and grass during their emergence. Diuron is a persistent herbicide that presents an extensive threat to the environment and health of individuals. The main disadvantages of diuron herbicide are its high solubility and mobility in water, water toxicity, and potential to be carcinogenic and act as an endocrine disruptor in humans. Moreover, it slowly biodegrades to 3,4-dichloroaniline that usually is more toxic than the original herbicide. Orange peels were used to make eco-friendly activated carbons that are good at removing diuron and glyphosate from water even when the water has a lot of other stuff in it. The activated carbons were made using a process that involves heating the orange peels and using carbon dioxide to activate them. This can be done using heat or special microwave heat. What is interesting is that the materials made using heat were better at removing herbicides like diuron and glyphosate than the ones made using microwave heat even though they did not look as good under a microscope. For example, when they tested the materials with diuron they found that 97 percent of the diuron was removed by the material made with heat and 73 percent was removed by the material made with microwave heat (Sylwia et al., 2025). Orange peels were used to make these activated carbons that can remove a lot of diuron from water. The material made with heat removed 97 percent of the diuron, which is a lot. This is good because diuron is an herbicide that can be bad for the environment. Orange peels were also used to make carbons that can remove glyphosate from water. The material made with heat removed 58 percent of the glyphosate while the material made with microwave heat only removed 25 percent.

The researchers also tested how well the activated carbons made from orange peels could remove diuron and glyphosate from water that has things in it like metals or special kinds of plastics. They used orange peels to make the activated carbons. Then they tested them with water that had things, like copper, cadmium, arsenic and selenium in it. They also tested the activated carbons with water that had kinds of plastics like polyacrylamide in it. It was noted that cationic polyacrylamide helped glyphosate bind more. However, its effect on how the herbicide stuck was not that big. The amount of diuron that came off the materials made was quite low. In total it was 4.36 % after 3 cycles of trying to remove it with water. Adding polymers made this value even lower. Cationic polyacrylamide greatly reduced how much glyphosate came off. It went from 40 % down to low as 0 %. The activated carbon that worked best for adsorption did not hurt plant growth. In fact, it helped plants grow better when glyphosate was around. The activated carbon with the adsorption capacity seemed to be okay, for plants. It helped plants grow well when glyphosate was present.

Table 2: Comparison of adsorption capacity or removal efficiency using different techniques.

	Results	**References**
Nano membranes filtration	Nano-membranes demonstrated high rejection efficiencies (94-97%) in removing reactive blue 15, reactive red 194, reactive yellow 145, reactive black 5, and reactive orange 16.	Reza et al., 2015
syringe filter membrane	Dyes removal was 99.61% for methylene blue and 90.86% and for Eriochrome Black T, respectively.	Subrahmanya et al., 2022
Nano filtration	high rejections to all the reactive blue dyes (> 98.12%)	Mei et al., 2018
Complexation-assisted ultrafiltration	removal of cadmium and zinc ions were found to be greater than 95% and 99%, respectively.	Katarina and Slavica, 2006
Biological treatment	*Trichoderma asperellum* fungus was indicated to have the highest efficiency of cadmium (76.17%) in the alkaline pH.	Mohsenzadeh, and Shahrokhi, (2014)
Biological treatment	Aspergillus *niger* was found to be effective in adsorbing Congo Red (12.1 mg/g of fungus for dye).	Fu and Viraraghavan, 2002
Biodegradation technique	*Galactomyces geotrichum* KL20A isolated from Kumis was employed for methylene blue, reached removal percentages of 70%.	Margarita et al., (2018)
Biological treatment	*Bacillus aryabhattai* DC100 can be used to remove Remazol Brilliant Blue R (23.7%), and indigo Carmine (99%).	Paz et. al., 2017
Hydrodynamic cavitation	The highest efficiency for methylene blue decolorization is about 25%.	Valentina et al., 2022
Photo-assisted advanced oxidation process	Maximum dye removal efficiencies were observed to be 77% for direct red 80.	Vahid and Marzieh, 2021
Advanced oxidation process with TiO_2 nanoparticles	The highest efficiencies of lead and cadmium ions were observed to be 96.69% and 93%, respectively.	Eman and Shahlaa, 2022
Hybrid advanced oxidation process	The highest efficiencies of methylene blue were 94.64% over 1 hour.	Kumar et al., 2017

Economic analysis of biochar technologies

Biochar production involves pyrolysis of abundantly found residues such as agricultural waste, malt dust, and sewage sludge; hence, costs associated with material sourcing and transportation are minimized. Biochar is very cost-effective in the treatment of wastewater since it is sold at about $350 to $1,200/tonne, which is far lower than that of powdered activated carbon ($1,100 to $1,700/tonne). Produced from cheaply available biomass and organic waste, biochar acts as an effective low-cost bio-adsorbent and can remove 70%-99.6% heavy metals, dyes, and organic compounds.

Regeneration potential and stability of biochar

Biochar is an extremely stable and carbonaceous adsorbent. The stability of biochar in wastewater lies in its strong aromatic carbon structure, which does not decompose in a chemical, biological, or thermal manner. This material can absorb metals such as Cu(II), Cd(II), Cr(VI), and Pb(II), owing to their functional groups that are highly stable with metal ions. Due to the strong structure of the pores of biochar, this material can resist hydraulic pressure in filter columns and construct wetlands without degrading easily. As for regeneration capacity, biochar can be used again several times because of its structural stability. It is possible to regenerate it chemically or thermally.

Conclusion:

Researchers prefer used agricultural wastes to make biochar. They do this by heating them up in a way. When they make the biochar, they try things to make it better at absorbing stuff. They want it to have a surface area and lots of pores. This makes it good at picking up things. The biochar is made from orange peels good at this. It has a lot of space to absorb things and the right properties to make it work well. That is why it is great for cleaning the air and water. The way it absorbs things matches what the Langmuir model or Freundlich isotherm says. There are also examples of how it can be used to clean wastewater, based on what other people have written. Research findings have proven that orange peel-based biochar could be used to remove dye compounds, herbicides, pesticides, antibiotics, heavy metal ions and organic pollutants. In future, its massive surface area and developed porous structure can trap pollutants from real wastewater samples.

References:

Aairah T, Pasha M, Shetty A, Pradhan S, Tong Y (2025) Valorization of orange peel via slow pyrolysis: Effect of particle size on biochar characteristics for wastewater remediation. Results in Engineering, 27, https://doi.org/10.1016/j.rineng.2025.106612.

Aboagye D, Kabenge I, Banadda N, Kiggundu N (2017) Assessment of orange peel waste availability in ghana and potential bio-oil yield using fast pyrolysis. Renewable and Sustainable Energy Reviews, DOI: 10.1016/j.rser.2016.11.262Copy to clipboard

Ben H, Sadaka C, Ivana M, Garzoli S, Svarc G (2023) The Chemical Variability, Nutraceutical Value, and Food-Industry and Cosmetic Applications of Citrus Plants: A Critical Review. Antioxidants, DOI: 10.3390/antiox12020481.

Dhafir T, Mohd S, Jawad A. (2019) Biochar from Orange (citrus sinensis) Peels by Acid Activation for Methylene Blue Adsorption. Iran J Chem Chem Eng, 38, 91-105.

Eman J., Shahlaa E. (2022). Lead and Cadmium Ions Removal from Wastewater by Advanced Oxidation Process Using TiO2 Nanoparticles. *Annals of the Romanian Society for Cell Biology*, *26*, 4114–4125.

Fu Y. and Viraraghavan, T. (2002). Removal of Congo Red from an aqueous solution by fungus *Aspergillus niger. Advances in Environmental Research, 7, 239-247.*

Gao Z, Xu Q, Liu Y, Qiu H, Lan G (2023) Biochar Composite Adsorbent for the Removal of Copper (II) and Lead (II) from Wastewater Prepared by the Pyrolysis of Oil-Based Drilling Cuttings and Orange Peels. Analytical Letters, 56, https://doi.org/10.1080/00032719.2023.2185249.

Garg B, Sethi P, Basu S (2025) Strategic innovation in CuBTC/PANI nanocomposites for dye remediation: a holistic approach for enhancing adsorption, isotherms, and kinetic studies. *RSC Sustainability*, 3, 2311-2324 .

Gholam H, Kambiz S, Parvin G, Maryam F, Moosa E (2026) Recent insights into g-C_3N_4 based composites for methylene blue photocatalytic degradation. Results in Engineering, 29, https://doi.org/10.1016/j.rineng.2025.108595.

Hai T, You S, Chao H, (2015) Effect of pyrolysis temperatures and times on the adsorption of cadmium onto orange peel derived biochar. *Waste Management & Research: The Journal for a Sustainable Circular Economy,* 34, https://doi.org/10.1177/0734242X15615.

Hossien S, Mohammad M, Hassan E, Ahmad A, Ahmad H (2017) Comparing cadmium removal efficiency of a magnetized biochar based on orange peel with those of conventional orange peel and unmodified biochar. Desalination and Water Treatment, 82, 157-169.

Hua Z, Pan Y, Hong Q (2023) Adsorption of Congo red dye in water by orange peel biochar modified with CTAB. Royal Society of Chemistry, 13, 12502-12508.

Kanwal A, Idris A, Abid J, Ullah H, Gul S, Waqar U (2025) Nickel-Modified Orange Peel Biochar for the Efficient Adsorptive Removal of Eriochrome Black T from Aqueous Solution. *17*(10), 1484; https://doi.org/10.3390/w17101484.

Katarina T and Slavica S, (2006) Removal of heavy metal ions from water by complexation-assisted ultrafiltration. Chemosphere, 64, 486-491.

Kumar M, Pandit A, Sonawane S (2017) Degradation of methylene blue dye in aqueous solution using hydrodynamic cavitation based hybrid advanced oxidation processes. Chemical Engineering and Processing Process Intensification, 122, 288-295.

Margarita C, Lopez C, Tovar C, William V (2019) Bio-Removal of Methylene Blue from Aqueous Solution by *Galactomyces geotrichum* KL20A. *Water,* , *11,* https://doi.org/10.3390/w11020282.

Mei J, Ye W, Zhao S, Van D, Zhang X (2018) Effective dye purification using tight ceramic ultrafiltration membrane. Journal of Membrane Science, 566, https://doi.org/10.1016/j.memsci.2018.09.001.

Mohsenzadeh, F., Shahrokhi, F. (2014) Biological removing of Cadmium from contaminated media by fungal biomass of *Trichoderma* species. *Journal of Environmental Health Science and Engineering,* **12**, https://doi.org/10.1186/2052-336X-12-102.

Nair M, Sethi P, Singh J, Basu S (2026) Waste-to-work photocatalysis: orange-peel-derived CQD@CdS/biochar hybrids enabling efficient visible-light-driven dye mineralisation and mechanistic elucidation. Royal Society of Chemistry, 7, 5791-5805.

Paz A, Julia C, Jose P, Jose D (2017) Biological treatment of model dyes and textile wastewaters. Chemosphere, 181, 168-177.

Revathi V, Bora S, Tabli G, Nurin A (2025) Orange peel composition, biopolymer extraction, and applications in paper and packaging sector: A review. Sustainable Chemistry and Pharmacy, 43, https://doi.org/10.1016/j.scp.2025.101908.

Reza R, Nik S, Awanis H, Rosmani C, Redzuan R (2015) Synthetic reactive dye wastewater treatment by using nano-membrane filtration, Desalination and Water Treatment, 55, 86-95.

Sethi P, Basu S, Barman S (2025) CuBTC–clay composites with tunable ratios for antibiotic removal: unraveling isotherm, kinetic, and thermodynamic study. Materials Advances, 6, 6370-6385.

Subrahmanya T, Januar W, Hu C, Lai J, (2022) An eco-friendly and reusable syringe filter membrane for the efficient removal of dyes from water via low pressure filtration assisted self-assembling of graphene oxide and SBA-15/PDA. Journal of Cleaner Production, 10.1016/j.jclepro.2022.131425.

Sun Z, Wang G, Chen M, Gao Y, Wang S. (2023) Synthesis, characterization and removal performance of Cr (VI) by orange peel-based activated porous biochar from water. Chemical Engineering Research and Design, 193, https://doi.org/10.1016/j.cherd.2023.03.011.

Sushmita B, Chattopadhyaya C (2013) Adsorption characteristics for the removal of a toxic dye, tartrazine from aqueous solutions by a low cost agricultural by-product. Arabian Journal of Chemistry, 10, S1629-S1638.

Sylwia K, Piotr N, Katarzyna S (2025) Valorization of orange peels through the production of eco-friendly, highly effective adsorbents for herbicides based on one-step CO_2-activation under conventional/microwave heating. Food and Bioproducts Processing, 153, https://doi.org/10.1016/j.fbp.2025.06.008.

Vahid J, Marzieh M (2021) Photo-assisted advanced oxidation processes for efficient removal of anionic and cationic dyes using Bentonite/TiO_2 nano-photocatalyst immobilized with silver nanoparticles. Journal of Molecular Structure, 1239, 10.1016/j.molstruc.2021.130496.

Valentina I, Alessio C, Marina P (2022) Advanced oxidation processes for the removal of dyes from synthetic industrial wastewaters. Desalination and Water Treatment, 315–320.

Weichao Z, Wang Y, Fan L, Liu X, Cao W, Ai H (2022) Sorbent Properties of Orange Peel-Based Biochar for Different Pollutants in Water. Processes, *10*(5), 856; https://doi.org/10.3390/pr10050856.

Yagub M, Sen T, Ang H, Afroze S (2014) Dye and its removal from aqueous solution by adsorption: A review. Advances in Colloid and Interface Science, 209, 172-184.

Yue Z, He X, Qi K, Zada A, Pan J (2023) Study on the adsorption of phosphate over biochar-based adsorbents from peanut shell and orange peel in water. Desalination and Water Treatment, 308, 102-109.